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OpenFAST is a multi-physics, multi-fidelity tool for simulating the coupled dynamic response of wind turbines. Practically speaking, OpenFAST is the framework (or “glue code”) that couples computational modules for aerodynamics, hydrodynamics for offshore structures, control and electrical system (servo) dynamics, and structural dynamics to enable coupled nonlinear aero-hydro-servo-elastic simulation in the time domain. OpenFAST enables the analysis of a range of wind turbine configurations, including two- or three-blade horizontal-axis rotor, pitch or stall regulation, rigid or teetering hub, upwind or downwind rotor, and lattice or tubular tower. The wind turbine can be modeled on land or offshore on fixed-bottom or floating substructures.

Established in 2017, OpenFAST is an open-source software package that builds on FAST v8 (see FAST v8 and the transition to OpenFAST). The glue code and underlying modules are mostly written in Fortran (adhering to the 2003 standard), and modules can also be written in C or C++. It was created with the goal of being a community model developed and used by research laboratories, academia, and industry. It is managed by a dedicated team at the National Renewable Energy Lab. Our objective is to ensure that OpenFAST is well tested, well documented, and self-sustaining software. To that end, we are continually improving the documentation and test coverage for existing code, and we expect that new capabilities will include adequate testing and documentation. If you’d like to contribute, see the Developer Documentation and any open GitHub issues with the Help Wanted tag.

The following links provide more insight into OpenFAST as a software package:

- OpenFAST Github Organization
- Github Repository

Documentation Directory
CHAPTER ONE

THIS DOCUMENTATION

OpenFAST documentation is hosted on readthedocs, and is automatically generated from both the master and dev branches whenever new commits are added. Clicking on the bar on the lower left corner of the page reveals a panel (see image below) containing options to select the branch of the repository, download the documentation other formats (PDF, HTML, EPub), and link to other relevant websites.

While OpenFAST developer documentation is being enhanced here, developers are encouraged to consult the legacy FAST v8 Programmer’s Handbook. Instructions on obtaining and installing OpenFAST are available in Installing OpenFAST, and documentation for verifying an installation with the automated tests is at Testing OpenFAST.

The majority of this documentation is divided into two parts:

User Documentation

Directed towards end-users, this part provides detailed documentation regarding usage of the OpenFAST and its underlying modules, as well as theory and verification documentation.

Developer Documentation

The developer guide is targeted towards users wishing to extend the functionality provided within OpenFAST. Here you will find details regarding the code structure, API supported by various classes, and links to source code documentation extracted using Doxygen.
Guidelines and procedures for obtaining precompiled binaries or compiling OpenFAST from source code are described here. While there are multiple ways to achieve the same outcome, the OpenFAST team has developed a comprehensive and well thought out system for compiling the source code. Thus, the methods described here are the only officially supported and maintained paths for obtaining an OpenFAST executable.

For Windows users only, precompiled binaries are available as described in the Download binaries section. For all platforms, OpenFAST is configured to build with CMake and a system-appropriate build tool. Background on CMake is given in Understanding CMake, and procedures for configuring and compiling are given in CMake with Make for Linux/macOS and CMake with Visual Studio for Windows. Finally, an alternative and more appropriate option for compiling on Windows while doing active software development is given in Visual Studio Solution for Windows.

### 2.1 Download binaries

OpenFAST releases are distributed through the Anaconda package manager via the conda forge channel for macOS and Linux. The OpenFAST glue-code executable as well as the available module drivers are included in the installation. The following commands describe how to create a new environment and install OpenFAST.

```bash
# Create a new conda environment
conda create -n openfast_env

# Install OpenFAST through the Conda Forge channel
conda install -c conda-forge openfast

# Test OpenFAST
openfast -v
```

For Windows users, each tagged release is accompanied by precompiled binaries. DLL’s for MAP and the DISCON controllers are also included. The following architecture and precision combinations are currently available:

- 32 bit single precision
- 64 bit single precision
- 64 bit double precision

All precompiled binaries can be found in the Assets dropdown in the GitHub Releases. To download the latest binaries, click here.

**Important:** The precompiled binaries require either the Intel fortran compiler or the Intel MKL redistributable libraries, which are not by default included with the binaries. To configure the libraries, download the installers from
here and run the MSI file(s) to install the libraries. If you have a Command Prompt open, you will need to close it after installing the libraries in order for the changes to take effect.

## 2.2 Compile from source

For compiling from source code, the NREL OpenFAST team has developed an approach that uses CMake to generate build files for all platforms. Currently, CMake support for Visual Studio while doing active development is not well supported, so OpenFAST maintains a Visual Studio solution giving Windows developers a better option for developing code, compiling and debugging in a streamlined manner. See Visual Studio Solution for Windows for more information.

### 2.2.1 Dependencies

Compiling OpenFAST from source requires additional libraries and tools that are not distributed with the OpenFAST repository. In many cases, these tools can be installed with a system’s package manager (e.g. homebrew for macOS, yum for CentOS/Red Hat, or apt for Debian-based systems like Ubuntu). If binaries are downloaded or compiled manually, be sure they are installed in a standard location for your system so that the other components of the OpenFAST build system can find the dependencies.

#### Build tools

An environment-specific build system is required and will consist of a combination of the packages listed in the table below.

<table>
<thead>
<tr>
<th>Package</th>
<th>Applicable systems</th>
<th>Minimum version</th>
<th>Link</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMake</td>
<td>All</td>
<td>3.0</td>
<td><a href="https://cmake.org">https://cmake.org</a></td>
</tr>
<tr>
<td>GNU Make</td>
<td>macOS, Linux</td>
<td>1.8</td>
<td><a href="https://www.gnu.org/software/make/">https://www.gnu.org/software/make/</a></td>
</tr>
<tr>
<td>GNU Compiler Collection (gfortran, gcc, g++)</td>
<td>macOS, Linux</td>
<td>4.6.0</td>
<td><a href="https://gcc.gnu.org">https://gcc.gnu.org</a></td>
</tr>
</tbody>
</table>

#### Math libraries

Math libraries with the BLAS and LAPACK interfaces are also required. These can be obtained as free, open source libraries or paid, closed source versions. Some packages contain separate libraries for each interface while others have the interfaces bundles into a single binary. The most common options are listed in the table below.

<table>
<thead>
<tr>
<th>Library</th>
<th>Maintainer</th>
<th>Paid/Free</th>
<th>Open Source?</th>
<th>Link</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLAS</td>
<td>NetLib</td>
<td>Free</td>
<td>Yes</td>
<td><a href="http://www.netlib.org/blas/">http://www.netlib.org/blas/</a></td>
</tr>
<tr>
<td>LAPACK</td>
<td>NetLib</td>
<td>Free</td>
<td>Yes</td>
<td><a href="http://www.netlib.org/lapack/">http://www.netlib.org/lapack/</a></td>
</tr>
<tr>
<td>BLAS/LAPACK</td>
<td>OpenBLAS</td>
<td>Free</td>
<td>Yes</td>
<td><a href="https://www.openblas.net">https://www.openblas.net</a></td>
</tr>
<tr>
<td>MKL</td>
<td>Intel</td>
<td>Paid</td>
<td>No</td>
<td><a href="https://software.intel.com/en-us/mkl">https://software.intel.com/en-us/mkl</a></td>
</tr>
</tbody>
</table>
Dependencies for the test suite

The following packages are required to run the test suite:

- Python 3
- MatPlotLib - used for generating error plots

Dependencies for the C++ API

When using the C++ API, the following packages are required:

- HDF5 (provided by HDF5_ROOT)
- yaml-cpp (provided by YAML_ROOT)

2.2.2 Get the code

OpenFAST can be cloned (i.e., downloaded) from its Github repository via the command line:

```
git clone https://github.com/OpenFAST/OpenFAST.git
```

An archive of the source code can also be downloaded directly from these links:

- “master” branch - Stable release
- “dev” branch - Latest updates

2.2.3 Visual Studio Solution for Windows

A complete Visual Studio solution is maintained for working with the OpenFAST on Windows systems. The procedure for configuring the system and proceding with the build process are documentated in the following section:

Building OpenFAST on Windows with Visual Studio

These instructions are specifically for the standalone Visual Studio project at openfast/vs-build. Separate CMake documentation is provided for Windows users at Section 2.2.6.

Prerequisites

1. A version of Visual Studio (VS).
   - Currently VS 2013 Professional and VS 2015 Community Edition have been tested with OpenFAST.
   - A list of Intel Fortran compatible VS versions and specific installation notes are found here.
   - The included C/C++ project files for MAP++ and the Registry are compatible with VS 2013, but will upgrade seemlessly to a newer version of VS.
   - If you download and install Visual Studio 2015 Community Edition, you will need to be sure and select the C/C++ component using the Customize option.

2. Intel Fortran Compiler
   - Currently only version 2017.1 has been tested with OpenFAST, but any newer version should be compatible.
• You can download an Intel Fortran compiler here.
• Only install Intel Fortran after you have completed your Visual Studio installation.

3. Git for Windows

• Download and install git for Windows.

4. Python 3.x for Windows (for regression/unit testing)

• The testing framework of OpenFAST requires the use of Python.
• Please see Section 3 on testing OpenFAST for further information on this topic.
• We have been working with Continuum’s Anaconda installation of Python 3.6 for Windows.

## Compiling OpenFAST

1. Open A command prompt, or git bash shell from the Start menu

2. Create a directory where you will clone OpenFAST repository (change code to your preferred name)

   ```
   mkdir code
   cd code
   ```

3. Clone the OpenFAST repository

   ```
   git clone https://github.com/openfast/openfast.git
   ```

   This will create a directory called openfast within the code directory.

4. Using Windows Explorer, navigate to the directory openfast\vs-build\FAST and double-click on the FAST.sln Visual Studio solution file. This will open Visual Studio with the FAST solution and its associated projects.

   **NOTE:** If you are using Visual Studio 2015 or newer, you will be asked to upgrade both the Fast_Registry.vcxproj and the MAP_dll.vcxproj files to a newer format. Go ahead and accept the upgrade on those files.

5. Select the desired Solution Configuration, such as Release, and the desired Solution Platform, such as x64 by using the drop down boxes located below the menubar.

6. Build the solution using the Build->Build Solution menu option.

7. If the solution built without errors, the executable will be located under the openfast\build\bin folder.

### 2.2.4 Understanding CMake

To more fully understand CMake and its methodology, visit this guide on **running CMake**.

CMake is a build configuration system that creates files as input to a build tool like GNU Make, Visual Studio, or Ninja. CMake does not compile code or run compilers directly, but rather creates the environment needed for another tool to run compilers and create binaries. A CMake project is described by a series of files called CMakeLists.txt located in directories throughout the project. The main CMake file for OpenFAST is located at openfast/CMakeLists.txt and each module and glue-code has its own CMakeLists.txt; for example, AeroDyn and BeamDyn have one at openfast/modules/aerodyn/CMakeLists.txt and openfast/modules/beamdyn/CMakeLists.txt, respectively.
Running CMake

Running CMake and a build tool will create many files (text files and binaries) used in the various stages of the build. For this reason, a build folder should be created to contain all of the generated files associated with the build process. Here, an important file called CMakeCache.txt contains the user-defined settings for the CMake configuration. This file functions like memory storage for the build. It is initially created the first time the CMake command is run and populated with the initial settings. Then, any subsequent changes to the settings will be updated and stored there.

CMake can be executed in a few ways:

- Command line interface: cmake
- Command line curses interface: ccmake
- Official CMake GUI

The CMake GUI is only distributed for Windows, but it can be built from source for other platforms. OpenFAST’s build process focuses on the command line execution of CMake for both the Linux/macOS and Windows terminals. The command line syntax to run CMake for OpenFAST is generally:

```
cmake <path-to-primary-CMakeLists.txt> [options]
```

Options

```
-D <var>[::<type>]=<value> = Create or update a cmake cache entry.
```

For example, a common CMake command issued from the openfast/build directory is:

```bash
# cmake <path-to-primary-CMakeLists.txt> [options]
# where
# <path-to-primary-CMakeLists.txt> is "./..
# [options] can be
# -DBUILD_SHARED_LIBS:BOOL=ON or
# -DBUILD_SHARED_LIBS=ON

cmake .. -DBUILD_SHARED_LIBS=ON
```

The command line curses interface can be invoked similarly:

```
ccmake..
```

The interface will be rendered in the terminal window and all navigation happens through keyboard inputs.

OpenFAST CMake options

CMake has a large number of general configuration variables available. A good resource for useful CMake variables is at this link: GitLab CMake variables. The CMake API documentation is also helpful for searching through variables and determining the resulting action. Note that the CMake process should be well understood before customizing the general options.

The CMake options specific to OpenFAST and their default settings are:

```
<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUILD_DOCUMENTATION</td>
<td>- Build documentation (Default: OFF)</td>
</tr>
<tr>
<td>BUILD_OPENFAST_CPP_API</td>
<td>- Enable building OpenFAST - C++ API (Default: OFF)</td>
</tr>
<tr>
<td>BUILD_OPENFAST_SIMULINK_API</td>
<td>- Enable building OpenFAST for use with Simulink</td>
</tr>
<tr>
<td>BUILD_SHARED_LIBS</td>
<td>- Enable building shared libraries (Default: OFF)</td>
</tr>
<tr>
<td>BUILD_TESTING</td>
<td>- Build the testing tree (Default: OFF)</td>
</tr>
<tr>
<td>CMAKE_BUILD_TYPE</td>
<td>- Choose the build type: Debug Release (Default: Release)</td>
</tr>
</tbody>
</table>
```

(continues on next page)
Additional system-specific options may exist for a given system, but those should not impact the OpenFAST configuration. As mentioned above, the configuration variables are set initially but can be changed at any time. For example, the defaults may be accepted to initially configure the project, but then the settings may be configured individually:

```
# Initial configuration with the default settings
cmake ..
```

```
# Change the build to Debug mode rather than Release
cmake .. -DCMAKE_BUILD_TYPE=Debug
```

```
# Use dynamic linking rather than static linking
cmake .. -DBUILD_SHARED_LIBS=ON
```

### CMAKE_BUILD_TYPE

This option allows to set the compiler optimization level and debug information. The value and its effect are listed in the table below.

<table>
<thead>
<tr>
<th>CMAKE_BUILD_TYPE</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Release</td>
<td>-O3 optimization level</td>
</tr>
<tr>
<td>RelWithDebInfo</td>
<td>-O2 optimization level with -g flag for debug info</td>
</tr>
<tr>
<td>MinSizeRel</td>
<td>-O1 optimization level</td>
</tr>
<tr>
<td>Debug</td>
<td>No optimization and -g flag for debug info; additional debugging flags: -fcheck=all -pedantic -fbacktrace</td>
</tr>
</tbody>
</table>

Use Debug during active development to add debug symbols for use with a debugger. This build type also adds flags for generating runtime checks that would otherwise result in undefined behavior. MinSizeRel adds basic optimizations and targets a minimal size for the generated executable. The next level, RelWithDebInfo, enables vectorization and other more aggressive optimizations. It also adds debugging symbols and results in a larger executable size. Finally, use Release for best performance at the cost of increased compile time.

This flag can be set with the following command:

```
cmake .. -DCMAKE_BUILD_TYPE=RelWithDebInfo
```
CMAKE_INSTALL_PREFIX

This flag sets the location of the compiled binaries when the build tool runs the install command. It should be a full path in a carefully chosen location. The binaries will be copied into include, lib, and bin subfolders under the value of this flag. The default is to install binaries within the repository in a folder called install.

This flag can be set with the following command:

```
cmake .. -DCMAKE_INSTALL_PREFIX="/usr/local/"
```

Setting the build tool

CMake can target a variety of build tools or generators. To obtain a list of available generators on the current system, run with the empty generator flag, select the target from the list, and rerun with the generator flag populated:

```
# Run with the empty -G flag to get a list of available generators
cmake .. -G

# CMake Error: No generator specified for -G
#
# Generators
# * Unix Makefiles = Generates standard UNIX makefiles.
# Ninja = Generates build.ninja files.
# Xcode = Generate Xcode project files.
# CodeBlocks - Ninja = Generates CodeBlocks project files.
# CodeBlocks - Unix Makefiles = Generates CodeBlocks project files.
# CodeLite - Ninja = Generates CodeLite project files.
# CodeLite - Unix Makefiles = Generates CodeLite project files.
# Sublime Text 2 - Ninja = Generates Sublime Text 2 project files.
# Sublime Text 2 - Unix Makefiles = Generates Sublime Text 2 project files.
# Kate - Ninja = Generates Kate project files.
# Kate - Unix Makefiles = Generates Kate project files.
# Eclipse CDT4 - Ninja = Generates Eclipse CDT 4.0 project files.
# Eclipse CDT4 - Unix Makefiles = Generates Eclipse CDT 4.0 project files.

# Choose one from the list above and pass it as an argument after -G
# NOTE: wrap this in quotes!
cmake .. -G"Sublime Text 2 - Ninja"
```

**Note:** If the chosen generator name contains spaces, be sure to wrap it in quotes.

Math libraries

The CMake project is configured to search for the required math libraries in default locations. However, if math libraries are not found, they can be specified directly to CMake. The two required libraries are BLAS and LAPACK, and their location can be passed to CMake with this command syntax:

```
cmake .. -DBLAS_LIBRARIES="/path/toblas" -DLAPACK_LIBRARIES="/path/to/lapack"
```

The paths given should be to the directory which contains the libraries, not to the libraries themselves.

2.2. Compile from source
2.2.5 CMake with Make for Linux/macOS

After reading *Understanding CMake*, proceed with configuring OpenFAST. The CMake project is well developed for Linux and macOS systems, so the default settings should work as given. These settings should only be changed when a custom build is required.

The procedure for configuring CMake and compiling with GNU Make on Linux and macOS systems is given below.

```bash
# Clone the repository from GitHub using git
git clone https://github.com/OpenFAST/OpenFAST.git

# Move into the OpenFAST directory
cd OpenFAST

# Create the build directory and move into it
mkdir build
cd build

# Execute CMake with the default options;
# this step creates the Makefiles
cmake ..

# Execute the Make-help command to list all available targets
make help

# Choose a particular target or give no target to compile everything
make

Tip: Compile in parallel by adding “-jN” where N is the number of parallel processes to use
```

This will build the OpenFAST project in the `build` directory. Binaries are located in `openfast/build/glue-codes/` and `openfast/build/modules/`. Since all build-related files are located in the `build` directory, a new fresh build process can be accomplished by simply deleting the build directory and starting again.

2.2.6 CMake with Visual Studio for Windows

After reading *Understanding CMake*, proceed with configuring OpenFAST. The result of this configuration process will be a Visual Studio solution which will be fully functional for compiling any of the targets within OpenFAST. However, this method lacks support for continued active development. Specifically, any settings that are configured in the Visual Studio solution directly will be lost any time CMake is executed. Therefore, this method should only be used to compile binaries, and the procure described in *Visual Studio Solution for Windows* should be used for active OpenFAST development on Windows.

The procedure for configuring CMake and compiling with Visual Studio on Windows systems is given below.

```bash
# Clone the repository from GitHub using git
git clone https://github.com/OpenFAST/OpenFAST.git

# Move into the OpenFAST directory
cd OpenFAST

# Create the build directory and move into it
mkdir build
cd build

(continues on next page)```
# Execute CMake with the default options and a specific Visual Studio version and build architecture. For a list of available CMake generators, run `cmake .. -G`.

This step creates the Visual Studio solution. Run `cmake .. -G "Visual Studio 14 2015 Win64"` to build.

Start the generated Visual Studio solution by running `start OpenFAST.sln`.

Visual Studio will open a solution containing all of the OpenFAST projects, and any module library, module driver, or glue-code can be compiled from there. The compiled binaries are located within a directory determined by the Visual Studio build type (Release, Debug, or RelWithDebInfo) in `openfast/build/glue-codes/` and `openfast/build/modules/`. For example, the OpenFAST executable will be located at `openfast/build/glue-codes/Release/openfast.exe` when compiling in Release mode.

The CMake-generated Visual Studio build is not currently fully functional. Any configurations made to the Solution in the Visual Studio UI will be lost when CMake is executed, and this can happen whenever a change is made to the structure of the file system or if the CMake configuration is changed. It is recommended that this method not be used for debugging or active development on Windows. Instead, see Visual Studio Solution for Windows.

## 2.3 Appendix

The following are additional methods for installation which may not be fully test or may be deprecated in the future.

### 2.3.1 Building OpenFAST with Spack

The process to build and install OpenFAST with Spack on Linux or macOS is described here.

#### Dependencies

OpenFAST has the following dependencies:

- LAPACK libraries. Users should set `BLAS_LIBRARIES` and `LAPACK_LIBRARIES` appropriately for CMake if the library isn’t found in standard paths. Use `BLASLIB` as an example when using Intel MKL.
- For the optional C++ API, HDF5 (provided by `HDF5_ROOT`) and yaml-cpp (provided by `YAML_ROOT`)
- For the optional testing framework, Python 3+ and Numpy

### Building OpenFAST Semi-Automatically Using Spack on macOS or Linux

The following describes how to build OpenFAST and its dependencies mostly automatically on macOS using Spack. This can also be used as a template to build OpenFAST on any Linux system with Spack.

These instructions were developed on macOS 10.11 with the following tools installed via Homebrew:

- GCC 6.3.0
- CMake 3.6.1
- pkg-config 0.29.2
Step 1

Checkout the official Spack repo from github (we will checkout into \${HOME}): 

```
cd ${HOME} && git clone https://github.com/LLNL/spack.git
```

Step 2

Add Spack shell support to your .profile by adding the lines:

```
export SPACK_ROOT=${HOME}/spack
. $SPACK_ROOT/share/spack/setup-env.sh
```

Step 3

Copy the https://raw.githubusercontent.com/OpenFAST/openfast/dev/share/spack/package.py file to your installation of Spack:

```
n mkdir ${SPACK_ROOT}/var/spack/repos/builtin/packages/openfast
cd ${SPACK_ROOT}/var/spack/repos/builtin/packages/openfast
```

Step 4

Try spack info openfast to see if Spack works. If it does, check the compilers you have available by:

```
machine:~ user$ spack compilers
=> Available compilers
-- gcc -----------------------------------------------
gcc@6.3.0  gcc@4.2.1

-- clang -----------------------------------------------
clang@8.0.0-apple  clang@7.3.0-apple
```

Step 5

Install OpenFAST with your chosen version of GCC:

```
spack install openfast %gcc@6.3.0
```

To install OpenFAST with the C++ API, do:

```
spack install openfast+cxx %gcc@6.3.0
```

That should be it! Spack will automatically use the most up-to-date dependencies unless otherwise specified. For example to constrain OpenFAST to use some specific versions of dependencies you could issue the Spack install command:
spack install openfast %gcc@6.3.0 ^hdf5@1.8.16

The executables and libraries will be located at

spack location -i openfast

Add the appropriate paths to your PATH and LD_LIBRARY_PATH to run OpenFAST.

2.3.2 Building OpenFAST on Windows with CMake and Cygwin 64-bit

WARNING: This build process takes a significantly long amount of time. If GNU tools are not required, it is recommended that Windows users see one of the following sections:

- Download binaries
- CMake with Visual Studio for Windows
- Building OpenFAST on Windows with Visual Studio.

Installing prerequisites

1. Download and install Cygwin 64-bit. You will need to Run as Administrator to complete the installation process.
   - Choose Install from internet
   - Choose the default install location
   - Choose the default package download location
   - Choose Direct connection
   - Choose a download site
   - See next step for select packages. Alternately, you can skip this step and run setup-x86_64.exe anytime later to select and install required software.

2. Select packages necessary for compiling OpenFAST. Choose binary packages and not the source option.
   - Choose Category view, we will be installing packages from Devel and Math
   - From Devel mark the following packages for installation
     - cmake
     - cmake-doc
     - cmake-gui
     - cygwin-devel
     - gcc-core
     - gcc-fortran
     - gcc-g++
     - git
     - make
     - makedepend
   - From Math mark the following packages for installation
To run the test suite, install these optional packages from Python:
- python3
- Python3-numpy

Click Next and accept all additional packages that the setup process requests to install to satisfy dependencies.

3. It is recommended that you reboot the machine after installing Cygwin and all the necessary packages.

**Compiling OpenFAST**

From here, pick up from the Linux with CMake instructions at *CMake with Make for Linux/macOS*.

**Other tips**

- If you would like to run openfast.exe from the cmd terminal, then you must add the `C:\cygwin64\lib\lapack` and `C:\cygwin64\home\<USERNAME>\software\bin` to your `%PATH%` variable in environment setting. Replace `<USERNAME>` with your account name on Windows system.

- It is suggested to compile with optimization level 2 for Cygwin. Do this by changing the build mode in the `cmake` command.

```bash
cmake .. -DCMAKE_BUILD_TYPE=RelWithDebInfo
```
CHAPTER
THREE

TESTING OPENFAST

The OpenFAST test suite consists of glue code and module level regression tests and unit tests. The regression tests compare locally generated solutions to a set of baseline solutions. The unit tests ensure that individual subroutines are functioning as intended.

All of the necessary files corresponding to the regression tests are contained in the `reg_tests` directory. The unit test framework is housed in `unit_tests` while the actual tests are contained in the directory corresponding to the tested module.

### 3.1 Configuring the test suite

Portions of the test suite are linked to the OpenFAST repository through a `git submodule`. Specifically,

- `r-test`
- `pFUnit`

**Tip:** Be sure to clone the repo with the `--recursive` flag or execute `git submodule update --init --recursive` after cloning.

The test suite can be configured with CMake similar to OpenFAST. The default CMake configuration is suitable for most systems, but may need customization for particular build environments. See the Understanding CMake section for more details on configuring the CMake targets. While the unit tests must be built with CMake due to its external dependencies, the regression test may be executed without CMake.

### 3.2 Test specific documentation

#### 3.2.1 Unit test

In a software package as dynamic and collaborative as OpenFAST, confidence in multiple layers of code is best accomplished with a strong system of unit tests. Through robust testing practices, the entire OpenFAST community can understand the intention behind code blocks and debug or expand functionality quicker and with more confidence and stability.

Unit testing in OpenFAST modules is accomplished through `pFUnit`. This framework provides a Fortran abstraction to the popular `xUnit` structure. `pFUnit` is compiled along with OpenFAST through CMake when the CMake variable `BUILD_TESTING` is turned on.

The BeamDyn and NWTC Library modules contain some sample unit tests and should serve as a reference for future development and testing.
Dependencies

The following packages are required for unit testing:

- Python 3.7+
- CMake
- pFUnit - Included in OpenFAST repo through a git-submodule

Compiling

Compiling the unit tests is handled with CMake similar to compiling OpenFAST in general. After configuring CMake with `BUILD_TESTING` turned on, new build targets are created for each module included in the unit test framework named `[module]_utest`. Then, make the target to test:

```cmake
cmake .. -DBUILD_TESTING=ON
make beamdyn_utest
```

This creates a unit test executable at `openfast/build/unit_tests/beamdyn/beamdyn_utest`.

Executing

To execute a module’s unit test, simply run the unit test binary. For example:

```bash
>>> ./openfast/build/unit_tests/beamdyn/beamdyn_utest
............
Time: 0.018 seconds
OK
(14 tests)
```

pFUnit will display a . for each unit test successfully completed and a F for each failing test. If any tests do fail, the failure criteria will be displayed listing which particular value caused the failure. Failure cases display the following output:

```bash
>>> ./unit_tests/beamdyn/beamdyn_utest
.....F.......
Time: 0.008 seconds
Failure in:
test_BD_CrvMatrixH_suite.test_BD_CrvMatrixH
Location:
test_BD_CrvMatrixH.F90:48
simple rotation with known parameters: Pi on xaxis expected +0.5000000 but found: +0.4554637; difference: |+0.4453627E-01| > tolerance:+0.1000000E-13; first difference at element [1, 1].
FAILURES!!!
Tests run: 13, Failures: 1, Errors: 0
Note: The following floating-point exceptions are signalling: IEEE_INVALID_FLAG IEEE_DIVIDE_BY_ZERO
ERROR STOP *** Encountered 1 or more failures/errors during testing. ***
Error termination. Backtrace:
```

(continues on next page)
Adding unit tests

Unit tests should be included for each new, testable code block (subroutine or function). What is testable is the discretion of the developer, but an element of the pull request review process will be evaluating test coverage.

New unit tests can be added to a tests directory alongside the src directory included in each module. For example, a module directory may be structured as

```
openfast/
    modules/
        sampledyn/
            src/
                SampleDyn.f90
                SampleDyn_Subs.f90
            tests/
                test_SampleDyn_Subroutine1.F90
                test_SampleDyn_Subroutine2.F90
                test_SampleDyn_Subroutine3.F90
```

Each unit test must be contained in a unique file called test_[SUBROUTINE].F90 where [SUBROUTINE] is the code block being tested. The new files should contain a Fortran module which itself contains a Fortran subroutine for each specific test case. Generally, multiple tests will be required to fully test one subroutine.

Finally, update the CMake configuration for building a module’s unit test executable by copying an existing unit test CMake configuration into a new module directory:

```
cp -r openfast/unit_tests/beamdyn openfast/unit_tests/[module]
```

Then, modify the new CMakeLists.txt with the appropriate list of test subroutines and module name variables.

For reference, a template unit test file is included at openfast/unit_tests/test_SUBROUTINE.F90. Each unit test should fully test the target code block. If full test coverage is not easily achievable, it may be an indication that refactoring would be beneficial.

Some useful topics to consider when developing and testing for OpenFAST are:

- Test driven development
- Separation of concerns
- pFUnit usage

3.2. Test specific documentation
3.2.2 Regression test

The regression test executes a series of test cases which intend to fully describe OpenFAST and its module’s capabilities. Jump to one of the following sections for instructions on running the regression tests:

- Executing with Python driver
- Executing with CTest
- Regression test examples
- Windows with Visual Studio regression test

Each locally computed result is compared to a static set of baseline results. To account for system, hardware, and compiler differences, the regression test attempts to match the current machine and compiler type to the appropriate solution set from these combinations:

<table>
<thead>
<tr>
<th>Operating System</th>
<th>Compiler</th>
<th>Hardware</th>
</tr>
</thead>
<tbody>
<tr>
<td>macOS</td>
<td>GNU</td>
<td>2017 MacbookPro</td>
</tr>
<tr>
<td>CentOS 7</td>
<td>Intel</td>
<td>NREL Eagle - Intel Skylake</td>
</tr>
<tr>
<td>CentOS 7</td>
<td>GNU</td>
<td>NREL Eagle - Intel Skylake</td>
</tr>
<tr>
<td>Windows 10</td>
<td>Intel</td>
<td>Dell Precision 3530</td>
</tr>
</tbody>
</table>

The compiler versions, specific math libraries, and more info on hardware used to generate the baseline solutions are documented in the r-test repository documentation. Currently, the regression test supports only double precision builds.

The regression test system can be executed with CMake (through its included test driver, CTest) or manually with a custom Python driver. Both systems provide similar functionality with respect to testing, but CTest integration provides access to multithreading, automation, and test reporting via CDash. Both modes of execution require some configuration as described in the following sections.

In both modes of execution a directory is created in the build directory called `reg_tests` where all of the input files for the test cases are copied and all of the locally generated outputs are stored. Ultimately, both CTest and the manual execution program call a series of Python scripts and libraries in `reg_tests` and `reg_tests/lib`. One such script is `lib/pass_fail.py` which reads the output files and computes a norm on each channel reported. If the maximum norm is greater than the given tolerance, that particular test is reported as failed. The failure criteria is outlined below.

```python
difference = abs(testData - baselineData)
for i in nChannels:
    if channelRange < 1:
        norm[i] = MaxNorm( difference[:,i] )
    else:
        norm[i] = MaxNorm( difference[:,i] ) / channelRange

if max(norm) < tolerance:
    pass = True
else:
    pass = False
```
Dependencies

The following packages are required for regression testing:

- Python 3.7+
- Numpy
- CMake and CTest (Optional)
- Bokeh 1.4 (Optional)

Executing with Python driver

The regression test can be executed manually with the included driver at openfast/reg_tests/manualRegressionTest.py. This program reads a case list file at openfast/reg_tests/r-test/glue-codes/openfast/CaseList.md. Cases can be removed or ignored by starting that line with a #. The driver program includes multiple optional flags which can be obtained by executing with the help option:

```
$ python manualRegressionTest.py -h
```

Executes OpenFAST and a regression test for a single test case.

Note: For the NREL 5MW turbine test cases, an external ServoDyn controller must be compiled and included in the appropriate directory or all NREL 5MW cases will fail without starting. More information is available in the documentation for the r-test repository, but be aware that these three DISCON controllers must exist:

```
openfast/build/reg_tests/glue-codes/openfast/5MW_Baseline/ServoData/DISCO2.dll
openfast/build/reg_tests/glue-codes/openfast/5MW_Baseline/ServoData/DISCO_ITIBarge.dll
openfast/build/reg_tests/glue-codes/openfast/5MW_Baseline/ServoData/DISCO_OC3Hywind.dll
```
Executing with CTest

CTest is included with CMake and is primarily a set of preconfigured targets and commands. To use the CTest driver for the regression test, execute CMake as described in Installing OpenFAST, but with this additional flag:

-DBUILD_TESTING=ON.

The regression test specific CMake variables are:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUILD_TESTING</td>
<td></td>
</tr>
<tr>
<td>CTEST_OPENFAST_EXECUTABLE</td>
<td></td>
</tr>
<tr>
<td>CTEST_[MODULE]_EXECUTABLE</td>
<td>Is the module name</td>
</tr>
<tr>
<td>CTEST_PLOT_ERRORS</td>
<td></td>
</tr>
<tr>
<td>CTEST_REGRESSION_TOL</td>
<td></td>
</tr>
</tbody>
</table>

Some additional resources that are required for the full regression test suite are included in the CMake project. Specifically, external ServoDyn controllers must be compiled for a given system and placed in a particular location. Thus, be sure to execute the build command with the install target:

```bash
# Configure CMake with testing enabled and accept the default values for all other test-specific CMake variables
cmake .. -DBUILD_TESTING=ON

# Build and install
make install
```

**Note:** REMINDER: For the NREL 5MW turbine test cases, an external ServoDyn controller must be compiled and included in the appropriate directory or all NREL 5MW cases will fail without starting. More information is available in the documentation for the r-test repository, but be aware that these three DISCON controllers must exist:

```bash
openfast/build/reg_tests/glue-codes/openfast/5MW_Baseline/ServoData/DISCON.dll
openfast/build/reg_tests/glue-codes/openfast/5MW_Baseline/ServoData/DISCON_ITIBarge.dll
openfast/build/reg_tests/glue-codes/openfast/5MW_Baseline/ServoData/DISCON_OC3Hywind.dll
```

After CMake configuration and compiling, the automated regression test can be executed by running either of the commands `make test` or `ctest` from the build directory. If the entire OpenFAST package is to be built, CMake will configure CTest to find the new binary at `openfast/build/glue-codes/openfast/openfast`. However, if the intention is to build only the test suite, the OpenFAST binary should be specified in the CMake configuration under the CTEST_OPENFAST_EXECUTABLE flag. There is also a corresponding CTEST_[MODULE]_NAME flag for each module included in the regression test.

When driven by CTest, the regression test can be executed by running various forms of the command `ctest` from the build directory. The basic commands are:

```bash
# Run the entire regression test
ctest

# Disable actual execution of tests; this is helpful in formulating a particular ctest command
ctest -N

# Run the entire regression test with verbose output
ctest -V
```

(continues on next page)
Each regression test case contains a series of labels associating all of the modules used. The labeling can be seen in the test instantiation in `reg_tests/CTestList.cmake` or with the command:

```bash
# Print all available test labels
cmake --print-labels
```

The test cases corresponding to a particular label can be executed with this command:

```bash
# Filter the test cases corresponding to a particular label
cmake -L [Label]
```

Flags can be compounded making useful variations such as

```bash
# Run all cases that use AeroDyn14 with verbose output
cmake -V -L aerodyn14

# Run all cases that use AeroDyn14 in 16 concurrent processes
cmake -j 16 -L aerodyn14

# Run the case with name "5MW_DLL_Potential_WTurb" with verbose output
cmake -V -R 5MW_DLL_Potential_WTurb

# List all tests with the "beamdyn" label
cmake -N -L beamdyn

# List the labels included in all tests matching the regex "bd"
cmake -N -R bd --print-labels
```

The automated regression test writes new files only into the build directory. Specifically, all locally generated solutions are located in the corresponding glue-code or module within `openfast/build/reg_tests`. The baseline solutions contained in `openfast/reg_tests/r-test` are strictly read and are not modified by the automated process.
Regression test examples

The following examples illustrate methods of running the regression tests on Unix-based systems. However, similar procedures can be used on Windows with CMake and CTest. An alternate method of running the regression tests on Windows is given in Detailed example of running on Windows.

Compile OpenFAST and execute with CTest

The following example assumes the user is starting completely from scratch. The commands below download the source code, configure the OpenFAST project with CMake, compile all executables, and execute the full regression test suite.

```bash
# Download the source code from GitHub
# Note: The default branch is 'master'
git clone --recursive https://github.com/openfast/openfast.git
cd openfast

# If necessary, switch to another target branch and update r-test
git checkout dev
git submodule update

# Create the build and install directories and move into build
mkdir build && cd build

# Configure CMake for testing
# - BUILD_TESTING - turn ON
# - CTEST_OPENFAST_EXECUTABLE - accept the default
# - CTEST_[MODULE]_EXECUTABLE - accept the default
cmake .. -DBUILD_TESTING=ON

# Compile and install
make install

# Execute the full test suite with 4 concurrent processes
ctest -j4
```

Configure with CMake and a given executable

This example assumes the user has a fully functional OpenFAST executable available along with any necessary libraries, but does not have the source code repository downloaded. This might be the case when executables are distributed within an organization or downloaded from an OpenFAST Release. Here, nothing will be compiled, but the test suite will be configured with CMake for use with the CTest command.

```bash
# Download the source code from GitHub
# Note: The default branch is 'master'
git clone --recursive https://github.com/openfast/openfast.git
cd openfast

# If necessary, switch to another target branch and update r-test
git checkout dev
git submodule update

# Create the build directory and move into it
mkdir build && cd build
```

(continues on next page)
Configure CMake with `openfast/reg_tests/CMakeLists.txt` for testing

- `BUILD_TESTING` - turn ON
- `CTEST_OPENFAST_EXECUTABLE` - provide a path
- `CTEST_[MODULE]_EXECUTABLE` - provide a path

```bash
cmake ../reg_tests
-DBUILD_TESTING=ON
-DCTEST_OPENFAST_EXECUTABLE=/home/user/Desktop/openfast_executable
-DCTEST_BEAMDYN_EXECUTABLE=/home/user/Desktop/beamdyn_driver
```

Install required files

```bash
make install
```

Execute the full test suite with 4 concurrent processes

```bash
ctest -j4
```

### Python driver with a given executable

This example assumes the user has a fully functional OpenFAST executable available along with any necessary libraries, but does not have the source code repository downloaded. This might be the case when executables are distributed within an organization or downloaded from an OpenFAST Release. Nothing will be compiled, but the test suite will be executed with the included Python driver.

Download the source code from GitHub

```bash
# Note: The default branch is 'master'
git clone --recursive https://github.com/openfast/openfast.git
cd openfast
```

If necessary, switch to another target branch and update r-test

```bash
git checkout dev
```

Execute the Python driver

```bash
cd reg_tests
python manualRegressionTest.py -h
```

Usage:

```bash
manualRegressionTest.py [-h] [-p [Plotting-Flag]] [-n [No-Execution]]
-v [Verbose-Flag] [-c [Case-Name]]
OpenFAST System-Name Compiler-Id Test-Tolerance
```

Executes OpenFAST and a regression test for a single test case.

Positional arguments:
- OpenFAST path to the OpenFAST executable
- System-Name current system’s name: [Darwin, Linux, Windows]
- Compiler-Id compiler’s id: [Intel, GNU]
- Test-Tolerance tolerance defining pass or failure in the regression test

Optional arguments:
- h, --help show this help message and exit
- p [Plotting-Flag], -plot [Plotting-Flag] bool to include plots in failed cases
- n [No-Execution], -no-exec [No-Execution] bool to prevent execution of the test cases
- v [Verbose-Flag], -verbose [Verbose-Flag] (continues on next page)
Detailed example of running on Windows

The *Python driver with a given executable* example can be used for running the regression tests on a Windows computer. However, a more detailed, step-by-step description is given in *Windows with Visual Studio regression test*.

**Windows with Visual Studio regression test**

1) Clone the openfast repo and initialize the testing database
   a) Open a git command shell window (like git bash)
   b) Change your working directory to the location above where you want your local repo to be located (the repo will be placed into a folder called openfast at this location)
   c. Type: `git clone https://github.com/openfast/openfast.git` (this creates a local version of the openfast repo on your computer). You should see something like this:

   ```
   Cloning into 'openfast'...
   remote: Counting objects: 23801, done.
   remote: Compressing objects: 100% (80/80), done.
   remote: Total 23801 (delta 73), reused 102 (delta 50), pack-reused 23670
   Receiving objects: 100% (23801/23801), 92.10 MiB 18.99 MiB/s, done.
   Resolving deltas: 100% (13328/13328), done.
   Checking connectivity... done.
   
   Submodule 'reg_tests/r-test' (https://github.com/openfast/r-test.git) registered for path 'reg_tests/r-test'
   Cloning into 'reg_tests/r-test'...
   remote: Counting objects: 3608, done.
   remote: Compressing objects: 100% (121/121), done.
   remote: Total 3608 (delta 22), reused 161 (delta 21), pack-reused 3442
   Receiving objects: 100% (3608/3608), 154.52 MiB 26.29 MiB/s, done.
   Resolving deltas: 100% (2578/2578), done.
   Checking connectivity... done.
   
   Submodule path 'reg_tests/r-test': checked out
   'b808f1f3c1331fe5d03c5aaa4167532c2492d378'
   ```
   d) Type: `cd openfast` (change your working directory to the openfast folder)
   e) Type: `git checkout dev` (this places your local repo on the correct branch of the openfast repo)
   f) Type: `git submodule update --init --recursive` (this downloads the testing database to your computer) You should see something like this:

2) Build The Regression Testing DISCON DLLs
a) Open the Visual Studio Solution (Discon.sln) located in openfast\vs-build\Discon folder
b) Choose Release and x64 for the Solutions Configuration and Solutions Platform, respectively
c) From the menu bar select Build->Build Solution
d) You should now see the files Discon.dll, Discon_ITIBarge.dll, and Discon_OC3Hywind.dll in your openfast\reg_tests\r-test\glue-codes\fast\5MW_Baseline\ServoData folder.

3) Build OpenFAST using Visual Studio
   a) Open the Visual Studio Solution (FAST.sln) located in openfast\vs-build\FAST folder
   b) Choose Release_Double and x64 for the Solutions Configuration and Solutions Platform, respectively
   c) From the menu bar select Build->Build Solution
      i) If this is the first time you have tried to build openfast, you will get build errors!!! [continue to steps (ii) and (iii), otherwise if FAST builds successfully, continue to step (3d)]
      ii) Cancel build using the menubar Build->Cancel [VS is confused about the build-order/dependency of the project files in FASTlib, but canceling and restarting VS, it somehow as enough info from the partial build to get this right, now]
      iii) Close your Visual Studio and then Repeat Steps (a) through (c)
   d) You should now see the file openfast_x64_Double.exe in your openfast\build\bin folder.

4) Prepare regression tests
   a) Create a subdirectory called reg_tests in your openfast\build folder.
   b) Copy the contents of openfast\reg_tests\r-test to openfast\build\reg_tests.

5) Execute the OpenFAST regression Tests
   a) Open a command prompt which is configured for Python [like Anaconda3]
   b) Change your working directory to openfast\reg_tests
   c) Type: python manualRegressionTest.py ..\build\bin\openfast_x64_Double.exe Windows Intel 1e-5
      You should see this: executing AWT_YFix_WSt
   d) The tests will continue to execute one-by-one until you finally see something like this:

```
executing AWT_YFix_WSt         PASS
executing AWT_WSt_StartUp_HighSpShutDown  PASS
executing AWT_YFree_WSt        PASS
executing AWT_YFree_WTurb      PASS
executing AWT_WSt_StartUpShutDown PASS
executing AOC_WSt              PASS
executing AOC_YFree_WTurb      PASS
executing AOC_YFix_WSt         PASS
executing UAE_Dnwind_YRamp_WSt PASS
executing UAE_Upwind_Rigid_WRamp_PwrCurve PASS
executing WP_VSP_WTurb_PitchFail PASS
executing WP_VSP_ECD           PASS
executing WP_VSP_WTurb         PASS
executing WP_Stationary_Linear PASS
executing SWRT_YFree_VS_EDG01  PASS
executing SWRT_YFree_VS_EDC01  PASS
executing SWRT_YFree_VS_WTurb  PASS
executing 5MW_Land_DLL_WTurb   PASS
```

(continues on next page)
### 3.3 Continuous Integration

A TravisCI configuration file is included with the OpenFAST source code at `openfast/.travis.yml`. The continuous integration infrastructure is still under development, but the status for all branches and pull requests can be found on the TravisCI OpenFAST page.

For development and testing purposes, a version of the TravisCI test can be run locally with Docker. The code snippet below outlines starting a TravisCI image on Docker.

```bash
# Running a travis ci image on docker locally

# Run this on your local machine's command line
BUILDID="build-1"
INSTANCE="travisci/ci-garnet:packer-1512502276-986baf0"
docker run --name $BUILDID -dit $INSTANCE /sbin/init
docker exec -it $BUILDID bash -l

# Now you're inside your docker image
sudo apt-get update
sudo apt-get install python3-pip
sudo -E apt-get -yq --no-install-suggests --no-install-recommends install gfortran_\n\nlibblas-dev liblapack-dev
git clone --depth=50 https://github.com/OpenFAST/openfast.git OpenFAST/openfast
cd OpenFAST/openfast

# Modify this line for the commit or pull request to build
git fetch origin +refs/pull/203/merge:
git checkout -qf FETCH_HEAD
git submodule update --init --recursive

export FC=/usr/bin/gfortran-7
export DOUBLE_PRECISION=ON
export TRAVIS_BUILD_INTEL=YES
export TRAVIS_COMPILER=gcc
export CC=gcc
gcc --version
pyenv shell 3.6.3

source ~/.bashrc
pip3 install numpy
mkdir build && cd build
```

(continues on next page)
3.3. Continuous integration

```bash
cmake .. -DBUILD_TESTING=ON -DDOUBLE_PRECISION=$DOUBLE_PRECISION -DBUILD_SHARED
→LIBS=ON
make -j 8 install
```
This section contains documentation for the OpenFAST module-coupling environment and its underlying modules. Documentation covers usage of models, underlying theory, and in some cases module verification.

We are in the process of transitioning legacy FAST v8 documentation, which can be found at https://nwtc.nrel.gov/. Details on the transition from FAST v8 to OpenFAST may be found in Section 4.12.

4.1 API changes between versions

This page lists the main changes in the OpenFAST API (input files) between different versions.

The changes are tabulated according to the module input file, line number, and flag name. The line number corresponds to the resulting line number after all changes are implemented. Thus, be sure to implement each in order so that subsequent line numbers are correct.

4.1.1 OpenFAST v2.5.0 to OpenFAST dev

Many changes were applied to SubDyn input file format. You may consult the following example: (SubDyn's Input File): and the online SubDyn documentation.

- ServoDyn
  - The input file parser is updated to a keyword/value pair based input. Each entry must have a corresponding keyword with the same spelling as expected
  - The TMD submodule of ServoDyn is replaced by an updated Structural Control module (StC) with updated capabilities and input file.
<table>
<thead>
<tr>
<th>Module</th>
<th>Line</th>
<th>Flag</th>
<th>Name</th>
<th>Example Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aero-Dyn</td>
<td>15</td>
<td>TwrTi</td>
<td>0.0000000E+00 6.0000000E+00 1.0000000E+00 1.0000000E-01</td>
<td>[additional column in Tower Influence and Aerodynamics table]</td>
</tr>
<tr>
<td>Sub-Dyn</td>
<td>8</td>
<td>Guyan-Load-Corr.</td>
<td>False GuyanLoadCorrection - Include extra moment from lever arm at interface and rotate FEM for floating</td>
<td></td>
</tr>
<tr>
<td>Sub-Dyn</td>
<td>15</td>
<td>Guyan-Damp-Mod</td>
<td>0 GuyanDampMod - Guyan damping {0=none, 1=Rayleigh Damping, 2=user specified 6x6 matrix}</td>
<td></td>
</tr>
<tr>
<td>Sub-Dyn</td>
<td>16</td>
<td>Rayleigh-Damp</td>
<td>0.001, 0.003 RayleighDamp - Mass and stiffness proportional damping coefficients (Rayleigh Damping) [only if GuyanDampMod=1]</td>
<td></td>
</tr>
<tr>
<td>Sub-Dyn</td>
<td>17</td>
<td>Guyan-Damp-Size</td>
<td>6 GuyanDampSize - Guyan damping matrix size (square, 6x6) [only if GuyanDampMod=2]</td>
<td></td>
</tr>
<tr>
<td>Sub-Dyn</td>
<td>18</td>
<td>Guyan-Damp-Mat</td>
<td>0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00</td>
<td></td>
</tr>
<tr>
<td>Sub-Dyn</td>
<td>-23</td>
<td>Guyan-Damp-Mat</td>
<td>0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00 0.0000e+00</td>
<td></td>
</tr>
<tr>
<td>Sub-Dyn</td>
<td>na</td>
<td>Cable-Les-Section</td>
<td>-</td>
<td>CABLE PROPERTIES</td>
</tr>
<tr>
<td>Sub-Dyn</td>
<td>na</td>
<td>Cable-Les-Section</td>
<td>0 NCablePropSets - Number of cable cable properties</td>
<td></td>
</tr>
<tr>
<td>Sub-Dyn</td>
<td>na</td>
<td>Cable-Les-Section</td>
<td>PropSetID EA MatDens T0</td>
<td></td>
</tr>
<tr>
<td>Sub-Dyn</td>
<td>na</td>
<td>Cable-Les-Section</td>
<td>(-) (N) (kg/m) (N)</td>
<td></td>
</tr>
<tr>
<td>Sub-Dyn</td>
<td>na</td>
<td>Rigid-Sec-Section</td>
<td>-</td>
<td>RIGID LINK PROPERTIES</td>
</tr>
<tr>
<td>Sub-Dyn</td>
<td>na</td>
<td>Rigid-Sec-Section</td>
<td>0 NRigidPropSets - Number of rigid link properties</td>
<td></td>
</tr>
<tr>
<td>Sub-Dyn</td>
<td>na</td>
<td>Rigid-Sec-Section</td>
<td>PropSetID MatDens</td>
<td></td>
</tr>
<tr>
<td>Sub-Dyn</td>
<td>na</td>
<td>Rigid-Sec-Section</td>
<td>(-) (kg/m)</td>
<td></td>
</tr>
<tr>
<td>Hydro-Dyn</td>
<td>52</td>
<td>NBody</td>
<td>1 NBody - Number of WAMIT bodies to be used (-) [≥1; only used when PotMod=1]. If NBodyMod=1, the WAMIT data contains a vector of size 6<em>NBody x 1 and matrices of size 6</em>NBody x 6*NBody; if NBodyMod&gt;1, there are NBody sets of WAMIT data each with a vector of size 6 x 1 and matrices of size 6 x 6]</td>
<td></td>
</tr>
<tr>
<td>Module</td>
<td>Line</td>
<td>Flag Name</td>
<td>Example Value</td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>------</td>
<td>-----------</td>
<td>---------------</td>
<td></td>
</tr>
<tr>
<td>AeroDyn 15</td>
<td>9</td>
<td>TwrShadow</td>
<td>0 TwrShadow - Calculate tower influence on wind based on downstream tower shadow (switch) {0=none, 1=Powles model, 2=Eames model}</td>
<td></td>
</tr>
<tr>
<td>SubDyn</td>
<td>26</td>
<td>Joints</td>
<td>JointID JointXss JointYss JointZss JointType JointDirX JointDirY JointDirZ JointStiff</td>
<td></td>
</tr>
<tr>
<td>SubDyn</td>
<td>27</td>
<td>Joints</td>
<td>(-) (m) (m) (m) (-) (-) (-) (-) (-) (Nm/rad)</td>
<td></td>
</tr>
<tr>
<td>SubDyn</td>
<td>na</td>
<td>Members</td>
<td>MemberID MJointID1 MJointID2 MPropSetID1 MPropSetID2 MType COSMID</td>
<td></td>
</tr>
<tr>
<td>SubDyn</td>
<td>na</td>
<td>Members</td>
<td>(-) (-) (-) (-) (-) (-) (-)</td>
<td></td>
</tr>
<tr>
<td>SubDyn</td>
<td>na</td>
<td>ConcentratedM</td>
<td>CMJointID JMass JMXX JMYX JMXZ JMYZ MCGX MCGY MCGZ</td>
<td></td>
</tr>
<tr>
<td>SubDyn</td>
<td>na</td>
<td>ConcentratedM</td>
<td>(-) (kg) (kg<em>m^2) (kg</em>m^2) (kg<em>m^2) (kg</em>m^2) (kg<em>m^2) (kg</em>m^2) (m) (m)</td>
<td></td>
</tr>
<tr>
<td>HydroDyn</td>
<td>48</td>
<td>ExtnMod</td>
<td>1 ExtnMod - Wave-excitation model {0: no wave-excitation calculation, 1: DFT, 2: state-space} (switch) [only used when PotMod=1; STATE-SPACE REQUIRES *.ssexctn INPUT FILE]</td>
<td></td>
</tr>
<tr>
<td>HydroDyn</td>
<td>49</td>
<td>RdtnMod</td>
<td>2 RdtnMod - Radiation memory-effect model {0: no memory-effect calculation, 1: convolution, 2: state-space} (switch) [only used when PotMod=1; STATE-SPACE REQUIRES *.ss INPUT FILE]</td>
<td></td>
</tr>
</tbody>
</table>

continues on next page
<table>
<thead>
<tr>
<th>Module</th>
<th>Line</th>
<th>Flag Name</th>
<th>Example Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HydroDyn</td>
<td>50</td>
<td>RdtnTMax</td>
<td>60 RdtnTMax - Analysis time for wave radiation kernel calculations (sec) [only used when PotMod=1 and RdtnMod&gt;0; determines RdtnDOmega=π/RdtnTMax in the cosine transform; MAKE SURE THIS IS LONG ENOUGH FOR THE RADIATION IMPULSE RESPONSE FUNCTIONS TO DECAY TO NEAR-ZERO FOR THE GIVEN PLATFORM!]</td>
</tr>
<tr>
<td>HydroDyn</td>
<td>51</td>
<td>RdtnDT</td>
<td>0.0125 RdtnDT - Time step for wave radiation kernel calculations (sec) [only used when PotMod=1 and ExctnMod&gt;0 or RdtnMod&gt;0; DT&lt;=RdtnDT&lt;=0.1 recommended; determines RdtnOmegaMax=π/RdtnDT in the cosine transform]</td>
</tr>
</tbody>
</table>

continues on next page
Table 4.1 – continued from previous page

<table>
<thead>
<tr>
<th>Module</th>
<th>Line</th>
<th>Flag Name</th>
<th>Example Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HydroDyn</td>
<td>54</td>
<td>PotFile</td>
<td>“Barge” PotFile - Root name of potential-flow model data; WAMIT output files containing the linear, nondimensionalized, hydrostatic restoring matrix (.hst), frequency-dependent hydrodynamic added mass matrix and damping matrix (.1), and frequency- and direction-dependent wave excitation force vector per unit wave amplitude (.3) (quoted string) [1 to NBody if NBodyMod&gt;1] [MAKE SURE THE FREQUENCIES INHERENT IN THESE WAMIT FILES SPAN THE PHYSICALLY-SIGNIFICANT RANGE OF FREQUENCIES FOR THE GIVEN PLATFORM; THEY MUST CONTAIN THE ZERO- AND INFINITE-FREQUENCY LIMITS!]</td>
</tr>
<tr>
<td>HydroDyn</td>
<td>55</td>
<td>WAMITULEN</td>
<td>1 WAMITULEN - Characteristic body length scale used to redimensionalize WAMIT output (meters) [1 to NBody if NBodyMod&gt;1] [only used when PotMod=1]</td>
</tr>
<tr>
<td>HydroDyn</td>
<td>56</td>
<td>PtfmRefxt</td>
<td>0.0 PtfmRefxt - The xt offset of the body reference point(s) from (0,0,0) (meters) [1 to NBody] [only used when PotMod=1]</td>
</tr>
<tr>
<td>HydroDyn</td>
<td>57</td>
<td>PtfmRefyt</td>
<td>0.0 PtfmRefyt - The yt offset of the body reference point(s) from (0,0,0) (meters) [1 to NBody] [only used when PotMod=1]</td>
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</tbody>
</table>

continues on next page
<table>
<thead>
<tr>
<th>Module</th>
<th>Line</th>
<th>Flag Name</th>
<th>Example Value</th>
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</thead>
<tbody>
<tr>
<td>HydroDyn</td>
<td>58</td>
<td>PtfmRefzt</td>
<td>0.0 PtfmRefzt - The zt offset of the body reference point(s) from (0,0,0) (meters) [1 to NBody] [only used when PotMod=1. If NBody-Mod=2,PtfmRefzt=0.0]</td>
</tr>
<tr>
<td>HydroDyn</td>
<td>59</td>
<td>PtfmRefztRot</td>
<td>0.0 PtfmRefztRot - The rotation about zt of the body reference frame(s) from xt/yt (degrees) [1 to NBody] [only used when PotMod=1]</td>
</tr>
<tr>
<td>HydroDyn</td>
<td>60</td>
<td>PtfmVol0</td>
<td>6000 PtfmVol0 - Displaced volume of water when the body is in its undisplaced position (m^3) [1 to NBody] [only used when PotMod=1; USE THE SAME VALUE COMPUTED BY WAMIT AS OUTPUT IN THE .OUT FILE!]</td>
</tr>
<tr>
<td>HydroDyn</td>
<td>61</td>
<td>PtfmCOBxt</td>
<td>0.0 PtfmCOBxt - The xt offset of the center of buoyancy (COB) from (0,0) (meters) [1 to NBody] [only used when PotMod=1]</td>
</tr>
<tr>
<td>HydroDyn</td>
<td>62</td>
<td>PtfmCOByt</td>
<td>0.0 PtfmCOByt - The yt offset of the center of buoyancy (COB) from (0,0) (meters) [1 to NBody] [only used when PotMod=1]</td>
</tr>
<tr>
<td>HydroDyn</td>
<td>69-74</td>
<td>AddF0</td>
<td>0 AddF0 - Additional preload (N, N-m) [If NBodyMod=1, one size 6*NBody x 1 vector; if NBodyMod&gt;1, NBody size 6 x 1 vectors]</td>
</tr>
<tr>
<td>HydroDyn</td>
<td>75-80</td>
<td>AddCLin</td>
<td>0 0 0 0 0 0 AddCLin - Additional linear stiffness (N/m, N/rad, N-m/m, N-m/rad) [If NBodyMod=1, one size 6<em>NBody x 6</em>NBody matrix; if NBodyMod&gt;1, NBody size 6 x 6 matrices]</td>
</tr>
</tbody>
</table>

continues on next page
<table>
<thead>
<tr>
<th>Module</th>
<th>Line</th>
<th>Flag Name</th>
<th>Example Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HydroDyn</td>
<td>81-86</td>
<td>AddBLin</td>
<td>0 0 0 0 0 0 AddBLin - Additional linear damping(N/(m/s), N/(rad/s), N-m/(m/s), N-m/(rad/s)) [If NBodyMod=1, one size 6<em>NBody x 6</em>NBody matrix; if NBodyMod&gt;1, NBody size 6 x 6 matrices]</td>
</tr>
<tr>
<td>HydroDyn</td>
<td>87-92</td>
<td>AddBQuad</td>
<td>0 0 0 0 0 0 AddBQuad - Additional quadratic drag(N/(m/s)^2, N/(rad/s)^2, N-m(m/s)^2, N-m/(rad/s)^2) [If NBodyMod=1, one size 6<em>NBody x 6</em>NBody matrix; if NBodyMod&gt;1, NBody size 6 x 6 matrices]</td>
</tr>
<tr>
<td>HydroDyn</td>
<td>na</td>
<td>Simple Coef Tab</td>
<td>SimplCd SimplCdMG SimplCa SimplCaMG SimplCp SimplCpMG SimplAxCa SimplAxCaMG SimplAxCaMG SimplAxCaMG SimplAxCaMG SimplAxCp SimplAxCpMG</td>
</tr>
<tr>
<td>HydroDyn</td>
<td>na</td>
<td>Depth Coef Tab</td>
<td>Dpth DpthCd DpthCdMG DpthCa DpthCaMG DpthCp DpthCpMG DpthAxCa DpthAxCaMG DpthAxCa DpthAxCaMG DpthAxCp DpthAxCpMG</td>
</tr>
<tr>
<td>HydroDyn</td>
<td>na</td>
<td></td>
<td>(m) (-) (-) (-) (-) (-) (-) (-) (-) (-) (-) (-)</td>
</tr>
</tbody>
</table>

continues on next page
### Modified in OpenFAST dev

<table>
<thead>
<tr>
<th>Module</th>
<th>Line</th>
<th>Flag Name</th>
<th>Example Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HydroDyn</td>
<td>na</td>
<td>Member Coef Tab</td>
<td>MemberID MemberCd1 MemberCd2 MemberCdMG1 MemberCdMG2 MemberCa1 MemberCa2 MemberCaMG1 MemberCaMG2 MemberCp1 MemberCp2 MemberCpMG1 MemberCpMG2 MemberAxCd1 MemberAxCd2 MemberAxCdMG1 MemberAxCdMG2 MemberAxCa1 MemberAxCa2 MemberAxCaMG1 MemberAxCaMG2 MemberAxCp1 MemberAxCp2 MemberAxCpMG1 MemberAxCpMG2</td>
</tr>
<tr>
<td>HydroDyn</td>
<td>na</td>
<td>OutList names</td>
<td>see OutlistParameters.xlsx for new and revised output channel names</td>
</tr>
</tbody>
</table>

### Removed in OpenFAST dev

<table>
<thead>
<tr>
<th>Module</th>
<th>Line</th>
<th>Flag Name</th>
<th>Example Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HydroDyn</td>
<td>68</td>
<td>na</td>
<td>FLOATING PLATFORM FORCE FLAGS [unused with WaveMod=6]</td>
</tr>
<tr>
<td>HydroDyn</td>
<td>69</td>
<td>PtfmSgF</td>
<td>True PtfmSgF - Platform horizontal surge translation force (flag) or DEFAULT</td>
</tr>
<tr>
<td>HydroDyn</td>
<td>70</td>
<td>PtfmSwF</td>
<td>True PtfmSwF - Platform horizontal sway translation force (flag) or DEFAULT</td>
</tr>
<tr>
<td>HydroDyn</td>
<td>71</td>
<td>PtfmHvF</td>
<td>True PtfmHvF - Platform vertical heave translation force (flag) or DEFAULT</td>
</tr>
<tr>
<td>HydroDyn</td>
<td>72</td>
<td>PtfmRF</td>
<td>True PtfmRF - Platform roll tilt rotation force (flag) or DEFAULT</td>
</tr>
<tr>
<td>HydroDyn</td>
<td>73</td>
<td>PtfmPF</td>
<td>True PtfmPF - Platform pitch tilt rotation force (flag) or DEFAULT</td>
</tr>
<tr>
<td>HydroDyn</td>
<td>74</td>
<td>PtfmYF</td>
<td>True PtfmYF - Platform yaw rotation force (flag) or DEFAULT</td>
</tr>
</tbody>
</table>
4.1.2 OpenFAST v2.4.0 to OpenFAST v2.5.0

- InflowWind
  - The input file parser is updated to a keyword/value pair based input. Each entry must have a corresponding keyword with the same spelling as expected. See Section 4.2 for an overview.
  - Driver code includes ability to convert between wind types

<table>
<thead>
<tr>
<th>Added in OpenFAST v2.5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Module</strong></td>
</tr>
<tr>
<td>IfW driver</td>
</tr>
<tr>
<td>IfW driver</td>
</tr>
<tr>
<td>IfW driver</td>
</tr>
<tr>
<td>IfW driver</td>
</tr>
<tr>
<td>InflowWind</td>
</tr>
</tbody>
</table>

4.1.3 OpenFAST v2.3.0 to OpenFAST v2.4.0

Additional nodal output channels added for AeroDyn15, BeamDyn, and ElastoDyn.
### Added in OpenFAST v2.4.0

<table>
<thead>
<tr>
<th>Module</th>
<th>Line</th>
<th>Flag</th>
<th>Name</th>
<th>Example Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydro-Dyn</td>
<td>53</td>
<td>ExctnMod</td>
<td>ExctnMod - Wave Excitation model {0: None, 1: DFT, 2: state-space} (-)</td>
<td></td>
</tr>
<tr>
<td>Open-FAST</td>
<td>44</td>
<td>CalcSteady</td>
<td>true CalcSteady - Calculate a steady-state periodic operating point before linearization? [unused if Linearize=False] (flag)</td>
<td></td>
</tr>
<tr>
<td>Open-FAST</td>
<td>45</td>
<td>TrimCase</td>
<td>3 TrimCase - Controller parameter to be trimmed {1:yaw; 2:torque; 3:pitch} [used only if CalcSteady=True] (-)</td>
<td></td>
</tr>
<tr>
<td>Open-FAST</td>
<td>46</td>
<td>TrimTol</td>
<td>0.0001 TrimTol - Tolerance for the rotational speed convergence [used only if CalcSteady=True] (-)</td>
<td></td>
</tr>
<tr>
<td>Open-FAST</td>
<td>47</td>
<td>TrimGain</td>
<td>0.001 TrimGain - Proportional gain for the rotational speed error (&gt;0) [used only if CalcSteady=True] (rad/(rad/s) for yaw or pitch; Nm/(rad/s) for torque)</td>
<td></td>
</tr>
<tr>
<td>Open-FAST</td>
<td>48</td>
<td>Twr_Kdmp</td>
<td>0 Twr_Kdmp - Damping factor for the tower [used only if CalcSteady=True] (N/(m/s))</td>
<td></td>
</tr>
<tr>
<td>Open-FAST</td>
<td>49</td>
<td>Bld_Kdmp</td>
<td>0 Bld_Kdmp - Damping factor for the blades [used only if CalcSteady=True] (N/(m/s))</td>
<td></td>
</tr>
<tr>
<td>In-flowWind</td>
<td>48</td>
<td>InitPosition(x)</td>
<td>0.0 InitPosition(x) - Initial offset in +x direction (shift of wind box) [Only used with WindType = 5] (m)</td>
<td></td>
</tr>
<tr>
<td>Aero-Dyn</td>
<td>13</td>
<td>CompAA</td>
<td>False CompAA - Flag to compute AeroAcoustics calculation [only used when WakeMod=1 or 2]</td>
<td></td>
</tr>
<tr>
<td>Aero-Dyn</td>
<td>14</td>
<td>AA_InputFile</td>
<td>“unused” AA_InputFile - Aeroacoustics input file</td>
<td></td>
</tr>
<tr>
<td>Air-FoilTables</td>
<td>35</td>
<td>[separator line]</td>
<td>======== OLAF cOnvecting LAgrangian Filaments (Free Vortex Wake) Theory Options ============== [used only when WakeMod=3]</td>
<td></td>
</tr>
<tr>
<td>Aero-Dyn</td>
<td>36</td>
<td>OLAFInputFileName</td>
<td>“Elliptic.OLAF.dat” OLAFInputFileName - Input file for OLAF [used only when WakeMod=3]</td>
<td></td>
</tr>
<tr>
<td>Air-FoilTables</td>
<td>4*</td>
<td>BL_file</td>
<td>“unused” BL_file - The file name including the boundary layer characteristics of the profile. Ignored if the aeroacoustic module is not called.</td>
<td></td>
</tr>
</tbody>
</table>

### Modified in OpenFAST v2.4.0

<table>
<thead>
<tr>
<th>Module</th>
<th>Line</th>
<th>New Flag</th>
<th>Name</th>
<th>Example Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air-FoilTables</td>
<td>40*</td>
<td>filtCut-Off</td>
<td>“DEFAULT” filtCut-Off - Reduced frequency cut-off for low-pass filtering the AoA input to UA, as well as the 1st and 2nd deriv (-) [default = 0.5]</td>
<td>[default = 20]</td>
</tr>
<tr>
<td>In-flowWind</td>
<td>17</td>
<td>File-name_Uni</td>
<td>“unused” Filename_Uni - Filename of time series data for uniform wind field. (-)</td>
<td>Filename</td>
</tr>
<tr>
<td>In-flowWind</td>
<td>18</td>
<td>RefHt_Uni</td>
<td>90 RefHt_Uni - Reference height for horizontal wind speed (m)</td>
<td>RefHt</td>
</tr>
<tr>
<td>In-flowWind</td>
<td>35</td>
<td>RefHt_Hawc</td>
<td>90 RefHt_Hawc - reference height; the height (in meters) of the vertical center of the grid (m)</td>
<td>RefHt</td>
</tr>
<tr>
<td>In-flowWind</td>
<td>47</td>
<td>PLEExp_Hawc</td>
<td>0 PLEExp_Hawc - Power law exponent (-) (used for PL wind profile type only)</td>
<td>PLEExp</td>
</tr>
<tr>
<td>In-flowWind</td>
<td>49</td>
<td>XOffset</td>
<td>0 XOffset - Initial offset in +x direction (shift of wind box)</td>
<td>InitPosition(x)</td>
</tr>
</tbody>
</table>

*non-comment line count, excluding lines contained if NumCoords is not 0.
4.1.4 OpenFAST v2.2.0 to OpenFAST v2.3.0

<table>
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<th>Line</th>
<th>Flag Name</th>
<th>Example Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AeroDyn Airfoil Input File - Airfoil Tables</td>
<td>2</td>
<td>Ctrl</td>
<td>0 Ctrl ! Control setting (must be 0 for current AirfoilInfo)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Added in OpenFAST v2.3.0</th>
<th>Module</th>
<th>Line</th>
<th>Flag Name</th>
<th>Example Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AeroDyn Airfoil Input File - Airfoil Tables</td>
<td>2</td>
<td>User-Prop</td>
<td>0 UserProp ! User property (control) setting</td>
</tr>
<tr>
<td></td>
<td>AeroDyn</td>
<td>37</td>
<td>AFTabMod</td>
<td>1 AFTabMod - Interpolation method for multiple airfoil tables {1=1D interpolation on AoA (first table only); 2=2D interpolation on AoA and Re; 3=2D interpolation on AoA and UserProp} (-)</td>
</tr>
</tbody>
</table>

4.1.5 OpenFAST v2.1.0 to OpenFAST v2.2.0

No changes required.

4.1.6 OpenFAST v2.0.0 to OpenFAST v2.1.0

<table>
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<th>Line</th>
<th>Flag Name</th>
<th>Example Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BeamDyn driver</td>
<td>21</td>
<td>GlbRotBladeT0</td>
<td>True GlbRotBladeT0 - Reference orientation for BeamDyn calculations is aligned with initial blade root</td>
</tr>
</tbody>
</table>
4.1.7 OpenFAST v1.0.0 to OpenFAST v2.0.0

<table>
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<td><strong>Module</strong></td>
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<td>BeamDyn</td>
</tr>
</tbody>
</table>

<table>
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<tr>
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</thead>
<tbody>
<tr>
<td><strong>Module</strong></td>
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</tr>
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<tr>
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<tr>
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</tr>
</tbody>
</table>

4.1.8 FAST v8.16 to OpenFAST v1.0.0

The transition from FAST v8 to OpenFAST is described in detail at *FAST v8 and the transition to OpenFAST*. 

<table>
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<tbody>
<tr>
<td><strong>Module</strong></td>
</tr>
<tr>
<td>OpenFAST</td>
</tr>
</tbody>
</table>
### Added in OpenFAST v1.0.0

<table>
<thead>
<tr>
<th>Module</th>
<th>Line</th>
<th>Flag Name</th>
<th>Example Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open-FAST</td>
<td>18</td>
<td>Comp-Sub</td>
<td>0 CompSub - Compute sub-structural dynamics (switch) (0=None; 1=SubDyn; 2=External Platform MCKF)</td>
</tr>
<tr>
<td>Aero-Dyn</td>
<td>12</td>
<td>Cavity-Check</td>
<td>False CavitCheck - Perform cavitation check? (flag)</td>
</tr>
<tr>
<td>Aero-Dyn</td>
<td>17</td>
<td>Patm</td>
<td>9999.9 Patm - Atmospheric pressure (Pa) [used only when CavitCheck=True]</td>
</tr>
<tr>
<td>Aero-Dyn</td>
<td>18</td>
<td>Pvap</td>
<td>9999.9 Pvap - Vapor pressure of fluid (Pa) [used only when CavitCheck=True]</td>
</tr>
<tr>
<td>Aero-Dyn</td>
<td>19</td>
<td>Fluid-Depth</td>
<td>9999.9 FluidDepth - Water depth above mid-hub height (m) [used only when CavitCheck=True]</td>
</tr>
</tbody>
</table>

### 4.2 Overview of input file formats

OpenFAST uses two primary input file formats: **value column** where the first value on the line is read, and **key+value** where a value and keyword pair are read. Both formats are line number based where a specific input is expected on a specific line, with some exceptions.

#### 4.2.1 Value column input files

Only the first column in a **value column** based input file is read. This is the historical format used by OpenFAST and its predecessors. Everything after the first value read is simply ignored by the code. This allowed the user to keep old values while modifying things. So for example, an input line like

```
2  20  TMax - Total run time (s)
```

would be read as 2 and the 20 and everything after it ignored.

This format and associated parsing methodology is somewhat limited in informing the user of errors in parsing, and limited the ability to pass entire input files as text strings from another code (such as a Python driver code).

#### 4.2.2 Key + Value input files

The first two columns are read in **key + value** input files. One of these two columns must contain the **exact** keyword, and the other must contain the value that corresponds to it. For example, an input line

```
20  TMax - Total run time (s)
```

is equivalent to

```
TMax  20 - Total run time (s)
```

One additional feature of this input file format is the ability to add an arbitrary number of comment lines wherever the user wishes. Any line starting with !, #, or % will be treated as a comment line and ignored. For example,

```
! This is a comment line that will be skipped
    % and this is also a comment line that will be skipped
# as is this comment line
```
The parser for this format of input file also tracks which lines were comments, and which lines contained the value and key pair. If a keyname is not found the parser will return an error with information about which line it was reading from.

### Modules using Key + Value Format

The following modules use the *key + value* format input files (all other modules use the *value column* format):

<table>
<thead>
<tr>
<th>Module</th>
<th>Input file</th>
</tr>
</thead>
<tbody>
<tr>
<td>AeroDyn</td>
<td>Main AD15 input file</td>
</tr>
<tr>
<td>AeroDyn</td>
<td>Airfoil files</td>
</tr>
<tr>
<td>InflowWind</td>
<td>Main HW input file</td>
</tr>
<tr>
<td>InflowWind</td>
<td>Uniform wind input file</td>
</tr>
<tr>
<td>InflowWind</td>
<td>Bladed wind summary file</td>
</tr>
<tr>
<td>ServoDyn</td>
<td>Main ServoDyn input file</td>
</tr>
<tr>
<td>ServoDyn</td>
<td>Structural control submodule input file</td>
</tr>
<tr>
<td>ServoDyn</td>
<td>Structural control submodule prescribed force input file</td>
</tr>
<tr>
<td>SubDyn</td>
<td>SubDyn SSI matrix input files</td>
</tr>
</tbody>
</table>

### Reasons for change

The main reason for the change in the input file parsing was to allow for the passing of a complete input file in memory from a wrapper code into OpenFAST or a module. For example, when including the AeroDyn module into a Python code, the input file can be passed in directly in memory without writing to disk first. This helps reduce the IO overhead in optimization loops where the module might be called many times sequentially with very small changes to the input file. *NOTE: this is still a work in progress, so not all modules can be linked this way yet.*

To accomplish this, the file parser written by Marshall Buhl for parsing airfoil tables in AeroDyn 15 in FAST8 was used. This parser included the more robust *key + value* input format.

### 4.2.3 Troubleshooting input files

When troubleshooting an input file error, try the following procedure:

1. An error message containing a line number and variable name, the file format being parsed is a *key + value* format. Check that the key is spelled exactly as the input file. See Section 4.2.2 below.

2. An error message containing only the variable name but no line number is a *value column* input file format. See Section 4.2.1 below.

3. Turn on *echo* option in the input file and check the resulting *.ech* for which line the file parsing stopped at. This may help isolate where the input file parsing failed when no line number is given in the error message.

4. Compare the problematic input file with an input file of the same type from the regression test suite distributed with OpenFAST. See section Section 3 for details on the regression tests, or check the repository at r-test.
4.3 AeroDyn Users Guide and Theory Manual

4.3.1 Introduction

AeroDyn is a time-domain wind turbine aerodynamics module that is coupled in the OpenFAST multi-physics engineering tool to enable aero-elastic simulation of horizontal-axis turbines. AeroDyn can also be driven as a standalone code to compute wind turbine aerodynamic response uncoupled from OpenFAST. When coupled to OpenFAST, AeroDyn can also be linearized as part of the linearization of the full coupled solution (linearization is not available in standalone mode). AeroDyn was originally developed for modeling wind turbine aerodynamics. However, the module equally applies to the hydrodynamics of marine hydrokinetic (MHK) turbines (the terms “wind turbine”, “tower”, “aerodynamics” etc. in this document imply “MHK turbine”, “MHK support structure”, “hydrodynamics” etc. for MHK turbines). Additional physics important for MHK turbines, not applicable to wind turbines, computed by AeroDyn include a cavitation check. This documentation pertains version of AeroDyn in the OpenFAST github repository. The AeroDyn version released of OpenFAST 1.0.0 is most closely related to AeroDyn version 15 in the legacy version numbering. AeroDyn version 15 was a complete overhaul from earlier version of AeroDyn. AeroDyn version 15 and newer follows the requirements of the FAST modularization framework.

AeroDyn calculates aerodynamic loads on both the blades and tower. Aerodynamic calculations within AeroDyn are based on the principles of actuator lines, where the three-dimensional (3D) flow around a body is approximated by local two-dimensional (2D) flow at cross sections, and the distributed pressure and shear stresses are approximated by lift forces, drag forces, and pitching moments lumped at a node in a 2D cross section. Analysis nodes are distributed along the length of each blade and tower, the 2D forces and moment at each node are computed as distributed loads per unit length, and the total 3D aerodynamic loads are found by integrating the 2D distributed loads along the length. When AeroDyn is coupled to OpenFAST, the blade and tower analysis node discretization may be independent from the discretization of the nodes in the structural modules. The actuator line approximations restrict the validity of the model to slender structures and 3D behavior is either neglected, captured through corrections inherent in the model (e.g., tip-loss, hub-loss, or skewed-wake corrections), or captured in the input data (e.g., rotational augmentation corrections applied to airfoil data).

AeroDyn assumes the turbine geometry consists of a one-, two-, or three-bladed rotor atop a single tower. While the undeflected tower is assumed to be straight and vertical, an undeflected blade may consider out-of-plane curvature and in-plane sweep. For blades, the 2D cross sections where the aerodynamic analysis take place may follow the out-of-plane curvature, but in-plane sweep is assumed to be accomplished by shearing, rather than rotation of the 2D cross section. Aerodynamic imbalances are possible through the use of geometrical differences between each blade.

When AeroDyn is coupled to OpenFAST, AeroDyn receives the instantaneous (possibly displaced/deflected) structural position, orientation, and velocities of analysis nodes in the tower, hub, and blades. As with curvature and sweep, the 2D cross sections where the blade aerodynamic analysis takes place will follow the out-of-plane deflection, but in-plane deflection is assumed to be accomplished by shearing, rather than rotation of the 2D cross section. AeroDyn also receives the local freestream (undisturbed) fluid velocities at the tower and blade nodes. (Fluid and structural calculations take place outside of the AeroDyn module and are passed as inputs to AeroDyn by the driver code.) The fluid and structural motions are provided at each coupling time step and then AeroDyn computes the aerodynamic loads on the blade and tower nodes and returns them back to OpenFAST as part of the aero-elastic calculation. In standalone mode, the inputs to AeroDyn are prescribed by a simple driver code, without aero-elastic coupling.

AeroDyn consists of four submodels: (1) rotor wake/induction, (2) blade airfoil aerodynamics, (3) tower influence on the fluid local to the blade nodes, and (4) tower drag. Nacelle, hub, and tail-vane fluid influence and loading, aeroacoustics, and wake and array effects between multiple turbines in a wind plant, are not yet available in AeroDyn v15 and newer.

For operating wind and MHK turbine rotors, AeroDyn calculates the influence of the wake via induction factors based on the quasi-steady Blade-Element/Momentum (BEM) theory, which requires an iterative nonlinear solve (implemented via Brent’s method). By quasi-steady, it is meant that the induction reacts instantaneously to loading changes. The induction calculation, and resulting inflow velocities and angles, are based on flow local to each analysis node of each blade, based on the relative velocity between the fluid and structure (including the effects of local inflow skew, ...
shear, turbulence, tower flow disturbances, and structural motion, depending on features enabled). The Glauert’s empirical correction (with Buhl’s modification) replaces the linear momentum balance at high axial induction factors. In the BEM solution, Prandtl tip-loss, Prandtl hub-loss, and Pitt and Peters skewed-wake are all 3D corrections that can optionally be applied. When the skewed-wake correction is enabled, it is applied after the BEM iteration. Additionally, the calculation of tangential induction (from the angular momentum balance), the use of drag in the axial-induction calculation, and the use of drag in the tangential-induction calculation are all terms that can optionally be included in the BEM iteration (even when drag is not used in the BEM iteration, drag is still used to calculate the nodal loads once the induction has been found). The wake/induction calculation can be bypassed altogether for the purposes of modeling rotors that are parked or idling, in which case the inflow velocity and angle are determined purely geometrically.

Prandtl tip-loss, Prandtl hub-loss, and Pitt and Peters skewed-wake are all 3D corrections that can optionally be applied. When the skewed-wake correction is enabled, it is applied after the BEM iteration. Additionally, the calculation of tangential induction (from the angular momentum balance), the use of drag in the axial-induction calculation, and the use of drag in the tangential-induction calculation are all terms that can optionally be included in the BEM iteration (even when drag is not used in the BEM iteration, drag is still used to calculate the nodal loads once the induction has been found). The wake/induction calculation can be bypassed altogether for the purposes of modeling rotors that are parked or idling, in which case the inflow velocity and angle are determined purely geometrically.

During linearization analyses with AeroDyn coupled to OpenFAST and BEM enabled, the wake can be assumed to be frozen (i.e., the axial and tangential induces velocities, \( -V_x a \) and \( V_y a' \), are fixed at their operating-point values during linearization) or the induction can be recalculated during linearization using BEM theory. Dynamic wake that accounts for induction dynamics as a result of transient conditions are not yet available in AeroDyn v15 and newer.

The blade airfoil aerodynamics can be steady or unsteady, except in the case that a cavitation check is requested for MHK, in which case only steady aerodynamics are supported. In the steady model, the supplied static airfoil data — including the lift force, drag force, and optional pitching moment and minimum pressure coefficients versus angle of attack (AoA) — are used directly to calculate nodal loads. The AirfoilPrep preprocessor can be used to generate the needed static airfoil data based on uncorrected 2D data (based, e.g., on airfoil tests in a wind tunnel or Xfoil), including features to blend data between different airfoils, apply 3D rotational augmentation, and extrapolate to high AoA. The unsteady airfoil aerodynamic (UA) models account for flow hysteresis, including unsteady attached flow, trailing-edge flow separation, dynamic stall, and flow reattachment. The UA models can be considered as 2D dynamic corrections to the static airfoil response as a result of time-varying inflow velocities and angles. Three semi-empirical UA models are available: the original theoretical developments of Beddoes-Leishman (B-L), extensions to the B-L developed by González, and extensions to the B-L model developed by Minnema/Pierce. While all of the UA models are documented in this manual, the original B-L model is not yet functional. Testing has shown that the González and Minnema/Pierce models produce reasonable hysteresis of the normal force, tangential force, and pitching-moment coefficients if the UA model parameters are set appropriately for a given airfoil, Reynolds number, and/or Mach number. However, the results will differ a bit from earlier versions of AeroDyn, (which was based on the Minnema/Pierce extensions to B-L) even if the default UA model parameters are used, due to differences in the UA model logic between the versions. We recommend that users run test cases with uniform wind inflow and fixed yaw error (e.g., through the standalone AeroDyn driver) to examine the accuracy of the normal force, tangential force, and pitching-moment coefficient hysteresis and to adjust the UA model parameters appropriately.

The airfoil-, Reynolds-, and Mach-dependent parameters of the UA models may be derived from the static airfoil data. These UA models are valid for small to moderate AoA under normal rotor operation; the steady model is more appropriate under parked or idling conditions. The static airfoil data is always used in the BEM iteration; when UA is enabled, it is applied after the BEM iteration and after the skewed-wake correction. The UA models are not set up to support linearization, so, UA must be disabled during linearization analyses with AeroDyn coupled to OpenFAST. The interpolation of airfoil data based on Reynolds number or aerodynamic-control setting (e.g., flaps) is not yet available in AeroDyn v15 and newer.

The influence of the tower on the fluid flow local to the blade is based on a potential-flow and/or a tower-shadow model. The potential-flow model uses the analytical potential-flow solution for flow around a cylinder to model the tower dam effect on upwind rotors. In this model, the freestream (undisturbed) flow at each blade node is disturbed based on the location of the blade node relative to the tower and the tower diameter, including lower velocities upstream and downstream of the tower, higher velocities to the left and right of the tower, and cross-stream flow. The Bak correction can optionally be included in the potential-flow model, which augments the tower upstream disturbance and improves the tower wake for downwind rotors based on the tower drag coefficient. The tower shadow model can also be enabled to account for the tower wake deficit on downwind rotors. This model includes an axial flow deficit on the freestream fluid at each blade node dependent on the location of the blade node relative to the tower and the tower diameter and drag coefficient, based on the work of Powles. Both tower-influence models are quasi-steady models, in that the disturbance is applied directly to the freestream fluid at the blade nodes without dynamics, and are applied within the BEM iteration.

The aerodynamic load on the tower is based directly on the tower diameter and drag coefficient and the local relative
fluid velocity between the freestream (undisturbed) flow and structure at each tower analysis node (including the effects of local shear, turbulence, and structural motion, depending on features enabled). The tower drag load calculation is quasi-steady and independent from the tower influence on flow models.

The primary AeroDyn input file defines modeling options, environmental conditions (except freestream flow), airfoils, tower nodal discretization and properties, as well as output file specifications. Airfoil data properties are read from dedicated inputs files (one for each airfoil) and include coefficients of lift force, drag force, and optional pitching moment and minimum pressure versus AoA, as well as UA model parameters. (Minimum pressure coefficients versus AoA are also included in the airfoil input files in case that a cavitation check is requested.) Blade nodal discretization, geometry, twist, chord, and airfoil identifier are likewise read from separate input files (one for each blade).

Section 4.3.2 describes the AeroDyn input files. Section 4.3.3 discusses the output files generated by AeroDyn; these include an echo file, summary file, and the results file. Section 4.3.4 provides modeling guidance when using AeroDyn. Example input files are included in Section 4.3.6. A summary of available output channels are found Section 4.3.6.

4.3.2 Input Files

The user configures the aerodynamic model parameters via a primary AeroDyn input file, as well as separate input files for airfoil and blade data. When used in standalone mode, an additional driver input file is required. This driver file specifies initialization inputs normally provided to AeroDyn by OpenFAST, as well as the per-time-step inputs to AeroDyn.

As an example, the driver.dvr file is the main driver, the input.dat is the primary input file, the blade.dat file contains the blade geometry data, and the airfoil.dat file contains the airfoil angle of attack, lift, drag, moment coefficients, and pressure coefficients. Example input files are included in Section 4.3.6. No lines should be added or removed from the input files, except in tables where the number of rows is specified and comment lines in the AeroDyn airfoil data files.

Units

AeroDyn uses the SI system (kg, m, s, N). Angles are assumed to be in radians unless otherwise specified.

AeroDyn Driver Input File

The driver input file is only needed for the standalone version of AeroDyn and contains inputs normally generated by OpenFAST, and necessary to control the aerodynamic simulation for uncoupled models. A sample AeroDyn driver input file is given in Section 4.3.6.

Set the Echo flag in this file to TRUE if you wish to have the AeroDyn_Driver executable echo the contents of the driver input file (useful for debugging errors in the driver file). The echo file has the naming convention of OutFileRoot.ech, where OutFileRoot is specified in the I/O SETTINGS section of the driver input file below. AD_InputFile is the filename of the primary AeroDyn input file. This name should be in quotations and can contain an absolute path or a relative path.

The TURBINE DATA section defines the AeroDyn-required turbine geometry for a rigid turbine, see Figure 1. NumBlades specifies the number of blades; only one-, two-, or three-bladed rotors are permitted. HubRad specifies the radius to the blade root from the center-of-rotation along the (possibly preconed) blade-pitch axis; HubRad must be greater than zero. HubHt specifies the elevation of the hub center above the ground (or above the mean sea level (MSL) for offshore wind turbines or above the seabed for MHK turbines). Overhang specifies the distance along the (possibly tilted) rotor shaft between the tower centerline and hub center; Overhang is positive downwind, so use a negative number for upwind rotors. ShftTilt is the angle (in degrees) between the rotor shaft and the horizontal plane. Positive ShftTilt means that the downwind end of the shaft is the highest; upwind turbines have negative ShftTilt for improved tower clearance. Precone is the angle (in degrees) between a flat rotor disk and the cone swept by the blades, positive downwind; upwind turbines have negative Precone for improved tower clearance.
The I/O SETTINGS section controls the creation of the results file. If `OutFileRoot` is specified, the results file will have the filename `OutFileRoot.out`. If an empty string is provided for `OutFileRoot`, then the driver file’s root name will be used instead. If `TabDel` is `TRUE`, a TAB character is used between columns in the output file; if `FALSE`, fixed-width is used otherwise. `OutFmt` is any valid Fortran numeric format string, which is used for text output, excluding the time channel. The resulting field should be 10 characters, but AeroDyn does not check `OutFmt` for validity. If you want a sound generated on program exit, set `Beep` to `true`.

Fig. 4.1: AeroDyn Driver Turbine Geometry

The COMBINED-CASE ANALYSIS section allows you to execute `NumCases` number of simulations for the given TURBINE DATA with a single driver input file. There will be one row in the subsequent table for each of the `NumCases` specified (plus two table header lines). The information within each row of the table fully specifies each simulation. Each row contains the following columns: `WndSpeed`, `ShearExp`, `RotSpd`, `Pitch`, `Yaw`, `dT`, and
The local undisturbed wind speed for any given blade or tower node is determined using,

\[ U(Z) = WndSpeed \times \left( \frac{Z}{HubHt} \right)^{ShearExp} \]  \hspace{1cm} (4.1)

where \( WndSpeed \) is the steady wind speed (fluid flow speed in the case of an MHK turbine) located at elevation \( HubHt \), \( Z \) is the instantaneous elevation of the blade or tower node above the ground (or above the MSL for offshore wind turbines or above the seabed for MHK turbines), and \( ShearExp \) is the power-law shear exponent. The fixed rotor speed (in rpm) is given by \( RotSpd \) (positive clockwise looking downwind), the fixed blade-pitch angle (in degrees) is given by \( Pitch \) (positive to feather, leading edge upwind), and the fixed nacelle-yaw angle (in degrees) is given by \( Yaw \) (positive rotation of the nacelle about the vertical tower axis, counterclockwise when looking downward). While the flow speed and direction in the AeroDyn driver is uniform and fixed (depending only on elevation above ground), \( Yaw \) and \( ShftTilt \) (from the TURBINE DATA section above) can introduce skewed flow. \( dT \) is the simulation time step, which must match the time step for the aerodynamic calculations (\( DTAero \)) as specified in the primary AeroDyn input file, and \( Tmax \) is the total simulation time.

Note that \( dT \) should be the same for each of the cases listed in the COMBINED-CASE ANALYSIS section. All of the cases will be output to the same file, with a Case column listed next to the Time output column for help with data processing.

For further debugging capability, the AeroDyn driver now also has the ability to read the combined case input data as a time-history file. In place of a row in the COMBINED-CASE ANALYSIS table, a separate input file can be listed instead. The name of the file should be preceded with the @ character, to indicate the data is a time-history file in a separate text input file. An example is provided in Section 4.3.6.

### AeroDyn Primary Input File

The primary AeroDyn input file defines modeling options, environmental conditions (except freestream flow), airfoils, tower nodal discretization and properties, as well as output file specifications.

The file is organized into several functional sections. Each section corresponds to an aspect of the aerodynamics model. A sample AeroDyn primary input file is given in Section 4.3.6.

The input file begins with two lines of header information which is for your use, but is not used by the software.

### General Options

Set the Echo flag to TRUE if you wish to have AeroDyn echo the contents of the AeroDyn primary, airfoil, and blade input files (useful for debugging errors in the input files). The echo file has the naming convention of OutRootFile_AD.ech. OutRootFile is either specified in the I/O SETTINGs section of the driver input file when running AeroDyn standalone, or by the OpenFAST program when running a coupled simulation.

\( DTAero \) sets the time step for the aerodynamic calculations. For accuracy and numerical stability, we recommend that \( DTAero \) be set such that there are at least 200 azimuth steps per rotor revolution. However, when AeroDyn is coupled to OpenFAST, OpenFAST may require time steps much smaller than this rule of thumb. If UA is enabled while using very small time steps, you may need to recompile AeroDyn in double precision to avoid numerical problems in the UA routines. The keyword DEFAULT for \( DTAero \) may be used to indicate that AeroDyn should employ the time step prescribed by the driver code (OpenFAST or the standalone driver program).

Set WakeMod to 0 if you want to disable rotor wake/induction effects or 1 to include these effects using the (quasi-steady) BEM theory model. When WakeMod is set to 2, a dynamic BEM theory model (DBEMT) is used (also referred to as dynamic inflow or dynamic wake model). When WakeMod is set to 3, the free vortex wake model is used, also referred to as OLAF (see Section 4.4). WakeMod cannot be set to 2 or 3 during linearization analyses.

Set AFAeroMod to 1 to include steady blade airfoil aerodynamics or 2 to enable UA; AFAeroMod must be 1 during linearization analyses with AeroDyn coupled to OpenFAST.

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Set `TwrPotent` to 0 to disable the potential-flow influence of the tower on the fluid flow local to the blade, 1 to enable the standard potential-flow model, or 2 to include the Bak correction in the potential-flow model.

Set the `TwrShadow` to 0 to disable the tower shadow model, 1 to enable the Powles tower shadow model, or 2 to use the Eames tower shadow model. These models calculate the influence of the tower on the flow local to the blade based on the downstream tower shadow model. If the tower influence from potential flow and tower shadow are both enabled, the two influences will be superimposed.

Set the `TwrAero` flag to TRUE to calculate fluid drag loads on the tower or FALSE to disable these effects.

During linearization analyses with AeroDyn coupled OpenFAST and BEM enabled (`WakeMod = 1`), set the `FrozenWake` flag to TRUE to employ frozen-wake assumptions during linearization (i.e. to fix the axial and tangential induces velocities, and, at their operating-point values during linearization) or FALSE to recalculate the induction during linearization using BEM theory.

Set the `CavitCheck` flag to TRUE to perform a cavitation check for MHK turbines or FALSE to disable this calculation. If `CavitCheck` is TRUE, `AFAeroMod` must be set to 1 because the cavitation check does not function with unsteady airfoil aerodynamics.

Set the `CompAA` flag to TRUE to run aero-acoustic calculations. This option is only available for `WakeMod = 1` or 2. See section Section 4.5 for information on how to use this feature.

The `AA_InputFile` is used to specify the input file for the aeroacoustics sub-module. See Section 4.5 for information on how to use this feature.

### Environmental Conditions

`AirDens` specifies the fluid density and must be a value greater than zero; a typical value is around 1.225 kg/m³ for air (wind turbines) and 1025 kg/m³ for seawater (MHK turbines). `KinVisc` specifies the kinematic viscosity of the air (used in the Reynolds number calculation); a typical value is around 1.460E-5 m²/s for air (wind turbines) and 1.004E-6 m²/s for seawater (MHK turbines). `SpdSound` is the speed of sound in air (used to calculate the Mach number within the unsteady airfoil aerodynamics calculations); a typical value is around 340.3 m/s. The last three parameters in this section are only used when `CavitCheck = TRUE` for MHK turbines. `Patm` is the atmospheric pressure above the free surface; typically around 101,325 Pa. `Pvap` is the vapor pressure of the fluid; for seawater this is typically around 2,000 Pa. `FluidDepth` is the distance from the hub center to the free surface.

### Blade-Element/Momentum Theory Options

The input parameters in this section are not used when `WakeMod = 0`.

`SkewMod` determines the skewed-wake correction model. Set `SkewMod` to 1 to use the uncoupled BEM solution technique without an additional skewed-wake correction. Set `SkewMod` to 2 to include the Pitt/Peters correction model. **The coupled model `SkewMod= 3` is not available in this version of AeroDyn.**

`SkewModFactor` is used only when `SkewMod = 1`. Enter a scaling factor to use in the Pitt/Peters correction model, or enter "default" to use the default value of \( \frac{15\pi}{32} \).

Set `TipLoss` to TRUE to include the Prandtl tip-loss model or FALSE to disable it. Likewise, set `HubLoss` to TRUE to include the Prandtl hub-loss model or FALSE to disable it.

Set `TanInd` to TRUE to include tangential tip-loss model or FALSE to neglect it. Likewise, set `AIDrag` to TRUE to include drag in the axial-induction calculation or FALSE to neglect it. If `TanInd = TRUE`, set `TIDrag` to TRUE to include drag in the tangential-induction calculation or FALSE to neglect it. Even when drag is not used in the BEM iteration, drag is still used to calculate the nodal loads once the induction has been found,
IndToler sets the convergence threshold for the iterative nonlinear solve of the BEM solution. The nonlinear solve is in terms of the inflow angle, but IndToler represents the tolerance of the nondimensional residual equation, with no physical association possible. When the keyword DEFAULT is used in place of a numerical value, IndToler will be set to 5E-5 when AeroDyn is compiled in single precision and to 5E-10 when AeroDyn is compiled in double precision; we recommend using these defaults. MaxIter determines the maximum number of iterations steps in the BEM solve. If the residual value of the BEM solve is not less than or equal to IndToler in MaxIter, AeroDyn will exit the BEM solver and return an error message.

**Dynamic Blade-Element/Momentum Theory Options**

The input parameters in this section are used only when WakeMod = 2.

Set DBEMT_Mod to 1 for the constant-tau1 model, or set DBEMT_Mod to 2 to use a model where tau1 varies with time.

If DBEMT_Mod=1 (constant-tau1 model), set tau1_const to the time constant to use for DBEMT.

**OLAF – cOnvecting LAgrangian Filaments (Free Vortex Wake) Theory Options**

The input parameters in this section are used only when WakeMod = 3.

The settings for the free vortex wake model are set in the OLAF input file described in Section 4.4.4. OLAFInputFileName is the filename for this input file.

**Unsteady Airfoil Aerodynamics Options**

The input parameters in this section are only used when AFAeroMod = 2.

UAMod determines the UA model. Setting UAMod to 1 enables original theoretical developments of B-L, 2 enables the extensions to B-L developed by González, and 3 enables the extensions to B-L developed by Minnema/Pierce. While all of the UA models are documented in this manual, the original B-L model is not yet functional. Testing has shown that the González and Minnema/Pierce models produce reasonable hysteresis of the normal force, tangential force, and pitching-moment coefficients if the UA model parameters are set appropriately for a given airfoil, Reynolds number, and/or Mach number. However, the results will differ a bit from earlier versions of AeroDyn, (which was based on the Minnema/Pierce extensions to B-L) even if the default UA model parameters are used, due to differences in the UA model logic between the versions. We recommend that users run test cases with uniform inflow and fixed yaw error (e.g., through the standalone AeroDyn driver) to examine the accuracy of the normal force, tangential force, and pitching-moment coefficient hysteresis and to adjust the UA model parameters appropriately.

FLookup determines how the nondimensional separation distance value, \( f' \), will be calculated. When FLookup is set to TRUE, \( f' \) is determined via a lookup into the static lift-force coefficient and drag-force coefficient data. Using best-fit exponential equations (``FLookup = FALSE``) is not yet available, so ``FLookup`` must be ``TRUE`` in this version of AeroDyn.
Airfoil Information

This section defines the airfoil data input file information. The airfoil data input files themselves (one for each airfoil) include tables containing coefficients of lift force, drag force, and optionally pitching moment, and minimum pressure versus AoA, as well as UA model parameters, and are described in Section 4.3.2.

The first 5 lines in the AIRFOIL INFORMATION section relate to the format of the tables of static airfoil coefficients within each of the airfoil input files. InCol_Alfa, InCol_Cl, InCol_Cd, InCol_Cm, and InCol_Cpmin are column numbers in the tables containing the AoA, lift-force coefficient, drag-force coefficient, pitching-moment coefficient, and minimum pressure coefficient, respectively (normally these are 1, 2, 3, 4, and 5, respectively). If pitching-moment terms are neglected with UseBlCm = FALSE, InCol_Cm may be set to zero, and if the cavitation check is disabled with CavitCheck = FALSE, InCol_Cpmin may be set to zero.

Specify the number of airfoil data input files to be used using NumAFfiles, followed by NumAFfiles lines of filenames. The file names should be in quotations and can contain an absolute path or a relative path e.g., “C:\airfoils\S809_CLN_298.dat” or “airfoils\S809_CLN_298.dat”. If you use relative paths, it is relative to the location of the file in which it is specified. The blade data input files will reference these airfoil data using their line identifier, where the first airfoil file is numbered 1 and the last airfoil file is numbered NumAFfiles.

Rotor/Blade Properties

Set UseBlCm to TRUE to include pitching-moment terms in the blade airfoil aerodynamics or FALSE to neglect them; if UseBlCm = TRUE, pitching-moment coefficient data must be included in the airfoil data tables with InCol_Cm not equal to zero.

The blade nodal discretization, geometry, twist, chord, and airfoil identifier are set in separate input files for each blade, described in Section 4.3.2. ADBlFile(1) is the filename for blade 1, ADBlFile(2) is the filename for blade 2, and ADBlFile(3) is the filename for blade 3, respectively; the latter is not used for two-bladed rotors and the latter two are not used for one-bladed rotors. The file names should be in quotations and can contain an absolute path or a relative path. The data in each file need not be identical, which permits modeling of aerodynamic imbalances.

Tower Influence and Aerodynamics

The input parameters in this section pertain to the tower influence and/or tower drag calculations and are only used when TwrPotent > 0, TwrShadow > 0, or TwrAero = TRUE.

NumTwrNds is the user-specified number of tower analysis nodes and determines the number of rows in the subsequent table (after two table header lines). NumTwrNds must be greater than or equal to two; the higher the number, the finer the resolution and longer the computational time; we recommend that NumTwrNds be between 10 and 20 to balance accuracy with computational expense. For each node, TwrElev specifies the local elevation of the tower node above ground (or above MSL for offshore wind turbines or above the seabed for MHK turbines), TwrDiam specifies the local tower diameter, TwrCd specifies the local tower drag-force coefficient, and TwrTI specifies the turbulence intensity used in the Eames tower shadow model (TwrShadow = 2). TwrElev must be entered in monotonically increasing order—from the lowest (tower-base) to the highest (tower-top) elevation. Values of TwrTI between 0.05 and 0.4 are recommended. Values larger than 0.4 up to 1 will trigger a warning that the results will need to be interpreted carefully, but the code will allow such values for scientific investigation purposes. See Fig. 4.2.
Outputs

Specifying SumPrint to TRUE causes AeroDyn to generate a summary file with name OutFileRoot**.AD. sum*. OutFileRoot is either specified in the I/O SETTINGS section of the driver input file when running AeroDyn standalone, or by the OpenFAST program when running a coupled simulation. See Section 4.3.3 for summary file details.

AeroDyn can output aerodynamic and kinematic quantities at up to nine nodes specified along the tower and up to nine nodes along each blade. For outputs at every blade node, see Section 4.3.2.

NBOuts specifies the number of blade nodes that output is requested for (0 to 9) and BlOutNd on the next line is a list NBOuts long of node numbers between 1 and NumBlNds (corresponding to a row number in the blade analysis node table in the blade data input files), separated by any combination of commas, semicolons, spaces, and/or tabs. All blades have the same output node numbers. NTwOuts specifies the number of tower nodes that output is requested for (0 to 9) and TwOutNd on the next line is a list NTwOuts long of node numbers between 1 and NumTwrNds (corresponding to a row number in the tower analysis node table above), separated by any combination of commas, semicolons, spaces, and/or tabs. The outputs specified in the OutList section determine which quantities are actually output at these nodes.

The OutList section controls output quantities generated by AeroDyn. Enter one or more lines containing quoted strings that in turn contain one or more output parameter names. Separate output parameter names by any combination of commas, semicolons, spaces, and/or tabs. If you prefix a parameter name with a minus sign, “-”, underscore, “_”, or the characters “m” or “M”, AeroDyn will multiply the value for that channel by –1 before writing the data. The parameters are written in the order they are listed in the input file. AeroDyn allows you to use multiple lines so that you can break your list into meaningful groups and so the lines can be shorter. You may enter comments after the closing quote on any of the lines. Entering a line with the string “END” at the beginning of the line or at the beginning of a quoted string found at the beginning of the line will cause AeroDyn to quit scanning for more lines of channel names. Blade and tower node-related quantities are generated for the requested nodes identified through the BlOutNd and TwOutNd lists above. If AeroDyn encounters an unknown/invalid channel name, it warns the users but will remove the suspect channel from the output file. Please refer to Appendix E for a complete list of possible output parameters.

Nodal Outputs

In addition to the named outputs in Section 4.3.2 above, AeroDyn allows for outputting the full set blade node motions and loads (tower nodes unavailable at present). Please refer to the AeroDyn_Nodes tab in the Excel file OutListParameters.xlsx for a complete list of possible output parameters.

This section follows the END statement from normal Outputs section described above, and includes a separator description line followed by the following options.

BldNd_BladesOut specifies the number of blades to output. Possible values are 0 through the number of blades AeroDyn is modeling. If the value is set to 1, only blade 1 will be output, and if the value is 2, blades 1 and 2 will be output.

BldNd_BlOutNd specifies which nodes to output. This is currently unused.

The OutList section controls the nodal output quantities generated by AeroDyn. In this section, the user specifies the name of the channel family to output. The output name for each channel is then created internally by AeroDyn by combining the blade number, node number, and channel family name. For example, if the user specifies AxInd as the channel family name, the output channels will be named with the convention of B\betaN###AxInd where \beta is the blade number, and ### is the three digit node number.
Fig. 4.2: AeroDyn Tower Geometry
Sample Nodal Outputs section

This sample includes the END statement from the regular outputs section.

```plaintext
END of input file (the word "END" must appear in the first 3 columns of this last OutList line)

---------------------- NODE OUTPUTS --------------------------------------------
3 BldNd_BladesOut - Blades to output
99 BldNd_B1OutNd - Blade nodes on each blade (currently unused)
OutList - The next line(s) contains a list of output parameters.
See OutListParameters.xlsx, AeroDyn_Nodes tab for a listing of available output channels, (-)

"VUndx" - x-component of undisturbed wind velocity at each node
"VUndy" - y-component of undisturbed wind velocity at each node
"VUndz" - z-component of undisturbed wind velocity at each node
"VDisx" - x-component of disturbed wind velocity at each node
"VDisy" - y-component of disturbed wind velocity at each node
"VDisz" - z-component of disturbed wind velocity at each node
"STVx" - x-component of structural translational velocity at each node
"STVy" - y-component of structural translational velocity at each node
"STVz" - z-component of structural translational velocity at each node
"VRe1" - Relative wind speed at each node
"DynP" - Dynamic pressure at each node
"Re" - Reynolds number (in millions) at each node
"M" - Mach number at each node
"Vindx" - Axial induced wind velocity at each node
"Vindy" - Tangential induced wind velocity at each node
"AxInd" - Axial induction factor at each node
"TnInd" - Tangential induction factor at each node
"Alpha" - Angle of attack at each node
"Theta" - Pitch+Twist angle at each node
"Phi" - Inflow angle at each node
"Curve" - Curvature angle at each node
"CI" - Lift force coefficient at each node
"Cd" - Drag force coefficient at each node
"Cm" - Pitching moment coefficient at each node
"Cx" - Normal force (to plane) coefficient at each node
"Cy" - Tangential force (to plane) coefficient at each node
"Cn" - Normal force (to chord) coefficient at each node
"Ct" - Tangential force (to chord) coefficient at each node
"Fl" - Lift force per unit length at each node
"Fd" - Drag force per unit length at each node
"Mm" - Pitching moment per unit length at each node
"Fx" - Normal force (to plane) per unit length at each node
"Fy" - Tangential force (to plane) per unit length at each node
"Fn" - Normal force (to chord) per unit length at each node
"Ft" - Tangential force (to chord) per unit length at each node
"Clrnc" - Tower clearance at each node (based on the absolute distance to the nearest point in the tower from blade node B#N# minus the local tower radius, in the deflected configuration); please note that this clearance is only approximate because the calculation assumes that the blade is a line with no volume (however, the calculation does use the local tower radius); when blade node B#N# is above the tower top (or below the tower base), the absolute distance to the tower top (or base) minus the local tower radius, in the deflected configuration, is output
"Vx" - Local axial velocity
"Vy" - Local tangential velocity
"GeomPhi" - Geometric phi? If phi was solved using normal BEMT equations, GeomPhi = -1; otherwise, if it was solved geometrically, GeomPhi = 0.
```

(continues on next page)
Airfoil Data Input File

The airfoil data input files themselves (one for each airfoil) include tables containing coefficients of lift force, drag force, and pitching moment versus AoA, as well as UA model parameters. In these files, any line whose first non-blank character is an exclamation point (!) is ignored (for inserting comment lines). The non-comment lines should appear within the file in order, but comment lines may be intermixed as desired for reading clarity. A sample airfoil data input file is given Section 4.3.6.

InterpOrd is the order the static airfoil data is interpolated when AeroDyn uses table look-up to find the lift-, drag-, and optional pitching-moment, and minimum pressure coefficients as a function of AoA. When InterpOrd is 1, linear interpolation is used; when InterpOrd is 3, the data will be interpolated with cubic splines; if the keyword DEFAULT is entered in place of a numerical value, InterpOrd is set to 1.

NonDimArea is the nondimensional airfoil area (normalized by the local BlChord squared), but is currently unused by AeroDyn. NumCoords is the number of points to define the exterior shape of the airfoil, plus one point to define the aerodynamic center, and determines the number of rows in the subsequent table; NumCoords must be exactly zero or greater than or equal to three. For each point, the nondimensional X and Y coordinates are specified in the table, X_Coord and Y_Coord (normalized by the local BlChord). The first point must always locate the aerodynamic center (reference point for the airfoil lift and drag forces, likely not on the surface of the airfoil); the remaining points should define the exterior shape of the airfoil. The airfoil shape is currently unused by AeroDyn, but when AeroDyn is coupled to OpenFAST, the airfoil shape will be used by OpenFAST for blade surface visualization when enabled.

BL_file is the name of the file containing boundary-layer characteristics of the profile. It is ignored if the aeroacoustic module is not used.

Specify the number of Reynolds number- or aerodynamic-control setting-dependent tables of data for the given airfoil via the NumTabs setting. The remaining parameters in the airfoil data input files are entered separately for each table. Re and UserProp are the Reynolds number (in millions) and aerodynamic-control (or user property) setting for the included table. These values are used only when the AFTabMod parameter in the primary AeroDyn input file is set to
use 2D interpolation based on \( \text{Re} \) or UserProp. If 1D interpolation (based only on angle of attack) is used, only the first table in the file will be used.

Set `InclUAdata` to `TRUE` if you are including the 32 UA model parameters (required when `AFAeroMod = 2` in the AeroDyn primary input file):

- `alpha0` specifies the zero-lift AoA (in degrees);
- `alpha1` specifies the AoA (in degrees) larger than `alpha0` for which \( f \) equals 0.7; approximately the positive stall angle;
- `alpha2` specifies the AoA (in degrees) less than `alpha0` for which \( f \) equals 0.7; approximately the negative stall angle;
- `eta_e` is the recovery factor and typically has a value in the range \([0.85 \text{ to } 0.95]\) for `UAMod = 1`; if the keyword `DEFAULT` is entered in place of a numerical value, `eta_e` is set to 0.9 for `UAMod = 1`, but `eta_e` is set to 1.0 for other `UAMod` values and whenever `FLookup = TRUE`;
- `C\_nalpha` is the slope of the 2D normal force coefficient curve in the linear region;
- `T\_f0` is the initial value of the time constant associated with \( Df \) in the expressions of \( Df \) and \( f' \); if the keyword `DEFAULT` is entered in place of a numerical value, `T\_f0` is set to 3.0;
- `T\_V0` is the initial value of the time constant associated with the vortex lift decay process, used in the expression of \( Cvn \); it depends on Reynolds number, Mach number, and airfoil; if the keyword `DEFAULT` is entered in place of a numerical value, `T\_V0` is set to 6.0;
- `T\_p` is the boundary-layer leading edge pressure gradient time constant in the expression for \( Dp \) and should be tuned based on airfoil experimental data; if the keyword `DEFAULT` is entered in place of a numerical value, `T\_p` is set to 1.7;
- `T\_VL` is the time constant associated with the vortex advection process, representing the nondimensional time in semi-chords needed for a vortex to travel from the leading to trailing edges, and used in the expression of \( Cvn \); it depends on Reynolds number, Mach number (weakly), and airfoil; valued values are in the range \([6 \text{ to } 13]\); if the keyword `DEFAULT` is entered in place of a numerical value, `T\_VL` is set to 11.0;
- `b1` is a constant in the expression of \( \phi_c^a \) and \( \phi_c^q \); this value is relatively insensitive for thin airfoils, but may be different for turbine airfoils; if the keyword `DEFAULT` is entered in place of a numerical value, `b1` is set to 0.14, based on experimental results;
- `b2` is a constant in the expression of \( \phi_c^a \) and \( \phi_c^q \); this value is relatively insensitive for thin airfoils, but may be different for turbine airfoils; if the keyword `DEFAULT` is entered in place of a numerical value, `b2` is set to 0.53, based on experimental results;
- `b5` is a constant in the expression of \( K_q^m \), \( Cm_q^nc \), and \( K_m_q \); if the keyword `DEFAULT` is entered in place of a numerical value, `b5` is set to 5, based on experimental results;
- `A1` is a constant in the expression \( \phi_c^a \) and \( \phi_c^q \); this value is relatively insensitive for thin airfoils, but may be different for turbine airfoils; if the keyword `DEFAULT` is entered in place of a numerical value, `A1` is set to 0.3, based on experimental results;
- `A2` is a constant in the expression \( \phi_c^a \) and \( \phi_c^q \); this value is relatively insensitive for thin airfoils, but may be different for turbine airfoils; if the keyword `DEFAULT` is entered in place of a numerical value, `A2` is set to 0.7, based on experimental results;
- `A5` is a constant in the expression \( K_q^m \), \( Cm_q^nc \), and \( K_m_q \); if the keyword `DEFAULT` is entered in place of a numerical value, `A5` is set to 1, based on experimental results;
- `S1` is the constant in the best fit curve of \( f \) for \( \alpha0 \leq \text{AoA} \leq \alpha1 \) for `UAMod = 1` (and is unused otherwise); by definition, it depends on the airfoil;
- `S2` is the constant in the best fit curve of \( f \) for \( \text{AoA} > \alpha1 \) for `UAMod = 1` (and is unused otherwise); by definition, it depends on the airfoil;
• $S_3$ is the constant in the best fit curve of $f$ for $\alpha_2 \leq \alpha \leq \alpha_0$ for $\text{UAMod} = 1$ (and is unused otherwise); by definition, it depends on the airfoil;

• $S_4$ is the constant in the best fit curve of $f$ for $\alpha < \alpha_2$ for $\text{UAMod} = 1$ (and is unused otherwise); by definition, it depends on the airfoil;

• $C_{n1}$ is the critical value of $C'_n$ at leading-edge separation for positive AoA and should be extracted from airfoil data at a given Reynolds number and Mach number; $C_{n1}$ can be calculated from the static value of $C_h$ at either the break in the pitching moment or the loss of chord force at the onset of stall; $C_{n1}$ is close to the condition of maximum lift of the airfoil at low Mach numbers;

• $C_{n2}$ is the critical value of $C'_n$ at leading-edge separation for negative AoA and should be extracted from airfoil data at a given Reynolds number and Mach number; $C_{n2}$ can be calculated from the static value of $C_h$ at either the break in the pitching moment or the loss of chord force at the onset of stall; $C_{n2}$ is close to the condition of maximum lift of the airfoil at low Mach numbers;

• $\text{St}_{\text{sh}}$ is the Strouhal’s shedding frequency; if the keyword \text{DEFAULT} is entered in place of a numerical value, $\text{St}_{\text{sh}}$ is set to 0.19;

• $C_{d0}$ is the drag-force coefficient at zero-lift AoA;

• $C_{m0}$ is the pitching-moment coefficient about the quarter-chord location at zero-lift AoA, positive for nose up;

• $k_0$ is a constant in the best fit curve of $\dot{\alpha}_{cp}$ and equals for $\dot{\alpha}_{AC} - 0.25$ $\text{UAMod} = 1$ (and is unused otherwise);

• $k_1$ is a constant in the best fit curve of $\dot{\alpha}_{cp}$ for $\text{UAMod} = 1$ (and is unused otherwise);

• $k_2$ is a constant in the best fit curve of $\dot{\alpha}_{cp}$ for $\text{UAMod} = 1$ (and is unused otherwise);

• $k_3$ is a constant in the best fit curve of $\dot{\alpha}_{cp}$ for $\text{UAMod} = 1$ (and is unused otherwise);

• $k_{1\_hat}$ is a constant in the expression of $C_c$ due to leading-edge vortex effects for $\text{UAMod} = 1$ (and is unused otherwise);

• $x_{\_cp\_bar}$ is a constant in the expression of $\dot{\alpha}_{cp}^\prime$ for $\text{UAMod} = 1$ (and is unused otherwise); if the keyword \text{DEFAULT} is entered in place of a numerical value, $x_{cp\_bar}$ is set to 0.2; and

• $\text{UACutOut}$ is the AoA (in degrees) in absolute value above which UA are disabled; if the keyword \text{DEFAULT} is entered in place of a numerical value, $\text{UACutOut}$ is set to 45.

• $\text{filtCutOff}$ is the cut-off reduced frequency of the low-pass filter applied to the AoA input to UA, as well as to the pitch rate and pitch acceleration derived from AoA within UA; if the keyword \text{DEFAULT} is entered in place of a numerical value, $\text{filtCutOff}$ is set to 0.5.

$\text{NumAlf}$ is the number of distinct AoA entries and determines the number of rows in the subsequent table of static airfoil coefficients; $\text{NumAlf}$ must be greater than or equal to one ($\text{NumAlf} = 1$ implies constant coefficients, regardless of the AoA).

AeroDyn will interpolate on AoA using the data provided via linear interpolation or via cubic splines, depending on the setting of input \text{InterpOrd} above. If $\text{AFTabMod}$ is set to 1, only the first airfoil table in each file will be used. If $\text{AFTabMod}$ is set to 2, AeroDyn will find the airfoil tables that bound the computed Reynolds number, and linearly interpolate between the tables, using the logarithm of the Reynolds numbers. If $\text{AFTabMod}$ is set to 3, it will find the bounding airfoil tables based on the \text{UserProp} field and linearly interpolate the tables based on it. Note that OpenFAST currently sets the \text{UserProp} input value to 0 unless the DLL controller is used and sets the value, so using this feature may require a code change.

For each AoA, you must set the AoA (in degrees), $\alpha$, the lift-force coefficient, $\text{Coefs}(:,1)$, the drag-force coefficient, $\text{Coefs}(:,2)$, and optionally the pitching-moment coefficient, $\text{Coefs}(:,3)$, and minimum pressure coefficient, $\text{Coefs}(:,4)$, but the column order depends on the settings of $\text{InCol\_Alfa}$, $\text{InCol\_C1}$, $\text{InCol\_Cd}$, $\text{InCol\_Cm}$, and $\text{InCol\_Cpmin}$ in the \text{AIRFOIL INFORMATION} section of the AeroDyn primary input file. AoA must be entered in monotonically increasing order—from lowest to highest AoA—and the first row should be for $\alpha = -180$ and the last should be for $\alpha = +180$ (unless $\text{NumAlf} = 1$, in which case AoA is unused). If
pitching-moment terms are neglected with `UseBlCm = FALSE` in the Rotor/Blade Properties section of the AeroDyn primary input file, the column containing pitching-moment coefficients may be absent from the file. Likewise, if the cavitation check is neglected with `CavitCheck = FALSE` in the General Options section of the AeroDyn primary input file, the column containing the minimum pressure coefficients may be absent from the file.

**Blade Data Input File**

The blade data input file contains the nodal discretization, geometry, twist, chord, and airfoil identifier for a blade. Separate files are used for each blade, which permits modeling of aerodynamic imbalances. A sample blade data input file is given in Section 4.3.6.

The input file begins with two lines of header information which is for your use, but is not used by the software. `NumBlNds` is the user-specified number of blade analysis nodes and determines the number of rows in the subsequent table (after two table header lines). `NumBlNds` must be greater than or equal to two; the higher the number, the finer the resolution and longer the computational time; we recommend that `NumBlNds` be between 10 and 20 to balance accuracy with computational expense. Even though `NumBlNds` is defined in each blade file, all blades must have the same number of nodes. For each node:

- `BlSpn` specifies the local span of the blade node along the (possibly preconed) blade-pitch axis from the root; `BlSpn` must be entered in monotonically increasing order—from the most inboard to the most outboard—and the first node must be zero, and when AeroDyn is coupled to OpenFAST, the last node should be located at the blade tip;
- `BlCrvAC` specifies the local out-of-plane offset (when the blade-pitch angle is zero) of the aerodynamic center (reference point for the airfoil lift and drag forces), normal to the blade-pitch axis, as a result of blade curvature; `BlCrvAC` is positive downwind; upwind turbines have negative `BlCrvAC` for improved tower clearance;
- `BlSwpAC` specifies the local in-plane offset (when the blade-pitch angle is zero) of the aerodynamic center (reference point for the airfoil lift and drag forces), normal to the blade-pitch axis, as a result of blade sweep; positive `BlSwpAC` is opposite the direction of rotation;
- `BlCrvAng` specifies the local angle (in degrees) from the blade-pitch axis of a vector normal to the plane of the airfoil, as a result of blade out-of-plane curvature (when the blade-pitch angle is zero); `BlCrvAng` is positive downwind; upwind turbines have negative `BlCrvAng` for improved tower clearance;
- `BlTwist` specifies the local aerodynamic twist angle (in degrees) of the airfoil; it is the orientation of the local chord about the vector normal to the plane of the airfoil, positive to feather, leading edge upwind; the blade-pitch angle will be added to the local twist;
- `BlChord` specifies the local chord length; and
- `BlAFID` specifies which airfoil data the local blade node is associated with; valid values are numbers between 1 and `NumAFfiles` (corresponding to a row number in the airfoil file table in the AeroDyn primary input file); multiple blade nodes can use the same airfoil data.

See Fig. 4.3. Twist is shown in Fig. 4.4 of Section 4.3.6.
4.3.3 Output Files

AeroDyn produces three types of output files: an echo file, a summary file, and a time-series results file. The following sections detail the purpose and contents of these files.

Echo Files

If you set the `Echo` flag to `TRUE` in the AeroDyn driver file or the AeroDyn primary input file, the contents of those files will be echoed to a file with the naming conventions, `OutFileRoot.ech` for the driver input file and `OutFileRoot.AD.ech` for the AeroDyn primary input file. `OutFileRoot` is either specified in the I/O SETTINGS section of the driver input file when running AeroDyn standalone, or by the FAST program when running a coupled simulation. The echo files are helpful for debugging your input files. The contents of an echo file will be truncated if AeroDyn encounters an error while parsing an input file. The error usually corresponds to the line after the last successfully echoed line.

Summary File

AeroDyn generates a summary file with the naming convention, `OutFileRoot.AD.sum` if the `SumPrint` parameter is set to `TRUE`. `OutFileRoot` is either specified in the I/O SETTINGS section of the driver input file when running AeroDyn standalone, or by the FAST program when running a coupled simulation. This file summarizes key information about your aerodynamics model, including which features have been enabled and what outputs have been selected.
Results Files

In standalone mode, the AeroDyn time-series results (a separate file for each case) are written to text-based files with the naming convention `OutFileRoot.#.out`, where `OutFileRoot` is specified in the I/O SETTINGS section of the driver input file and the `#` character is an integer number corresponding to a test case line found in the COMBINED-CASE ANALYSIS section. If AeroDyn is coupled to FAST, then FAST will generate a master results file that includes the AeroDyn results and AeroDyn will not write out its own results. The results are in table format, where each column is a data channel (the first column always being the simulation time), and each row corresponds to a simulation output time step. The data channels are specified in the OUTPUTS section of the AeroDyn primary input file. The column format of the AeroDyn-generated files is specified using the `OutFmt` parameter of the driver input file.

4.3.4 Modeling Considerations

AeroDyn was designed as an extremely flexible tool for modeling a wide-range of aerodynamic conditions and turbine configurations. This section provides some general guidance to help you construct models that are compatible with AeroDyn.

Please refer to the theory of Section 7 for detailed information about the implementation approach we have followed in AeroDyn.

Standalone AeroDyn Driver

The standalone AeroDyn driver code is very useful for computing turbine aerodynamics independent of aero-elastic coupling. The standalone AeroDyn driver code essentially replaces the functionality previously available in the separate wind turbine rotor-performance tool WT_Perf. For example, the standalone AeroDyn driver code can be used to compute the surfaces of power coefficient ($C_{P}$), thrust coefficient ($C_T$), and/or torque coefficient ($C_Q$) as a function of tip-speed ratio (TSR) and blade-pitch angle for a given rotor. Moreover, the standalone AeroDyn driver code is more powerful than WT_Perf in that the standalone AeroDyn driver can capture time-varying dynamics as a result of nacelle-yaw error, shaft tilt, and/or wind shear.

Environmental Conditions

For air, typical values for `AirDens`, `KinVisc`, `SpdSound`, and `Patm` are around 1.225 kg/m$^3$, 1.460E-5 m$^2$/s, 340.3 m/s, and 101,325 Pa, respectively. For seawater, typical values for `AirDens`, `KinVisc`, and `Pvap` are around 1025 kg/m$^3$, 1.004E-6 m$^2$/s, and 2000 Pa, respectively.

Temporal and Spatial Discretization

For accuracy and numerical stability, we recommend that `DTAero` be set such that there are at least 200 azimuth steps per rotor revolution. However, when AeroDyn is coupled to FAST, FAST may require time steps much smaller than this rule of thumb. If UA is enabled while using very small time steps, you may need to recompile AeroDyn in double precision to avoid numerical problems in the UA routines.

For the blade and tower spatial discretization, using higher number of analysis nodes will result in a more accurate solution at the expense of longer computational time. When AeroDyn is coupled to FAST, the blade and tower analysis node discretization may be independent from the discretization of the nodes in the structural modules.

We recommend that `NumBlNds` be between 10 and 20 to balance accuracy with computational expense for the rotor aerodynamic load calculation. It may be beneficial to use a finer resolution of nodes where large gradients are expected in the aerodynamic loads e.g. near the blade tip. Aerodynamic imbalances are possible through the use of geometrical differences between each blade.
When the tower potential-flow \((\text{TwrPotent} > 0)\), tower shadow \((\text{TwrShadow} > 0)\), and/or the tower aerodynamic load \((\text{TwrAero} = \text{TRUE})\) models are enabled, we also recommend that \(\text{NumTwrNds}\) be between 10 and 20 to balance accuracy with computational expense. Normally the local elevation of the tower node above ground (or above MSL for offshore wind turbines or above the seabed for MHK turbines) \((\text{TwrElev})\), must be entered in monotonically increasing order from the lowest (tower-base) to the highest (tower-top) elevation. However, when AeroDyn is coupled to FAST, the tower-base node in AeroDyn cannot be set lower than the lowest point where wind is specified in the InflowWind module. To avoid truncating the lower section of the tower in AeroDyn, we recommend that the wind be specified in InflowWind as low to the ground (or MSL for offshore wind turbines or above the seabed for MHK turbines) as possible (this is a particular issue for full-field wind file formats).

**Model Options Under Operational and Parked/Idling Conditions**

To model an operational rotor, we recommend to include the dynamic BEM model \((\text{WakeMod} = 2)\) and UA \((\text{AFAeroMod} = 2)\). Normally, the Pitt and Peters skewed-wake \((\text{SkewMod} = 2)\), Prandtl tip-loss \((\text{TipLoss} = \text{TRUE})\), Prandtl hub-loss \((\text{HubLoss} = \text{TRUE})\), and tangential induction \((\text{TanInd} = \text{TRUE})\) models should all be enabled, but \(\text{SkewMod} = 2\) is invalid for very large yaw errors (much greater than 45 degrees). The nonlinear solve in the BEM solution is in terms of the inflow angle, but \(\text{IndToler}\) represents the tolerance of the nondimensional residual equation, with no physical association possible; we recommend setting \(\text{IndToler}\) to DEFAULT.

While all of the UA models are documented in this manual, the original B-L model is not yet functional. Testing has shown that the González and Minnema/Pierce models produce reasonable hysteresis of the normal force, tangential force, and pitching-moment coefficients if the UA model parameters are set appropriately for a given airfoil, Reynolds number, and/or Mach number. However, the results will differ a bit from earlier versions of AeroDyn, (which was based on the Minnema/Pierce extensions to B-L) even if the default UA model parameters are used, due to differences in the UA model logic between the versions. We recommend that users run test cases with uniform inflow and fixed yaw error (e.g., through the standalone AeroDyn driver) to examine the accuracy of the normal force, tangential force, and pitching-moment coefficient hysteresis and to adjust the UA model parameters appropriately.

To model a parked or idling rotor, we recommend to disable induction \((\text{WakeMod} = 0)\) and UA \((\text{AFAeroMod} = 1)\), in which case the inflow velocity and angle are determined purely geometrically and the airfoil data is determined statically.

The direct aerodynamic load on the tower often dominates the aerodynamic load on the rotor for parked or idling conditions above the cut-out wind speed, in which case we recommend that \(\text{TwrAero} = \text{TRUE}\). Otherwise, \(\text{TwrAero} = \text{FALSE}\) may be satisfactory.

We recommend to include the influence of the tower on the fluid local to the blade for both operational and parked/idling rotors. We recommend that \(\text{TwrPotent} > 0\) for upwind rotors and that \(\text{TwrPotent} = 2\) or \(\text{TwrShadow} > 0\) for downwind rotors.

**Linearization**

When coupled to FAST, AeroDyn can be linearized as part of the linearization of the full coupled solution. When induction is enabled \((\text{WakeMod} = 1)\), we recommend to base the linearized solution on the frozen-wake assumption, by setting \(\text{FrozenWake} = \text{TRUE}\). The UA models are not set up to support linearization, so, UA must be disabled during linearization by setting \(\text{AFAeroMod} = 1\).
4.3.5 AeroDyn Theory

This theory manual is work in progress, please refer to the AeroDyn manual for more details.

Tower shadow models

Powles tower shadow model (\texttt{TwrShadow=1}) is given by:

\[
    u_{\text{TwrShadow}} = -\frac{C_d}{\sqrt{\tau}} \cos \left( \frac{\pi}{2\tau} \right) \left( \frac{\pi}{\sqrt{\tau}} \right)^2
\]

where \(\tau = \sqrt{x^2 + y^2}\).

Eames tower shadow model (\texttt{TwrShadow=2}) is given by:

\[
    u_{\text{TwrShadow}} = -\frac{C_d}{T/I} \frac{1}{\sqrt{2\pi}} \exp \left( -\frac{1}{2} \left( \frac{y}{T/I} \pi \right)^2 \right)
\]

where \(T/I\) is the turbulence intensity at the tower node.

4.3.6 Appendix

AeroDyn Input Files

In this appendix we describe the AeroDyn input-file structure and provide examples.

1) AeroDyn Driver Input File (driver input file example):

The driver input file is only needed for the standalone version of AeroDyn and contains inputs normally generated by OpenFAST, and necessary to control the aerodynamic simulation for uncoupled models.

2) AeroDyn Driver Timeseries Input File (driver timeseries input file example): The timeseries input file for a case in the AeroDyn driver allows the parameters to vary with time. This feature can be useful for debugging the aerodynamic response outside of OpenFAST.

3) AeroDyn Primary Input File (primary input file example):

The primary AeroDyn input file defines modeling options, environmental conditions (except freestream flow), airfoils, tower nodal discretization and properties, as well as output file specifications.

The file is organized into several functional sections. Each section corresponds to an aspect of the aerodynamics model.

The input file begins with two lines of header information which is for your use, but is not used by the software.

4) Airfoil Data Input File (airfoil data input file example):

The airfoil data input files themselves (one for each airfoil) include tables containing coefficients of lift force, drag force, and pitching moment versus AoA, as well as UA model parameters. In these files, any line whose first non-blank character is an exclamation point (!) is ignored (for inserting comment lines). The non-comment lines should appear within the file in order, but comment lines may be intermixed as desired for reading clarity.

5) Blade Data Input File (blade data input file example):

The blade data input file contains the nodal discretization, geometry, twist, chord, and airfoil identifier for a blade. Separate files are used for each blade, which permits modeling of aerodynamic imbalances.
AeroDyn List of Output Channels

This is a list of all possible output parameters for the AeroDyn module. The names are grouped by meaning, but can be ordered in the OUTPUTS section of the AeroDyn input file as you see fit. BN, refers to output node of blade, where \( n \) is a number in the range \([1,3]\) and \( n \) is a number in the range \([1,9]\), corresponding to entry in the BlOutNd list. Twn refers to output node of the tower and is in the range \([1,9]\), corresponding to entry in the TwOutNd list.

The local tower coordinate system is shown in Fig. 4.2 and the local blade coordinate system is shown in Fig. 4.4 below. Figure Fig. 4.4 also shows the direction of the local angles and force components.

4.4 OLAF User’s Guide and Theory Manual (Free Vortex Wake in AeroDyn15)

4.4.1 Introduction

Over the past few decades, substantial reductions in the cost of wind energy have come from large increases in rotor size. One important consideration for such large turbines is increased blade flexibility. In particular, large blade deflections may lead to a swept area that deviates significantly from the rotor plane. Such deviations violate assumptions used by common aerodynamic models, such as the blade element momentum (BEM) method. Such methods rely on actuator-disk assumptions that are only valid for axisymmetric rotor loads contained in a plane. Large blade deflections may also cause near wake of the turbine to diverge from a uniform helical shape. Further, interactions between turbine blades and the local near wake may increase, thus violating assumptions of models that do not account for the position and dynamics of the near wake. Additionally, highly flexible blades will likely cause increased unsteadiness and three-dimensionality of aerodynamic effects, increasing the importance of accurate and robust dynamic stall models. There are many other complex wind turbine situations that violate simple engineering assumptions. Such
### Blade

<table>
<thead>
<tr>
<th>Channel Name(s)</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BuAzimuth</td>
<td>(deg)</td>
<td>Azimuth angle of Bu</td>
</tr>
<tr>
<td>BuPitch</td>
<td>(deg)</td>
<td>Pitch angle of Bu</td>
</tr>
<tr>
<td>BuNJIClnc</td>
<td>(m)</td>
<td>Tower clearance at BuNJ</td>
</tr>
<tr>
<td>BuNJIVUndx, BuNJIVUndy</td>
<td>(m/s), (m/s), (m/s)</td>
<td>Undisturbed wind velocity at BuNJ in the local blade coordinate system</td>
</tr>
<tr>
<td>BuNJIVUndz</td>
<td>(m/s), (m/s), (m/s)</td>
<td>Undisturbed wind velocity at BuNJ in the local blade coordinate system</td>
</tr>
<tr>
<td>BuNJIVDisx, BuNJIVDisy, BuNJIVDisz</td>
<td>(m/s), (m/s), (m/s)</td>
<td>Disturbed wind velocity at BuNJ in the local blade coordinate system</td>
</tr>
<tr>
<td>BuNJISTVx, BuNJISTVy, BuNJISTVz</td>
<td>(m/s), (m/s), (m/s)</td>
<td>Structural translational velocity at BuNJ in the local blade coordinate system</td>
</tr>
<tr>
<td>BuNJIVrel</td>
<td>(m/s)</td>
<td>Relative wind speed at BuNJ</td>
</tr>
<tr>
<td>BuNJIDynP</td>
<td>(Pa)</td>
<td>Dynamic pressure at BuNJ</td>
</tr>
<tr>
<td>BuNJIM</td>
<td>(-)</td>
<td>Mach number at BuNJ</td>
</tr>
<tr>
<td>BuNJIVIndx, BuNJIVIndy</td>
<td>(m/s), (m/s)</td>
<td>Axial and tangential induced wind velocity at BuNJ</td>
</tr>
<tr>
<td>BuNJIAxInd, BuNJITalInd</td>
<td>(m/s), (m/s)</td>
<td>Axial and tangential induction factors at BuNJ</td>
</tr>
<tr>
<td>BuNJISlP, BuNJISlC, BuNJISlCm, BuNJISlCmin</td>
<td>(deg), (deg), (deg), (deg)</td>
<td>Lift force, drag force, pitching moment, minimum pressure, normal force (to plane), tangential force (to plane), normal force (to plane)</td>
</tr>
<tr>
<td>1 BuNJIClnc is based on the absolute distance to the nearest point in the tower from BuNJ minus the local tower radius, in the deflected configuration. Please note that this clearance is only approximate because the calculation assumes that the blade is a line with no volume (however, the calculation does use the local tower radius). When BuNJ is above the tower top (or below the tower base), the absolute distance to the tower top (or base) minus the local tower radius, in the deflected configuration, is output.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**Fig. 4.5: AeroDyn Output Channel List**
situations include obtaining accurate aerodynamic loads for nonstraight blade geometries (e.g., built-in curvature or sweep); skewed flow caused by yawed inflow or turbine tilt; and large rotor motion as a result of placing the turbine atop a compliant offshore floating platform.

Higher-fidelity aerodynamic models are necessary to account for the increased complexity of flexible and floating rotors. Although computational fluid dynamics (CFD) methods are able to capture such features, their computational cost limits the number of simulations that can be feasibly performed, which is an important consideration in load analysis for turbine design. FVW methods are less computationally expensive than CFD methods while modeling similarly complex physics. As opposed to the BEM methods, FVW methods do not rely on ad-hoc engineering models to account for dynamic inflow, skewed wake, tip losses, or ground effects. These effects are inherently part of the model. Numerous vorticity-based tools have been implemented, ranging from the early treatments by Rosenhead ([olaf-Ros31]), the formulation of vortex particle methods by Winckelmans and Leonard ([olaf-WL93]), to the recent mixed Eulerian–Lagrangian compressible formulations of Papadakis ([olaf-Pap14]). Examples of long-standing codes that have been applied in the field of wind energy are GENUVP ([olaf-Vou06]), using vortex particles methods, and AWSM ([olaf-vG03]), using vortex filament methods. Both tools have successfully been coupled to structural solvers. The method was extended by Branlard et al. ([olaf-BPG+15]) to consistently use vortex methods to perform aero-elastic simulations of wind turbines in sheared and turbulent inflow. Most formulations rely on a lifting-line representation of the blades, but recently, a viscous-inviscid representation was used in combination with a structural solver ([olaf-SGarciaSorensenS17]).

Convecting LAgrangian Filaments (OLAF) is a free vortex wake (FVW) module used to compute the aerodynamic forces on moving two- or three-bladed horizontal-axis wind turbines. This module has been incorporated into the National Renewable Energy Laboratory physics-based engineering tool, OpenFAST, which solves the aero-hydro-servo-elastic dynamics of individual wind turbines. OLAF is incorporated into the OpenFAST module, AeroDyn15, as an alternative to the traditional blade-element momentum (BEM) option, as shown in Figures Fig. 4.6 and Fig. 4.7.

Incorporating the OLAF module within OpenFAST allows for the modeling of highly flexible turbines along with the aero-hydro-servo-elastic response capabilities of OpenFAST. The OLAF module follows the requirements of the OpenFAST modularization framework ([olaf-SJJ15][olaf-Jon13]).

The OLAF module uses a lifting-line representation of the blades, which is characterized by a distribution of bound circulation. The spatial and time variation of the bound circulation results in free vorticity being emitted in the wake.
OLAF solves for the turbine wake in a time-accurate manner, which allows the vortices to convect, stretch, and diffuse. The OLAF model is based on a Lagrangian approach, in which the turbine wake is discretized into Lagrangian markers. There are many methods of representing the wake with Lagrangian markers ([olaf-Bra17]). In this work, a hybrid lattice/filament method is used, as depicted in Figure Fig. 4.8.

Here, the position of the Lagrangian markers is defined in terms of wake age, \( \zeta \), and azimuthal position, \( \psi \). A lattice method is used in the near wake of the blade. The near wake spans over a user-specified angle or distance for nonrotating cases. Though past research has indicated that a near-wake region of 30° is sufficient ([olaf-Lei06][olaf-ALR02]), it has been shown that a larger near wake is required for high thrust and other challenging conditions. After the near wake region, the wake is assumed to instantaneously roll up into a tip vortex and a root vortex, which are assumed to be the most dominant features for the remainder of the wake ([olaf-LBB02]). Each Lagrangian marker is connected to adjacent markers by straight-line vortex filaments, approximated to second-order accuracy ([olaf-GL02]). The wake is discretized based on the spanwise location of the blade sections and a specified time step \( (dt) \), which may be different from the time step of AeroDyn. After an optional initialization period, the wake is allowed to move and distort, thus changing the wake structure as the markers are convected downstream. To limit computational expense, the root and tip vortices are truncated after a specified distance \( \text{(WakeLength)} \) downstream from the turbine. The wake truncation violates Helmholtz’s first law and hence introduces an erroneous boundary condition. To alleviate this, the wake is “frozen” in a buffer zone between a specified buffer distance, \( \text{FreeWakeLength} \), and \( \text{WakeLength} \). In this buffer zone, the markers convect at the average ambient velocity. In this way, truncation error is minimized--([olaf-LBB02]). The buffer zone is typically chosen as the convected distance over one rotor revolution.

As part of OpenFAST, induced velocities at the lifting line/blade are transferred to AeroDyn15 and used to compute the effective blade angle of attack at each blade section, which is then used to compute the aerodynamic forces on the blades. The OLAF method returns the same information as the BEM method, but allows for more accurate calculations in areas where BEM assumptions are violated, such as those discussed above. As the OLAF method is more computationally expensive than BEM, both methods remain available in OpenFAST, and the user may specify in the AeroDyn15 input file which method is used.

The OLAF input file defines the wake convection and circulation solution methods; wake size and length options; Lagrangian marker regularization (viscous core) method; and other simulation and output parameters. The extents of the near and far wakes are specified by a nondimensional length in terms of rotor diameter. Different regularization functions for the vortex elements are available. Additionally, different methods to compute the regularization parameters of the bound and wake vorticity may be selected. In particular, viscous diffusion may be accounted for by dynamically changing the regularization parameter. Wake visualization output options are also available.

This document is organized as follows. Section 4.4.3 covers downloading, compiling, and running OLAF. Section 4.4.4 describes the OLAF input file and modifications to the AeroDyn15 input file. Section 4.4.5 details the OLAF output file. Section 4.4.6 provides an overview of the OLAF theory, including the free vortex wake method as well as integration into the AeroDyn15 module. Example input files and a list of output channels are detailed in Appendices A, B, and C.
Fig. 4.8: Evolution of near-wake lattice, blade-tip vortex, and Lagrangian markers
4.4.2 List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEM</td>
<td>blade-element momentum</td>
</tr>
<tr>
<td>CFD</td>
<td>computational fluid dynamics</td>
</tr>
<tr>
<td>DOE</td>
<td>U.S. Department of Energy</td>
</tr>
<tr>
<td>$F_v$</td>
<td>core radius factor</td>
</tr>
<tr>
<td>$t$</td>
<td>time</td>
</tr>
<tr>
<td>FVW</td>
<td>free vortex wake</td>
</tr>
<tr>
<td>$N$</td>
<td>number of rotor revolutions before wake cutoff condition</td>
</tr>
<tr>
<td>$\vec{r}$</td>
<td>vector between point of interest and vortex segment</td>
</tr>
<tr>
<td>$\vec{r}(\psi, \zeta)$</td>
<td>position vector of Lagrangian markers</td>
</tr>
<tr>
<td>$r_c$</td>
<td>core radius</td>
</tr>
<tr>
<td>$r_{c0}$</td>
<td>initial core radius</td>
</tr>
<tr>
<td>OLAF</td>
<td>cOnvecting LAgrangian Filaments</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>numerical constant = 1.25643</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>circulation strength</td>
</tr>
<tr>
<td>$\delta$</td>
<td>measure of viscous diffusion</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>measure of strain</td>
</tr>
<tr>
<td>$\Delta \psi$</td>
<td>step size for blade rotation</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>rotational speed of wind turbine</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>vortex wake age</td>
</tr>
<tr>
<td>$\zeta_0$</td>
<td>vortex wake age offset</td>
</tr>
<tr>
<td>$\nu$</td>
<td>kinematic viscosity</td>
</tr>
<tr>
<td>$\psi$</td>
<td>azimuth blade position</td>
</tr>
</tbody>
</table>

4.4.3 Running OLAF

As OLAF is a module of OpenFAST, the process of downloading, compiling, and running OLAF is the same as that for OpenFAST. Such instructions are available in the *Installing OpenFAST* documentation.

**Note:** To improve the speed of FVW module, the user may wish to compile with OpenMP. To do so, add the `-DOPENMP=ON` option with CMake.

4.4.4 Input Files

No lines should be added or removed from the input files, except in tables where the number of rows is specified.

**Units**

OLAF uses the International System of Units (e.g., kg, m, s, N). Angles are assumed to be in degrees unless otherwise specified.
OLAF Primary Input File

The primary OLAF input file defines general free wake options, circulation model selection and specification, near- and far-wake length, and wake visualization options. Each section within the file corresponds to an aspect of the OLAF model. For most parameters, the user may specify the value “default” (with or without quotes), in which case a default value, defined below, is used by the program.

See Section 4.4.9 for a sample OLAF primary input file.

General Options

**IntMethod** [switch] specifies which integration method will be used to convect the Lagrangian markers. There are four options: 1) fourth-order Runge-Kutta [1], 2) fourth-order Adams-Bashforth [2], 3) fourth-order Adams-Bashforth-Moulton [3], and 4) first-order forward Euler [5]. The default option is [5]. These methods are specified in Section 4.4.6.

**DTfwv** [sec] specifies the time interval at which the module will update the wake. The time interval must be a multiple of the time step used by *AeroDyn15*. The blade circulation is updated at each intermediate time step based on the intermediate blade positions and wind velocities. The default value is \( dt_{aero} \), where \( dt_{aero} \) is the time step used by *AeroDyn*.

**FreeWakeStart** [sec] specifies at what time the wake evolution is classified as “free.” Before this point is reached, the Lagrangian markers are simply convected with the freestream velocity. After this point, induced velocities are computed and affect the marker convection. If a time less than or equal to zero is given, the wake is “free” from the beginning of the simulation. The default value is 0.

**FullCircStart** [sec] specifies at what time the blade circulation reaches its full strength. If this value is specified to be > 0, the circulation is multiplied by a factor of 0 at \( t = 0 \) and linearly increasing to a factor of 1 for \( t > FullCircStart \). The default value is 0.

Circulation Specifications

**CircSolvMethod** [switch] specifies which circulation method is used. There are three options: 1) \( C_l \)-based iterative procedure [1], 2) no-flow through [2], and 3) prescribed [3]. The default option is [1]. These methods are described in Section 4.4.6.

**CircSolvConvCrit** [-] specifies the dimensionless convergence criteria used for solving the circulation. This variable is only used if **CircSolvMethod** = [1]. The default value is 0.001, corresponding to 0.1% error in the circulation between two iterations.

**CircSolvRelaxation** [-] specifies the relaxation factor used to solve the circulation. This variable is only used if **CircSolvMethod** = [1]. The default value is 0.1.

**CircSolvMaxIter** [-] specifies the maximum number of iterations used to solve the circulation. This variable is only used if **CircSolvMethod** = [1]. The default value is 30.

**PrescribedCircFile** [quoted string] specifies the file containing the prescribed blade circulation. This option is only used if **CircSolvMethod** = [3]. The circulation file format is a delimited file with one header line and two columns. The first column is the dimensionless radial position \([r/R]\); the second column is the bound circulation value in \([m^2/s]\). The radial positions do not need to match the *AeroDyn* node locations. A sample prescribed circulation file is given in Section 4.4.10.
Wake Extent and Discretization Options

\textbf{nNWPanel} [-] specifies the number of FVW time steps (DTfvw) for which the near-wake lattice is computed. In the future, this value will be defined as an azimuthal span in degrees or a downstream distance in rotor diameter.

\textbf{WakeLength} [D] specifies the length, in rotor diameters, of the far wake. The default value is 8.\footnote{At present, this variable is called nFWPanel and specified as the number of far wake panels. This will be changed soon.}

\textbf{FreeWakeLength} [D] specifies the length, in rotor diameters, for which the turbine wake is convected as “free.” If \textit{FreeWakeLength} is greater than \textit{WakeLength}, then the entire wake is free. Otherwise, the Lagrangian markers located within the buffer zone delimited by \textit{FreeWakeLength} and \textit{WakeLength} are convected with the average velocity. The default value is 6.\footnote{At present, this variable is called nFWPanelFree and specified as the number of free far wake panels. This will be changed soon.}

\textbf{FWShedVorticity} [flag] specifies whether shed vorticity is included in the far wake. The default value is \textit{[False]}, specifying that the far wake consists only of the trailed vorticity from the root and tip vortices.

Wake Regularization and Diffusion Options

\textbf{DiffusionMethod} [switch] specifies which diffusion method is used to account for viscous diffusion. There are two options: 1) no diffusion \textit{[0]} and 2) the core-spreading method \textit{[1]}. The default option is \textit{[0]}.

\textbf{RegDetMethod} [switch] specifies which method is used to determine the regularization parameters. There are two options: 1) manual \textit{[0]} and 2) optimized \textit{[1]}. The manual option requires the user to specify the parameters listed in this subsection. The optimized option determines the parameters for the user. The default option is \textit{[0]}.

\textbf{RegFunction} [switch] specifies the regularization function used to remove the singularity of the vortex elements, as specified in \textsection 4.4.6. There are five options: 1) no correction \textit{[0]}, 2) the Rankine method \textit{[1]}, 3) the Lamb-Oseen method \textit{[2]}, 4) the Vatistas method \textit{[3]}, and 5) the denominator offset method \textit{[4]}. The functions are given in . The default option is \textit{[3]}.

\textbf{WakeRegMethod} [switch] specifies the method of determining viscous core radius (i.e., the regularization parameter). There are three options: 1) constant \textit{[1]}, 2) stretching \textit{[2]}, and 3) age \textit{[3]}. The methods are described in \textsection 4.4.6. The default option is \textit{[1]}.

\textbf{WakeRegParam} [m] specifies the wake regularization parameter, which is the regularization value used at the initialization of a vortex element. If the regularization method is “constant”, this value is used throughout the wake.

\textbf{BladeRegParam} [m] specifies the bound vorticity regularization parameter, which is the regularization value used for the vorticity elements bound to the blades.

\textbf{CoreSpreadEddyVisc} [-] specifies the eddy viscosity parameter $\delta$. The parameter is used for the core-spreading method ($\text{DiffusionMethod} = \textit{[1]}$) and the regularization method with age ($\text{WakeRegMethod} = \textit{[3]}$). The variable $\delta$ is described in \textsection 4.4.6. The default value is 100.

Wake Treatment Options

\textbf{TwrShadowOnWake} [flag] specifies whether the tower potential flow and tower shadow have an influence on the wake convection. The tower shadow model, when activated in AeroDyn, always has an influence on the lifting line, hence the induction and loads on the blade. This option only concerns the wake. The default option is \textit{[False]}.

\textbf{ShearVorticityModel} [switch] specifies whether shear vorticity is modeled in addition to the sheared inflow prescribed by \textit{InflowWind}. There are two options: 1) no treatment \textit{[0]} and 2) mirrored vorticity \textit{[1]}. The mirrored vorticity accounts for the ground effect. Dedicated options to account for the shear vorticity will be implemented at a later time. The shear velocity profile is handled by \textit{InflowWind} irrespective of this input. The default option is \textit{[0]}.\footnote{Dedicated options to account for the shear vorticity will be implemented at a later time. The shear velocity profile is handled by \textit{InflowWind} irrespective of this input. The default option is \textit{[0]}.
Speedup Options

VelocityMethod [switch] specifies the method used to determine the velocity. There are two options: 1) Biot-Savart law applied to the vortex segments [1] and 2) tree formulation using a particle representation [2]. The default option is [1].

TreeBranchFactor [-] specifies the dimensionless distance, in branch radius, above which a multipole calculation is used instead of a direct evaluation. This option is only used in conjunction with the tree code (VelocityMethod = [2]).

PartPerSegment [-] specifies the number of particles that are used when a vortex segment is represented by vortex particles. The default value is 1.

Output Options

WrVTK [flag] specifies if Visualization Toolkit (VTK) visualization files are to be written out. WrVTK = [0] does not write out any VTK files. WrVTK = [1] outputs a VTK file at every time step. The outputs are written in the folder, `vtk_fvw`. The parameters WrVTK, VTKCoord, and VTK_fps are independent of the glue code VTK output options.

VTKBlades [-] specifies how many blade VTK files are to be written out. VTKBlades = n outputs VTK files for n blades, with 0 being an acceptable value. The default value is 1.

VTKCoord [switch] specifies in which coordinate system the VTK files are written. There are two options: 1) global coordinate system [1] and 2) hub coordinate system [2]. The default option is [1].

VTK_fps [1/sec] specifies the output frequency of the VTK files. The provided value is rounded to the nearest allowable multiple of the time step. The default value is 1/dt_fvw. Specifying VTK_fps = [all], is equivalent to using the value 1/dt_aero.

AeroDyn15 Input File

Input file modifications

As OLAF is incorporated into the AeroDyn15 module, a wake computation option has been added to the AeroDyn15 input file and a line has been added. These additions are as follows.

WakeMod specifies the type of wake model that is used. WakeMod = [3] has been added to allow the user to switch from the traditional BEM method to the OLAF method.

FVWFile [string] specifies the OLAF module file, the path is relative to the AeroDyn file, unless an absolute path is provided.

Relevant sections

The BEM options (e.g. tip-loss, skew, and dynamic models) are read and discarded when WakeMod = [3]. The following sections and parameters remain relevant and are used by the vortex code:

- general options (e.g., airfoil and tower modeling);
- environmental conditions;
- dynamic stall model options;
- airfoil and blade information;
- tower aerodynamics; and
- outputs.
4.4.5 Output Files

The OLAF module itself does not produce its own output file. However, additional output channels are made available in AeroDyn15. As such, the AeroDyn15 output file is briefly described as well as the outputs made available with OLAF. Visualization files are generated by using the parameter, WrVTK. This parameter is available in the OLAF input file, in which case the VTK files are written to the folder `vtk_fvw`, or the primary `.fst` file, in which case the VTK files are written to the folder `vtk`.

Results File

OpenFAST generates a master results file that includes the AeroDyn15 results. The results are in table format, where each column is a data channel, and each row corresponds to a simulation-output time step. The data channels are specified in the `OUTPUTS` section in the AeroDyn15 primary input file. The column format of the AeroDyn-generated files is specified using the `OutFmt` parameter of the OpenFAST driver input file.

4.4.6 OLAF Theory

This section details the OLAF method and provides an overview of the computational method, followed by a brief explanation of its integration with OpenFAST.

Introduction - Vorticity Formulation

The vorticity equation for incompressible homogeneous flows in the absence of non-conservative force is given by Eq. (4.2)

\[
\frac{d\vec{\omega}}{dt} = \frac{\partial \vec{\omega}}{\partial t} + (\vec{u} \cdot \nabla) \vec{\omega} = (\vec{\omega} \cdot \nabla)\vec{u} + \nu \Delta \vec{\omega} 
\]

Here, \(\vec{\omega}\) is the vorticity, \(\vec{u}\) is the velocity, and \(\nu\) is the viscosity. In free vortex wake methods, the vorticity equation is used to describe the evolution of the wake vorticity. Different approximations are introduced to ease its resolution, such as projecting the vorticity onto a discrete number of vortex elements (here vortex filaments), and separately treating the convection and diffusion steps, known as viscous-splitting. Several complications arise from the method; in particular, the discretization requires a regularization of the vorticity field (or velocity field) to ensure a smooth approximation.

The forces exerted by the blades onto the flow are expressed in vorticity formulation as well. This vorticity is bound to the blade and has a circulation associated with the lift force. A lifting-line formulation is used here to model the bound vorticity.

The different models of the implemented free vortex code are described in the following sections.

Discretization - Projection

The numerical method uses a finite number of states to model the continuous vorticity distribution. To achieve this, the vorticity distribution is projected onto basis function which is referred to as vortex elements. Vortex filaments are here used as elements that represents the vorticity field. A vortex filament is delimited by two points and hence assumes a direction formed by these two points. A vorticity tube is oriented along the unit vector \(\vec{e}_x\) of cross section \(dS\) and length \(l\). It can then be approximated by a vortex filament of length \(l\) oriented along the same direction. The total vorticity of the tube and the vortex filaments are the same and related by:

\[
\vec{\omega} dS = \vec{1}
\]
where $\vec{\Gamma}$ is the circulation intensity of the vortex filament. If the vorticity tubes are complex and occupy a large volume, the projection onto vortex filaments is difficult and the projection onto vortex particle is more appropriate. Assuming the wake is confined to a thin vorticity layer which defines a velocity jump of know direction, it is possible to approximate the wake vorticity sheet as a mesh of vortex filaments. This is the basis of vortex filament wake methods. Vortex filaments are a singular representation of the vorticity field, as they occupy a line instead of a volume. To better represent the vorticity field, the filaments are “inflated”, a process referred to as regularization (see Section 4.4.6). The regularization of the vorticity field also regularizes the velocity field and avoids the singularities that would otherwise occur.

**Lifting-Line Representation**

The code relies on a lifting-line formulation. Lifting-line methods effectively lump the loads at each cross-section of the blade onto the mean line of the blade and do not account directly for the geometry of each cross-section. In the vorticity-based version of the lifting-line method, the blade is represented by a line of varying circulation. The line follows the motion of the blade and is referred to as “bound” circulation. The bound circulation does not follow the same dynamic equation as the free vorticity of the wake. Instead, the intensity is linked to airfoil lift via the Kutta-Joukowski theorem. Spanwise variation of the bound circulation results in vorticity being emitted into the the wake. This is referred to as “trailed vorticity”. Time changes of the bound circulation are also emitted in the wake, referred to as “shed” vorticity. The subsequent paragraphs describe the representation of the bound vorticity.

**Lifting-Line Panels and Emitted Wake Panels**

The lifting-line and wake representation is illustrated in Fig. 4.9. The blade lifting-line is discretized into a finite number of panels, each of them forming a four sided vortex rings. The spanwise discretization follows the discretization of the AeroDyn blade input file. The number of spanwise panels, $n_{ll}$, is one less than the total number of AeroDyn nodes, NumBlNds. The sides of the panels coincide with the lifting-line and the trailing edge of the blade. The lifting-line is currently defined as the 1/4 chord location from the leading edge (LE). More details on the panelling is provided in Section 4.4.6. At a given time step, the circulation of each lifting-line panel is determined according to one of the three methods developed in Section 4.4.6. At the end of the time step, the circulation of each lifting-line panel is emitted into the wake, forming free vorticity panels. To satisfy the Kutta condition, the circulation of the first near wake panel and the bound circulation are equivalent (see Fig. 4.9 b). The wake panels model the thin shear layer resulting from the continuation of the blade boundary layer. This shear layer can be modelled using a continuous distribution of vortex doublets. A constant doublet strength is assumed on each panel, which in turn is equivalent to a vortex ring of constant circulation.

The current implementation stores the positions and circulations of the panel corner points. In the vortex ring formulation, the boundary between two panels corresponds to a vortex segment of intensity equal to the difference of circulation between the two panels. The convention used to define the segment intensity based on the panels intensity is shown in Fig. 4.9 c. Since the circulation of the bound panels and the first row of near wake panels are equal, the vortex segments located on the trailing edge have no circulation.

**Panelling**

The definitions used for the panelling of the blade are given in Fig. 4.9 d, following the notations of van Garrel ([olaf-vG03]). The leading edge and trailing edge (TE) locations are directly obtained from the AeroDyn mesh. At two spanwise locations, the LE and TE define the corner points: $x_1$, $x_2$, $x_3$, and $x_4$. The current implementation assumes that the aerodynamic center, the lifting-line, and the 1/4 chord location all coincide. For a given panel, the lifting-line is then delimited by the points $x_9 = 3/4 \, x_1 + 1/4 \, x_2$ and $x_{10} = 3/4 \, x_3 + 1/4 \, x_4$. The mid points of the four panel sides are noted $x_5$, $x_6$, $x_7$, and $x_8$. The lifting-line vector ($\vec{d}l$) as well as the vectors tangential ($\vec{T}$) and...
Fig. 4.9: Wake and lifting-line vorticity discretized into vortex ring panels. (a) Overview. (b) Cross-sectional view, defining the leading-edge, trailing edge, and lifting-line. (c) Circulation of panels and corresponding circulation for vorticity segments between panels. (d) Geometrical quantities for a lifting-line panel.
normal ($\vec{N}$) to the panel are defined as:

$$\vec{d}l = \vec{x}_{10} - \vec{x}_{9}, \quad \vec{T} = \frac{\vec{x}_6 - \vec{x}_8}{|\vec{x}_6 - \vec{x}_8|}, \quad \vec{N} = \frac{\vec{T} \times \vec{d}l}{|\vec{T} \times \vec{d}l|}$$  \hspace{1cm} (4.4)

The area of the panel is obtained as $dA = |(\vec{x}_6 - \vec{x}_8) \times (\vec{x}_7 - \vec{x}_5)|$. For CircSolvMethod=[1], the control points are located on the lifting-line at the location $\vec{x}_9 + \eta_j \vec{d}l$. The factor $\eta_j$ is determined based on the full-cosine approximation of van Garrel. This is based on the spanwise widths of the current panel, $w_j$, and the neighboring panels $w_{j-1}$ and $w_{j+1}$:

$$\eta_1 = \frac{w_1}{w_1 + w_2},$$  
$$\eta_j = \frac{1}{4} \left[ \frac{w_{j-1}}{w_{j-1} + w_j} + \frac{w_j}{w_j + w_{j+1}} + 1 \right], \quad j = 2..n - 1,$$  
$$\eta_n = \frac{w_{n-1}}{w_{n-1} + w_n}.$$

For an equidistant spacing, this discretization places the control points at the middle of the lifting-line ($\eta = 0.5$). Theoretical circulation results for an elliptic wing with a cosine spacing are retrieved with such discretization since it places the control points closer to stronger trailing segments at the wing extremities (see e.g. [olaf-Ker00]).

### Circulation Solving Methods

Three methods are implemented to determine the bound circulation strength. They are selected using the input CircSolvMethod, and are presented in the following sections.

#### Cl-Based Iterative Method

The Cl-based iterative method determines the circulation within a nonlinear iterative solver that makes use of the polar data at each control point located on the lifting line. The algorithm ensures that the lift obtained using the angle of attack and the polar data matches the lift obtained with the Kutta-Joukowski theorem. At present, it is the preferred method to compute the circulation along the blade span. It is selected with CircSolvMethod=[1]. The method is described in the work from van Garrel ([olaf-vG03]). The algorithm is implemented in an iterative approach using the following steps:

1. The circulation distribution from the previous time step is used as a guessed circulation, $\Gamma_{prev}$.
2. The velocity at each control points $j$ is computed as the sum of the wind velocity, the structural velocity, and the velocity induced by all the vorticity in the domain, evaluated at the control point location.

   $$\vec{v}_j = \vec{V}_0 - \vec{V}_{elast} + \vec{v}_{\omega,free} + \vec{v}_{\Gamma,li}$$

   $\vec{v}_{\omega,free}$ is the velocity induced by all free vortex filaments, as introduced in Eq. (4.11). The contribution of $\vec{v}_{\Gamma,li}$ comes from the lifting-line panels and the first row of near wake panels, for which the circulation is set to $\Gamma_{prev}$.
3. The circulation for all lifting-line panels $j$ is obtained as follows.

   $$\Gamma_{li,j} = \frac{1}{2} C_{li,j}(\alpha_j) \frac{\left[ (\vec{v}_j \cdot \vec{N})^2 + (\vec{v}_j \cdot \vec{T})^2 \right]^{\frac{3}{2}} dA}{\sqrt{[(\vec{v}_j \times \vec{d}l) \cdot \vec{N}]^2 + [(\vec{v}_j \times \vec{d}l) \cdot \vec{T}]^2}},$$  \hspace{1cm} with \hspace{1cm} $\alpha_j = \tan^{-1} \left( \frac{\vec{v}_j \cdot \vec{N}}{\vec{v}_j \cdot \vec{T}} \right)$

   The function $C_{li,j}$ is the lift coefficient obtained from the polar data of blade section $j$ and $\alpha_j$ is the angle of attack at the control point.
4. The new circulation is set using the relaxation factor \( k_{relax} \) (CircSolvRelaxation):

\[
\Gamma_{\text{new}} = \Gamma_{\text{prev}} + k_{relax} \Delta \Gamma, \quad \Delta \Gamma = \Gamma_{\text{lit}} - \Gamma_{\text{prev}}
\]

5. Convergence is checked using the criterion \( k_{crit} \) (CircSolvConvCrit):

\[
\frac{\max(|\Delta \Gamma|)}{\text{mean}(|\Gamma_{\text{new}}|)} < k_{crit}
\]

If convergence is not reached, steps 2-5 are repeated using \( \Gamma_{\text{new}} \) as the guessed circulation \( \Gamma_{\text{prev}} \).

**No-flow-through Method**

A Weissinger-L-based representation ([olaf-Wei47]) of the lifting surface is also available ([olaf-BL94][olaf-Gup06][olaf-Rib07]). In this method, the circulation is solved by satisfying a no-flow through condition at the 1/4-chord points. It is selected with CircSolvMethod=[2].

**Prescribed Circulation**

The final available method prescribes a constant circulation. A user specified spanwise distribution of circulation is prescribed onto the blades. It is selected with CircSolvMethod=[3].

**Free Vorticity Convection**

The governing equation of motion for a vortex filament is given by the convection equation of a Lagrangian marker:

\[
\frac{d\vec{r}}{dt} = \vec{V} (\vec{r}, t)
\]  

(4.5)

where \( \vec{r} \) is the position of a Lagrangian marker. The Lagrangian markers are the end points of the vortex filaments. The Lagrangian convection of the filaments stretches the filaments and thus automatically accounts for strain in the vorticity equation.

At present, a first-order forward Euler method is used to numerically solve the left-hand side of Eq. (4.5) for the vortex filament location (IntMethod=[5]). This is an explicit method solved using Eq. (4.6).

\[
\vec{r} = \vec{r} + \vec{V} \Delta t
\]  

(4.6)

**Free Vorticity Convection in Polar Coordinates**

The governing equation of motion for a vortex filament is given by:

\[
\frac{d\vec{r}(\psi, \zeta)}{dt} = \vec{V}[\vec{r}(\psi, \zeta), t]
\]  

(4.7)

Using the chain rule, Eq. (4.7) is rewritten as:

\[
\frac{\partial \vec{r}(\psi, \zeta)}{\partial \psi} + \frac{\partial \vec{r}(\psi, \zeta)}{\partial \zeta} = \frac{\vec{V}[\vec{r}(\psi, \zeta), t]}{\Omega}
\]  

(4.8)

where \( d\psi/dt = \Omega \) and \( d\psi = d\zeta \) ([olaf-LBB02]). Here, \( \vec{r}(\psi, \zeta) \) is the position vector of a Lagrangian marker, and \( \vec{V}[\vec{r}(\psi, \zeta)] \) is the velocity.
Induced Velocity and Velocity Field

The velocity term on the right-hand side of Eq. (4.5) is a nonlinear function of the vortex position, representing a combination of the freestream and induced velocities ([olaf-Han08]). The induced velocities at point $\vec{x}$, caused by each straight-line filament, are computed using the Biot-Savart law, which considers the locations of the Lagrangian markers and the intensity of the vortex elements ([olaf-LBB02]):

$$d\vec{v}(\vec{x}) = \frac{\Gamma}{4\pi} d\vec{l} \times \vec{r} \frac{1}{r^3}$$

Here, $\Gamma$ is the circulation strength of the filament, $d\vec{l}$ is an elementary length along the filament, $\vec{r}$ is the vector between a point on the filament and the control point $\vec{x}$, and $r = |\vec{r}|$ is the norm of the vector. The integration of the Biot-Savart law along the filament length, delimited by the points $\vec{x}_1$ and $\vec{x}_2$ leads to:

$$\vec{v}(\vec{x}) = \vec{V}_0(\vec{x}) + \vec{v}_\omega(\vec{x}), \quad \text{with} \quad \vec{v}_\omega(\vec{x}) = \sum_k \vec{v}_k(\vec{x})$$

where the sum is over all the vortex filaments, each of intensity $\Gamma_k$. The intensity of each filament is determined by spanwise and time changes of the bound circulation, as discussed in Section 4.4.6. In tree-based methods, the sum over all vortex elements is reduced by lumping together the elements that are far away from the control points.

Regularization

Regularization and viscous diffusion

The singularity that occurs in Eq. (4.9) greatly affects the numerical accuracy of vortex methods. By regularizing the “1-over-r” kernel of the Biot-Savart law, it is possible to obtain a numerical method that converges to the Navier-Stokes equations. The regularization is used to improve the regularity of the discrete vorticity field, as compared to the “true” continuous vorticity field. This regularization is usually obtained by convolution with a smooth function. In this case, the regularization of the vorticity field and the velocity field are the same. Some engineering models also perform regularization by directly introducing additional terms in the denominator of the Biot-Savart velocity kernel. The factor, $F_\nu$, was introduced in Eq. (4.10) to account for this regularization.

In the convergence proofs of vortex methods, regularization and viscous diffusion are two distinct aspects. It is common practice in vortex filament methods to blur the notion of regularization with the notion of viscous diffusion. Indeed, for a physical vortex filament, viscous effects prevent the singularity from occurring and diffuse the vortex strength with time. The circular zone where the velocity drops to zero around the vortex is referred to as the vortex core. A length increase of the vortex segment will result in a vortex core radius decrease, and vice versa. Diffusion, on the other hand, continually spreads the vortex radially.

Because of the previously mentioned analogy, practitioners of vortex filament methods often refer to regularization as “viscous-core” models and regularization parameters as “core-radii.” Additionally, viscous diffusion is often introduced by modifying the regularization parameter in space and time instead of solving the diffusion from the vorticity equation. The distinction is made explicit in this document when clarification is required, but a loose terminology is used when the context is clear.
Determinations of the regularization parameter

The regularization parameter is both a function of the physics being modeled (blade boundary layer and wake) and the choice of discretization. Contributing factors are the chord length, the boundary layer height, and the volume that each vortex filament is approximating. Currently the choice is left to the user (RegDetMethod=0). Empirical results for a rotating blade are found in the work of Gupta (Gu06). As a guideline, the regularization parameter may be chosen as twice the average spanwise discretization of the blade. This guideline is implemented when the user chooses RegDetMethod=1. Further refinement of this option will be considered in the future.

Implemented regularization functions

Several regularization functions have been developed ([olaf-Ran58][olaf-Scu75][olaf-VKM91]). At present, five options are available: 1) No correction, 2) the Rankine method, 3) the Lamb-Oseen method, 4) the Vatistas method, or 5) the denominator offset method. If no correction method is used, (RegFunction=0), $F_{\nu} = 1$. The remaining methods are detailed in the following sections. Here, $r_c$ is the regularization parameter (WakeRegParam) and $\rho$ is the distance to the filament. Both variables are expressed in meters.

Rankine

The Rankine method ([olaf-Ran58]) is the simplest regularization model. With this method, the Rankine vortex has a finite core with a solid body rotation near the vortex center and a potential vortex away from the center. If this method is used (RegFunction=1), the viscous core correction is given by Eq. (4.12).

$$F_{\nu} = \begin{cases} \rho^2/r_c^2 & 0 < \rho < 1 \\ 1 & \rho > 1 \end{cases} \quad (4.12)$$

Here, $r_c$ is the viscous core radius of a vortex filament, detailed in Section 4.4.6.

Lamb-Oseen

If the Lamb-Oseen method is used (RegFunction=2), the viscous core correction is given by Eq. (4.13).

$$F_{\nu} = \left[ 1 - \exp\left( -\frac{\rho^2}{r_c^2} \right) \right] \quad (4.13)$$

Vatistas

If the Vatistas method is used (RegFunction=3), the viscous core correction is given by Eq. (4.14).

$$F_{\nu} = \frac{\rho^2}{(\rho^{2n} + r_c^{2n})^{1/n}} = \frac{(\rho/r_c)^{2n}}{(1 + (\rho/r_c)^{2n})^{1/n}} \quad (4.14)$$

Here, $\rho$ is the distance from a vortex segment to an arbitrary point ([olaf-Abe16]). Research from rotorcraft applications suggests a value of $n = 2$, which is used in this work ([olaf-BL93]).
Denominator Offset/Cut-Off

If the denominator offset method is used \([\text{RegFunction}=[4]]\), the viscous core correction is given by Eq. (4.15)

\[
\vec{v}(\vec{x}) = \frac{\Gamma}{4\pi r_1 r_2 (r_1 + r_2)} \left( r_1 + r_2 \right) + r_2^2 r_0 \vec{r}_1 \times \vec{r}_2
\]  

(4.15)

Here, the singularity is removed by introducing an additive factor in the denominator of Eq. (4.10), proportional to the filament length \(r_0\). In this case, \(F_v = 1\). This method is found in the work of van Garrel ([olaf-vG03]).

Time Evolution of the Regularization Parameter–Core Spreading Method

There are four available methods by which the regularization parameter may evolve with time: 1) constant value, 2) stretching, 3) wake age, or 4) stretching and wake age. The three latter methods blend the notions of viscous diffusion and regularization. The notation \(r_c^0\) used in this section corresponds to input file parameter value \(\text{WakeRegParam}\).

Constant

If a constant value is selected, \((\text{WakeRegMethod}=[1])\), the value of \(r_c\) remains unchanged for all Lagrangian markers throughout the simulation and is taken as the value given with the parameter \(\text{WakeRegParam}\) in meters.

\[r_c(\zeta) = r_c^0\]

(4.16)

Here, \(\zeta\) is the vortex wake age, measured from its emission time.

Stretching

If the stretching method is selected, \((\text{WakeRegMethod}=[2])\), the viscous core radius is modeled by Eq. (4.17).

\[r_c(\zeta, \epsilon) = r_c^0 (1 + \epsilon)^{-1}\]

(4.17)

\[\epsilon = \frac{\Delta l}{l}\]

Here, \(\epsilon\) is the vortex-filament strain, \(l\) is the filament length, and \(\Delta l\) is the change of length between two time steps. The integral in Eq. (4.17) represents strain effects.

Wake Age / Core-Spreading

If the wake age method is selected, \((\text{WakeRegMethod}=[3])\), the viscous core radius is modeled by Eq. (4.18).

\[r_c(\zeta) = \sqrt{r_c^2 + 4\alpha \delta \nu \zeta}\]

(4.18)

where \(\alpha = 1.25643\), \(\nu\) is kinematic viscosity, and \(\delta\) is a viscous diffusion parameter (typically between 1 and 1,000). The parameter \(\delta\) is provided in the input file as \(\text{CoreSpreadEddyVisc}\). Here, the term \(4\alpha \delta \nu \zeta\), accounts for viscous effects as the wake propagates downstream. The higher the background turbulence, the more diffusion of the vorticity with time, and the higher the value of \(\delta\) should be. This method partially accounts for viscous diffusion of the vorticity while neglecting the interaction between the wake vorticity itself or between the wake vorticity and the background flow. It is often referred to as the core-spreading method. Setting \(\text{DiffusionMethod}=[1]\) is the same as using the wake age method \((\text{WakeRegMethod}=[3])\).
Stretching and Wake Age

If the stretching and wake-age method is selected (\texttt{WakeRegMethod=}4), the viscous core radius is modeled by Eq. (4.19).

\[ r_c(\zeta, \epsilon) = \sqrt{r_c^2 + 4\alpha \delta \nu (1 + \epsilon)^{-1}} \] (4.19)

Diffusion

The viscous-splitting assumption is used to solve for the convection and diffusion of the vorticity separately. The diffusion term $\nu \Delta \vec{\omega}$ represents molecular diffusion. This term allows for viscous connection of vorticity lines. Also, turbulent flows will diffuse the vorticity in a similar manner based on a turbulent eddy viscosity.

The parameter \texttt{DiffusionMethod} is used to switch between viscous diffusion methods. Currently, only the core-spreading method is implemented. The method is described in Section 4.4.6 since it is equivalent to the increase of the regularization parameter with the wake age.

4.4.7 State-Space Representation and Integration with OpenFAST

State, Constraint, Input, and Output Variables

The OLAF module has been integrated into the latest version of OpenFAST via \textit{AeroDyn15}, following the OpenFAST modularization framework ([olaf-Jon13][olaf-SJJ15]). To follow the OpenFAST framework, the vortex code is written as a module, and its formulation comprises state, constraint, and output equations. The data manipulated by the module include the following vectors: constant parameters, $\vec{p}$; inputs, $\vec{u}$; constrained state, $\vec{z}$; states, $\vec{x}$; and outputs, $\vec{y}$. The vectors are defined as follows:

- Parameters, $\vec{p}$ — a set of internal system values that are independent of the states and inputs. The parameters can be fully defined at initialization and characterize the system state and output equations.
- Inputs, $\vec{u}$ — a set of values supplied to the module that, along with the states, are needed to calculate future states and the system output.
- Constraint states, $\vec{z}$ — algebraic variables that are calculated using a nonlinear solver, based on values from the current time step.
- States, $\vec{x}$ — a set of internal values of the module. They are influenced by the inputs and used to calculate future state values and output. Continuous states are employed, meaning that the states are differentiable in time and characterized by continuous time-differential equations.
- Outputs, $\vec{y}$ — a set of values calculated and returned by the module that depend on the states, inputs, and/or parameters through output equations.

The parameters of the vortex code include:

- Fluid characteristics: kinematic viscosity, $\nu$.
- Airfoil characteristics: chord $c$ and polar data – $C_l(\alpha)$, $C_d(\alpha)$, $C_m(\alpha)$.
- Algorithmic methods and parameters, e.g., regularization, viscous diffusion, discretization, wake geometry, and acceleration.

The inputs of the vortex code are:

- Position, orientation, translational velocity, and rotational velocity of the different nodes of the lifting lines ($\vec{r}_{ll}$, $\Lambda_{ll}$, $\vec{\omega}_{ll}$, respectively), gathered into the vector, $\vec{x}_{elast,ll}$, for conciseness. These quantities are handled using the mesh-mapping functionality and data structure of OpenFAST.
• Disturbed velocity field at requested locations, written \( \vec{V}_0 = [\vec{V}_{0,lt}, \vec{V}_{0,m}] \). Locations are requested for lifting-line points, \( \vec{r}_{lt} \), and Lagrangian markers, \( \vec{r}_m \). Based on the parameters, this disturbed velocity field may contain the following influences: freestream, shear, veer, turbulence, tower, and nacelle disturbance. The locations where the velocity field is requested are typically the location of the Lagrangian markers.

The constraint states are:
- The circulation intensity along the lifting lines, \( \Gamma_{lt} \).

The continuous states are:
- The position of the Lagrangian markers, \( \vec{r}_m \)
- The vorticity associated with each vortex element, \( \vec{\omega}_e \). For a projection of the vorticity onto vortex segments, this corresponds to the circulation, \( \vec{\Gamma}_e \). For each segment, \( \vec{\Gamma}_e = \vec{\Gamma}_e d\vec{l}_e = \vec{\omega}_e dV_e \), with \( d\vec{l}_e \) and \( dV_e \), the vortex segment length and its equivalent vortex volume.

The outputs are:
- The induced velocity at the lifting-line nodes, \( \vec{v}_{i,lt} \)
- The locations where the undisturbed wind is computed, \( \vec{r}_r \) (typically \( \vec{r}_r = \vec{r}_m \)).

**State, Constraint, and Output Equations**

An overview of the states, constraints, and output equations is given here. More details are provided in Section 4.4.6. The constraint equation is used to determine the circulation distribution along the span of each lifting line. For the van Garrel method, this circulation is a function of the angle of attack along the blade and the airfoil coefficients. The angle of attack at a given lifting-line node is a function of the undisturbed velocity, \( \vec{V}_{0,lt} \), and the velocity induced by the vorticity, \( \vec{v}_{i,lt} \), at that point. Part of the induced velocity is caused by the vorticity being shed and trailed at the current time step, which in turn is a function of the circulation distribution along the lifting line. This constraint equation may be written as:

\[
\vec{Z} = \vec{0} = \vec{\Gamma}_{lt} - \vec{\Gamma}_p(\vec{\alpha}(\vec{x}, \vec{u}), \vec{\omega})
\]

where \( \vec{\Gamma}_p \) is the function that returns the circulation along the blade span, according to one of the methods presented in Section 4.4.6.

The state equation specifies the time evolution of the vorticity and the convection of the Lagrangian markers:

\[
\frac{d\vec{\omega}_e}{dt} = \left( (\vec{\omega} \cdot \nabla)\vec{v} + \nu \nabla^2 \vec{\omega} \right)_e
\]

\[
\frac{d\vec{r}_m}{dt} = \vec{V}(\vec{r}_m) = \vec{V}_0(\vec{r}_m) + \vec{v}_\omega(\vec{r}_m) = \vec{V}_0(\vec{r}_m) + \vec{V}_\omega(\vec{r}_m, \vec{r}_m, \vec{\omega})
\]

(4.20)

Here,
- \( \vec{v}_\omega \) is the velocity induced by the vorticity in the domain;
- \( \vec{V}_\omega(\vec{r}, \vec{r}_m, \vec{\omega}) \) is the function that computes this induced velocity at a given point, \( \vec{r} \), based on the location of the Lagrangian markers and the intensity of the vortex elements;
- the subscript \( \epsilon \) indicates that a quantity is applied to an element; and
- the vorticity, \( \vec{\omega} \), is recovered from the vorticity of the vortex elements by means of discrete convolutions.

\[1\] The loads on the lifting line are not an output of the vortex code; their calculation is handled by a separate submodule of AeroDyn.
For vortex-segment simulations, the viscous-splitting algorithm is used, and the convection step (Eq. (4.20)) is the main state equation being solved for. The vorticity stretching is automatically accounted for, and the diffusion is performed \textit{a posteriori}. The velocity function, \( \vec{V}_\omega \), uses the Biot-Savart law. The output equation is:

\[
\begin{align*}
\vec{y}_1 &= \vec{v}_{i,lt} = \vec{V}_\omega(\vec{r}_{lt}, \vec{r}_{m}, \vec{\omega}) \\
\vec{y}_2 &= \vec{r}_r
\end{align*}
\]

**Integration with AeroDyn15**

The vortex code has been integrated as a submodule of the aerodynamic module of OpenFAST, AeroDyn15. The data workflow between the different modules and submodules of OpenFAST is illustrated in Fig. 4.10. AeroDyn inputs such as BEM options (e.g., tip-loss factor), skew model, and dynamic inflow are discarded when the vortex code is used. The environmental conditions, tower shadow, and dynamic stall model options are used. This integration required a restructuring of the AeroDyn15 module to isolate the parts of the code related to tower shadow modeling, induction computation, lifting-line-forces computations, and dynamic stall. The dynamic stall model is adapted when used in conjunction with the vortex code to ensure the effect of shed vorticity is not accounted for twice. The interface between AeroDyn15 and the inflow module, InflowWind, was accommodated to include the additionally requested points by the vortex code.

**Fig. 4.10: OpenFAST-OLAF code integration workflow**

**4.4.8 Future Work**

This first implementation phase focused on single-turbine capabilities, fulfilling the basic requirements for the design of large and novel rotor concepts. Future development work will turn toward the implementation of features enabling multiple-turbine simulations on medium-to-large-scale computational clusters. The reduction of the computational time will also be of focus. This may be achieved using tree techniques such as the fast multipole method. Further algorithmic options, such as vortex amalgamation in the far wake, will be considered to speed up the simulation. The framework presented in this manual is compatible with grid-free or grid-based vortex particle formulations. Such particle-based implementations will also be envisaged in the future. Further validation of the code against measurements and higher-order tools will be pursued. Applications to cases known to be challenging for the BEM algorithm will also be investigated, such as highly flexible rotors, offshore floating turbines, small-scale wind farms, multiple-rotor turbines, or kites.

The following list contains future work on OLAF software:
• Lagrangian particles
• Multiple turbines, integration into FAST.Farm
• Code speed-up
• Dedicated dynamic stall model

4.4.9 Appendix A: OLAF Primary Input File

Check the regression test cases for updates to this input file.

--- OLAF (cOnvecting LAgrangian Filaments) INPUT FILE ---
Free wake input file for the Helix test case
--- GENERAL OPTIONS ---
5 IntMethod Integration method {5: Forward Euler 1st order, default: 5} (switch)
0.2 DTfw Time interval for wake propagation. (default: dtaero) (s)
5 FreeWakeStart Time when wake is free. (-) value = always free. (default: -0.0) (s)
2.0 FullCircStart Time at which full circulation is reached. (default: 0.0) (s)
--- CIRCULATION SPECIFICATIONS ---
1 CircSolvingMethod Circulation solving method {1: Cl-Based, 2: No-Flow, 3: Prescribed, default: 1} (switch)
0.01 CircSolvConvCrit Convergence criteria {default: 0.001} [only if CircSolvingMethod=1] (-)
0.1 CircSolvRelaxation Relaxation factor {default: 0.1} [only if CircSolvingMethod=1] (-)
30 CircSolvMaxIter Maximum number of iterations for circulation solving {default: 30} (-)
"NA" PrescribedCircFile File containing prescribed circulation [only if CircSolvingMethod=3] (quoted string)
--- WAKE OPTIONS ---
--- WAKE EXTENT AND DISCRETIZATION ---
50 nNWPanel Number of near-wake panels [integer] (-)
400 WakeLength Total wake distance [integer] (number of time steps)
default FreeWakeLength Wake length that is free [integer] (number of time steps) {default: WakeLength}
False FWShedVorticity Include shed vorticity in the far wake {default: false}
--- WAKE REGULARIZATIONS AND DIFFUSION ---
0 DiffusionMethod Diffusion method to account for viscous effects {0: None, 1: Core Spreading, "default": 0}
0 RegDeterMethod Method to determine the regularization parameters {0: Manual, 1: Optimized, default: 0}
2 RegFunction Viscous diffusion function {0: None, 1: Rankine, 2: LambOseen, 3: Vatistas, 4: Denominator, "default": 3} (switch)
0 WakeRegMethod Wake regularization method {1: Constant, 2: Stretching, 3: Age, default: 1} (switch)

(continues on next page)
2.0 WakeRegFactor    Wake regularization factor (m)
2.0 WingRegFactor     Wing regularization factor (m)
100 CoreSpreadEddyVisc Eddy viscosity in core spreading methods, typical values 1-1000

------------------- WAKE TREATMENT OPTIONS -------------------------------------------

False TwrShadowOnWake Include tower flow disturbance effects on wake convection
   {default:false} [only if TwrPotent or TwrShadow]
0 ShearModel          Shear Model {0: No treatment, 1: Mirrored vorticity, }....
   {default: 0}

------------------- SPEEDUP OPTIONS --------------------------------------------------

2.0 VelocityMethod    Method to determine the velocity {1:Biot-Savart Segment, 2:Particle tree, default: 1}
1.5 TreeBranchFactor  Branch radius fraction above which a multipole calculation
   is used {default: 2.0} [only if VelocityMethod=2]
1 PartPerSegment      Number of particles per segment [only if VelocityMethod=2]

===============================================================================================

--------------------------- OUTPUT OPTIONS ------------------------------------------

1 WrVTk Outputs Visualization Toolkit (VTK) (independent of .fst option) {0: NoVTK, 1: Write VTK at each time step} (flag)
1 nVTKBlades Number of blades for which VTK files are exported {0: No, VTK per blade, n: VTK for blade 1 to n} (-)
2 VTKCoord Coordinate system used for VTK export. {1: Global, 2: Hub, "default": 1}
1 VTK_fps Frame rate for VTK output (frames per second) {"all" for all glue code timesteps, "default" for all OLAF timesteps} [used only if WrVTk=1]

4.4.10 Appendix B: Prescribed Circulation Input File

Check the regression tests for updated versions of this file.

<table>
<thead>
<tr>
<th>r/R [-], Gamma [m^2/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.048488, 0.000000</td>
</tr>
<tr>
<td>0.087326, 0.442312</td>
</tr>
<tr>
<td>0.126163, 6.909277</td>
</tr>
<tr>
<td>0.165000, 23.678557</td>
</tr>
<tr>
<td>0.203837, 55.650700</td>
</tr>
<tr>
<td>0.242674, 74.091529</td>
</tr>
<tr>
<td>0.281512, 84.205843</td>
</tr>
<tr>
<td>0.320349, 88.740429</td>
</tr>
<tr>
<td>0.359186, 89.730814</td>
</tr>
<tr>
<td>0.398023, 88.568114</td>
</tr>
<tr>
<td>0.436860, 87.114743</td>
</tr>
<tr>
<td>0.475698, 86.110557</td>
</tr>
<tr>
<td>0.514535, 85.705529</td>
</tr>
<tr>
<td>0.553372, 85.215829</td>
</tr>
<tr>
<td>0.592209, 84.547371</td>
</tr>
<tr>
<td>0.631047, 83.774329</td>
</tr>
<tr>
<td>0.669884, 82.889157</td>
</tr>
<tr>
<td>0.708721, 81.635600</td>
</tr>
<tr>
<td>0.747558, 79.788700</td>
</tr>
</tbody>
</table>

(continues on next page)
### 4.4.11 Appendix C: OLAF List of Output Channels

This is a list of all possible output parameters from the OLAF module. The names are grouped by meaning, but can be ordered in the OUTPUTS section of the *AeroDyn15* primary input file, as the user sees fit. $N\beta$ refers to output node, $\beta$, where $\beta$ is a number in the range [1,9], corresponding to entry, $\beta$, in the OutNd list. $B\alpha$ is prefixed to each output name, where $\alpha$ is a number in the range [1,3], corresponding to the blade number.

<table>
<thead>
<tr>
<th>Channel Name(s)</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B\alpha N\beta \Gamma$</td>
<td>$m^2/s$</td>
<td>Circulation along the blade</td>
</tr>
</tbody>
</table>

### 4.5 Aeroacoustics Noise Model of OpenFAST

#### 4.5.1 List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPM</td>
<td>Brooks-Pope-Marcolini airfoil noise model</td>
</tr>
<tr>
<td>dB</td>
<td>decibels</td>
</tr>
<tr>
<td>dBA</td>
<td>A-weighted decibels</td>
</tr>
<tr>
<td>deg</td>
<td>degrees</td>
</tr>
<tr>
<td>Hz</td>
<td>hertz</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>kg</td>
<td>kilograms</td>
</tr>
<tr>
<td>kHz</td>
<td>kilohertz</td>
</tr>
<tr>
<td>LFC</td>
<td>low-frequency correction</td>
</tr>
<tr>
<td>m</td>
<td>meters</td>
</tr>
<tr>
<td>N</td>
<td>newtons</td>
</tr>
<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
</tr>
</tbody>
</table>
4.5.2 List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( l )</td>
<td>low frequency</td>
</tr>
<tr>
<td>( h )</td>
<td>high frequency</td>
</tr>
<tr>
<td>( p )</td>
<td>airfoil pressure side</td>
</tr>
<tr>
<td>( s )</td>
<td>airfoil suction side</td>
</tr>
<tr>
<td>( t )</td>
<td>turbulence</td>
</tr>
<tr>
<td>( 0 )</td>
<td>reference</td>
</tr>
<tr>
<td>( 1 )</td>
<td>parallel to airfoil chord</td>
</tr>
<tr>
<td>( 2 )</td>
<td>normal to airfoil chord</td>
</tr>
<tr>
<td>( 3 )</td>
<td>blade spanwise direction</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>angle of attack ([\text{rad}])</td>
</tr>
<tr>
<td>( \beta^2 )</td>
<td>Prandtl-Glauert correction factor ([-])</td>
</tr>
<tr>
<td>( \delta )</td>
<td>airfoil boundary layer thickness ([-])</td>
</tr>
<tr>
<td>( \delta^* )</td>
<td>airfoil boundary layer displacement thickness ([-])</td>
</tr>
<tr>
<td>( \theta )</td>
<td>airfoil boundary layer momentum thickness ([-])</td>
</tr>
<tr>
<td>( \Theta_e, \Phi_e )</td>
<td>angles between emitter and observer ([\text{rad}])</td>
</tr>
</tbody>
</table>
Table 4.4 – continued from previous page

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho )</td>
<td>air density</td>
<td>[kg/m³]</td>
</tr>
<tr>
<td>( \omega )</td>
<td>radial frequency</td>
<td>[rad/s]</td>
</tr>
<tr>
<td>( A_{w} )</td>
<td>A-weight</td>
<td>[dB]</td>
</tr>
<tr>
<td>( c )</td>
<td>speed of sound</td>
<td>[m/s]</td>
</tr>
<tr>
<td>( c_i )</td>
<td>chord at blade spanwise position ( i )</td>
<td>[m]</td>
</tr>
<tr>
<td>( d )</td>
<td>blade span at station ( i )</td>
<td>[m]</td>
</tr>
<tr>
<td>( D )</td>
<td>directivity function</td>
<td>[-]</td>
</tr>
<tr>
<td>( f )</td>
<td>frequency</td>
<td>[Hz]</td>
</tr>
<tr>
<td>( G )</td>
<td>empirical function</td>
<td>[-]</td>
</tr>
<tr>
<td>( h )</td>
<td>height of the trailing edge thickness</td>
<td>[m]</td>
</tr>
<tr>
<td>( H )</td>
<td>airfoil kinematic shape factor</td>
<td>[-]</td>
</tr>
<tr>
<td>( I )</td>
<td>turbulence intensity</td>
<td>[-]</td>
</tr>
<tr>
<td>( k )</td>
<td>wave number</td>
<td>[m⁻¹]</td>
</tr>
<tr>
<td>( \overline{k} )</td>
<td>nondimensional wave number</td>
<td>[-]</td>
</tr>
<tr>
<td>( \Delta K_1, K_1, K_2 )</td>
<td>empirical parameters of the BPM model</td>
<td>[-]</td>
</tr>
<tr>
<td>( l )</td>
<td>spanwise extent of the separation zone from blade tip</td>
<td>[m]</td>
</tr>
<tr>
<td>( L )</td>
<td>lift force</td>
<td>[N]</td>
</tr>
<tr>
<td>( L_t )</td>
<td>length scale</td>
<td>[m]</td>
</tr>
<tr>
<td>( M )</td>
<td>Mach number</td>
<td>[-]</td>
</tr>
<tr>
<td>( M_c )</td>
<td>Mach number past the trailing edge</td>
<td>[-]</td>
</tr>
<tr>
<td>( r_e )</td>
<td>effective observer distance</td>
<td>[m]</td>
</tr>
<tr>
<td>( \text{Re} )</td>
<td>Reynolds number</td>
<td>[-]</td>
</tr>
<tr>
<td>( S^2 )</td>
<td>Sears function</td>
<td>[-]</td>
</tr>
<tr>
<td>( \text{St} )</td>
<td>Strouhal number</td>
<td>[-]</td>
</tr>
<tr>
<td>( t_x )</td>
<td>relative thickness of the airfoil at chordwise position ( x )</td>
<td>[-]</td>
</tr>
</tbody>
</table>
4.5.3 Introduction

The increasing penetration of wind energy into the electricity mix has been possible thanks to a constantly growing installed capacity, which has so far been mostly located on land. Land-based installations are, however, increasingly constrained by local ordinances and an often-limiting factor that comprises maximum allowable levels of noise. To further increase the number of land-based installations, it is important to develop accurate modeling tools to estimate the noise generated by wind turbines. This allows for a more accurate assessment of the noise emissions and the possibility to design quieter wind turbines.

Wind turbines emit two main sources of noise:

- Aeroacoustics noise from the interaction between rotor blades and the turbulent atmospheric boundary layer
- Mechanical noise from the nacelle component, mostly the gearbox, generator, and yaw mechanism.

This work targets the first class of noise generation and aims at providing a set of open-source models to estimate the aeroacoustics noise generated by an arbitrary wind turbine rotor. The models are implemented in Fortran and are fully coupled to the aeroservoelastic wind turbine simulator OpenFAST. The code is available in the GitHub repository of OpenFAST. The code builds on the implementation of NAFNoise and the documentation presented in [aa-MM03] and [aa-Mor05]. OpenFAST is implemented as a modularization framework and the aeroacoustics model is implemented as a submodule of AeroDyn ([aa-MH05]).

The set of models is described in Section 4.5.4 and exercised on the noise estimate of the International Energy Agency (IEA) land-based reference wind turbine in Section 4.5.5. In Section 4.5.5, we also show a comparison to results obtained running the noise models implemented at the Technical University of Munich. This documentation closes with conclusions, an outlook on future work, and appendices, where the input files to OpenFAST are presented.

4.5.4 Aeroacoustics Noise Models

The aeroacoustics noise of wind turbine rotors emanates from pressure oscillations that are generated along the blades and propagate in the atmosphere. This source of noise has been historically simulated with models characterized by different fidelity levels. At lower fidelity, models correlated aeroacoustics noise with rotor thrust and torque ([aa-Low70][aa-Vit81]). At higher fidelity, three-dimensional incompressible computational fluid dynamics models are coupled with the Ffowcs Williams-Hawkings model to propagate pressure oscillations generated along the surface of the rotor blades to the far field ([aa-KGW+18]). The latter models are often only suitable to estimate noise at low frequency because capturing noise in the audible range, which is commonly defined between 20 (hertz) Hz and 20 kilohertz (kHz), requires a very fine space-time discretization with enormous computational costs.

For the audible range, a variety of models is available in the public domain, and [aa-SBCB18] offers the most recent literature review. These models have inputs that match the inputs and outputs of modern aeroservoelastic solvers, such as OpenFAST, and have therefore often been coupled together. Further, the computational costs of these acoustic models are similar to the costs of modern aeroservoelastic solvers, which has facilitated the coupling.

---

1 https://github.com/OpenFAST/openfast
Models have targeted different noise generation mechanisms following the distinction defined by [aa-BPM89], and the mechanism of turbulent inflow noise. The latter represents a broadband noise source that is generated when a body of arbitrary shape experiences an unsteady lift because of the presence of an incident turbulent flow. For an airfoil, this phenomenon can be interpreted as leading-edge noise. Turbulent inflow noise was the topic of multiple investigations over the past decades and, as a result, multiple models have been published ([aa-SBCB18]). The BPM model includes five mechanisms of noise generation for an airfoil immersed in a flow:

1. Turbulent boundary layer – trailing edge (TBL-TE)
2. Separation stall
3. Laminar boundary layer – vortex shedding
4. Tip vortex
5. Trailing-edge bluntness – vortex shedding.

For the five mechanisms, semiempirical models were initially defined for the NACA 0012 airfoil. The BPM model is still a popular model for wind turbine noise prediction, and subsequent studies have improved the model by removing some of the assumptions originally adopted. Recent studies have especially focused on the TBL-TE mechanism, which is commonly the dominant noise source of modern wind turbines. As a result, each noise source defined in the BPM model now has a variety of permutations.

The following subsections describe the details of each mechanism and the models implemented in this model of OpenFAST.

### Turbulent Inflow

A body of any arbitrary shape, when immersed in a turbulent flow, generates surface pressure fluctuations. Over the years, several formulations of the turbulent inflow noise model have been developed ([aa-SBCB18]). In this model of OpenFAST, the formulation defined in [aa-MGM04] is adopted. The formulation is based on the model of Amiet ([aa-Ami75][aa-PA76]) and is presented in Section 4.5.4. Additionally, the user can activate the correction defined by [aa-MH05], which builds upon the Amiet model and accounts for the thickness of the airfoils adopted along the blade span. This second model is named Simplified Guidati and is presented in Section 4.5.4.

### Amiet model

The formulation is based on work from [aa-Ami75] and [aa-PA76], and it represents the blade as a flat plate and neglects the shape of the airfoil.

The model starts by first computing the wave number, $k_1$, for a given frequency $f$:

$$k_1 = \frac{2f}{U_1}$$  \hspace{1cm} (4.21)

where $U_1$ is the incident inflow velocity on the profile. From $k_1$, the wave numbers $\bar{k}_1$ and $\hat{k}_1$ are computed:

$$\bar{k}_1 = \frac{k_1 c_i}{2}$$  \hspace{1cm} (4.22)

$$\hat{k}_1 = \frac{k_1}{k_e}$$  \hspace{1cm} (4.23)

where $c_i$ is the local chord, and $k_e$ is the wave number range of energy containing eddies, defined as:

$$k_e = \frac{3}{4L_t}.$$  \hspace{1cm} (4.24)
Lₜ is the turbulent length scale, and many different formulations have been proposed over the years. As default implementation, $L_t$ is defined following the formulation proposed in [aa-ZHS05]:

$$L_t = 25z^{0.35}z_0^{-0.063} \quad (4.25)$$

where $z$ is the height above the ground of the leading edge of section $i$ at a given instant, $t$, while $z_0$ is the surface roughness. Note that setting $L_t$ appropriately is a challenge, and advanced users of this model may want to validate this formulation against experimental data.

The value of sound pressure level (SPL) is expressed in one-third octave bands at the given frequency, $f$, originated at the given blade station, $i$, which can be computed as:

$$\text{SPL}_{\text{TI}} = 10 \log_{10} \left( \frac{\rho^2 c^4 L_t d M^5 I_1^2}{2r_e^4} \frac{\hat{k}_1^2}{(1 + \hat{k}_1^2)} \frac{D}{T} \right) + 78.4 \quad (4.26)$$

where $\rho$ is the air density, $c$ the speed of sound, $d$ the blade element span, $r_e$ the effective distance between leading edge and observer, $M$ the Mach number, $I_1$ the turbulence intensity of the airfoil inflow, and $D/T$ the directivity term. $D$ is different below ($D_l$) and above ($D_h$) a certain frequency, which is named “cut-off” and defined as:

$$f_{co} = \frac{10U_1}{\pi c_1} \quad (4.27)$$

The formulations of $D_h$ and $D_l$ are presented in Section 4.5.4.

The current implementation offers two approaches to estimate $I_1$. The first one is through a user-defined grid of $I_1$; see Section 4.5.7. The second option is to have the code reconstructing $I_1$ from the turbulent wind grid, where the code computes the airfoil relative position of each blade section, $i$, at every time instant and, given the rotor speed, reconstructs the inflow component, $I_1$, of the turbulence intensity.

Two corrections to this model are also implemented. The first one comprises a correction for the angle of attack, $\alpha$, in which the effect is neglected in the original formulation from [aa-Ami75] and Amiet and Peterson (1976). This correction is formulated as:

$$\text{SPL}_{\text{TI}} = \text{SPL}_{\text{TI}} + 10 \log_{10} \left( 1 + 9a^2 \right) \quad (4.28)$$

The second correction is called low-frequency correction (LFC), and is formulated as:

$$S^2 = \left( \frac{2 \pi T_1}{\beta^2} + \left( 1 + 2.4 \frac{T_1}{\beta^2} \right)^{-1} \right)^{-1} \quad (4.29)$$

$$LFC = 10S^2M\hat{k}_1^2\beta^{-2} \quad (4.30)$$

$$\text{SPL}_{\text{TI}} = \text{SPL}_{\text{TI}} + 10 \log_{10} \left( \frac{1 + LFC}{LFC} \right) \quad (4.31)$$

In (4.29) and (4.30), $S^2$ represents the squared Sears function, and $\beta^2$ is the Prandtl-Glauert correction factor, which is defined as:

$$\beta^2 = 1 - M^2 \quad (4.32)$$

It is worth stressing that numerous alternative formulations of the turbulent inflow noise model exist ([aa-SBCB18]), where the main differences comprise different definitions of $L_t$ and $k_1$. 

4.5. Aeroacoustics Noise Model of OpenFAST
Simplified Guidati

Sound spectra are often overpredicted by the Amiet model implemented here. Guidatai ([aa-GBW97]) derived a correction to the sound pressure levels by adding a term considering shape and camber of the airfoil profiles, but the method proved computationally too expensive for wind turbine simulations. Moriarty et al. ([aa-MGM05]) proposed a simplified model based on geometric characteristics of six wind turbine airfoils. The validity of the correction is limited to Mach numbers on the order of 0.1 0.2 and Strouhal number St below 75. St is defined based on airfoil chord and mean inflow velocity:

\[ St = \frac{f c_i}{U_1}. \]  

(4.33)

The formula for the correction to the noise spectra is provided in Eq. 4 in [aa-MGM05]:

\[ t = t_{1\%} + t_{10\%} \]  

(4.34)

\[ \Delta SPL_{TI} = - \left(1.123t + 5.317t^2\right)(2\pi St + 5) \]  

(4.35)

where \( t_{x\%} \) is the relative thickness of the profile at \( x \) position along the chord (i.e., 0% being the leading edge and 100% the trailing edge).

It should be highlighted here that a validation campaign was conducted in a wind tunnel on two-dimensional airfoils ([aa-MGM04]), returning a fairly poor match between the Simplified Guidati model and the experimental results. Therefore, a correction of +10 decibels (dB) on the SPL levels across the whole frequency spectrum was proposed. This correction is still implemented, but a validation at turbine level should assess the accuracy of the models for turbulent inflow. It should also be noted that the code currently does not check whether Mach and Strouhal numbers are within the range of validity of this model.

Turbulent Boundary Layer – Trailing Edge

Airfoils immersed in a flow develop a boundary layer, which at high Reynolds numbers is turbulent. When the turbulence passes over the trailing edge, noise is generated. This noise source was named TBL-TE in [aa-BPM89] and it is a relevant source of aeroacoustics noise for modern wind turbine rotors. Two formulations of TBL-TE noise are implemented in the code: (1) the original formulation from the BPM model, described in Section 4.5.4, and (2) a more recent model developed at the Dutch research institute, TNO, described in Section 4.5.4. Both models take as input the characteristics of the airfoil boundary layer. These must be provided by the user and are discussed in Section 4.5.7.

BPM

The SPL of the TBL-TE noise in the BPM model is made from three contributions:

\[ SPL_{TBL-TE} = 10 \log_{10} \left(10^{\text{sple}} + 10^{\text{sles}} + 10^{\text{sloa}}\right) \]  

(4.36)

where the subscripts \( p, s, \) and \( a \) refer to the contributions of pressure side, suction side, and angle of attack, respectively. The equations describing the three contributions are described in great detail in Section 5.1.2, in [aa-BPM89], and are summarized here.

For the suction and pressure contributions, the equations are:

\[ SPL_p = 10 \log_{10} \left(\frac{\delta^* M^5 d D_h}{r^2_c}\right) + A \left(\frac{St_p}{St_1}\right) + (K_1 - 3) + \Delta K_1 \]  

(4.37)

\[ SPL_s = 10 \log_{10} \left(\frac{\delta^* M^5 d D_h}{r^2_c}\right) + A \left(\frac{St_s}{St_1}\right) + (K_1 - 3). \]  

(4.38)
The terms in the equations, which are also described in the nomenclature at the beginning of this document, list \( \delta^* \) as the boundary layer displacement thickness on either side of the airfoil, \( St \), as the Strouhal number based on \( \delta^* \), and \( A', B, \Delta K_1, K_1, \) and \( K_2 \) as empirical functions based on \( St \).

For the angle-of-attack contribution, a distinction is made above and below the stall angle, which in the original BPM model is set equal to 12.5 degrees, whereas it is here assumed to be the actual stall angle of attack of the airfoil at blade station \( i \). Below stall, \( \text{SPL}_{\alpha} \) is equal to:

\[
\text{SPL}_{\alpha} = 10 \log_{10} \left( \frac{\delta^* M^5 dD_h}{r_c^2} \right) + B \left( \frac{St}{St_2} \right) + K_2. \tag{4.39}
\]

At angles of attack above the stall point, the flow along the profile is fully separated and noise radiates from the whole chord. \( \text{SPL}_{\alpha} \) and \( \text{SPL}_{p} \) are then set equal to \(-\infty\), whereas \( \text{SPL}_{\alpha} \) becomes:

\[
\text{SPL}_{\alpha} = 10 \log_{10} \left( \frac{\delta^* M^5 dD_l}{r_c^2} \right) + A' \left( \frac{St}{St_2} \right) + K_2. \tag{4.40}
\]

Notably, above stall the low-frequency directivity \( D_l \) is adopted in Eqs. 18 and 19 (see Section 4.5.4).

**TNO model**

The TNO model is a more recent model to simulate the noise emitted by the vortices shed at the trailing edge of the blades and was formulated by Parchen ([aa-Par98]). The implementation adopted here is the one described in Moriarty et al. (2005). The TNO model uses the spectrum of the wave number, \( k \), of unsteady surface pressures to estimate the far-field noise. The spectrum, \( P \), is assumed to be:

\[
P (k_1, k_3, \omega) = 4 \rho_0^2 \frac{k_3^2}{k_1^2 + k_3^2} \int_0^{10 \frac{\omega c}{k_1}} L_2 u_2^2 \left( \frac{\partial U_1}{\partial x_2} \right)^2 \phi_{m} (\omega - U_c (x_2) k_1) e^{(-2|\vec{k}|x_2)} \, dx_2. \tag{4.41}
\]

In the equation, the indices 1, 2, and 3 refer to the directions parallel to the airfoil chord, normal to the airfoil chord, and along span, respectively; \( \phi_{22} \) is the vertical velocity fluctuation spectrum; \( \phi_{m} \) is the moving axis spectrum; and \( U_c \) is the convection velocity of the eddies along the trailing edge. Lastly, \( L_2 \) is the vertical correlation length, perpendicular to the chord length, which indicates the vertical extension of the vortices that convect over the trailing edge. In this work, \( L_2 \) is assumed equal to the mixing length, \( L_m \) (Moriarty et al. 2005). This decision is partially arbitrary, and dedicated research should better assess the correct integral length to be adopted within the TNO model.

From \( P \), the far-field spectrum, \( S (\omega) \), is computed as:

\[
S (\omega) = \frac{dD_h}{4 \pi r_c^2} \int_0^{\delta} \frac{\omega}{ck_1} P (k_1, 0, \omega) \, dk_1. \tag{4.42}
\]

The implementation of the TNO model is identical to the one described in [aa-MGM05]. The inputs to the model are generated from the boundary layer characteristics provided by the user (see Section 4.5.7).

**Laminar Boundary Layer – Vortex Shedding**

Another source of airfoil self-noise noise included in the BPM model is the noise generated by a feedback loop between vortices being shed at the trailing edge and instability waves in the laminar boundary layer. This noise is typically distributed on a narrow band of frequencies and occurs when the boundary layer of the airfoil remains laminar. This may occur in the inboard region of smaller wind turbines, where the Reynolds number can be smaller than 1 million, but hardly occurs in modern rotors that operate at a Reynolds number one order of magnitude larger.
The formula to estimate the noise spectrum in a one-third-octave presentation is:

$$SPL_{L_iB_iL-VS} = 10 \log_{10} \left( \frac{\delta^5 M^5 d D_h}{r_c^2} \right) + G_4 \left( \frac{St'}{St'_{peak}} \right) + G_2 \left[ \frac{Re_c}{(Re_c)_0} \right] + G_3 (\alpha_s)$$  \hspace{1cm} (4.43)

where $G$ represents empirical functions, $St'_{peak}$ is the peak Strouhal number function of $Re_c$, which is the Reynolds number at chord, $c_i$. The subscript $0$ refers to a reference Reynolds number that is a function of the angle of attack (Brooks et al. 1989).

### Tip Vortex

The vortices generated at blade tips are another source of noise of the BPM model. Although rarely relevant in modern wind turbines, the possibility to include this noise source is offered. The sound pressure level is estimated as:

$$SPL_{tip} = 10 \log_{10} \left( \frac{M^2 M_{max}^2 D_h}{r_c^2} \right) - 30.5 \left( \log_{10} St'' + 0.3 \right)^2 + 126$$  \hspace{1cm} (4.44)

where $M_{max} = M_{max}(\alpha_{tip})$ is the maximum Mach number, measured near the blade tip within the separated flow region that is assumed to depend on $\alpha_{tip}$, which is the angle of attack at the tip; $l$ is the spanwise extent of the separation zone; and $St''$ is the Strouhal number based on $l$. For a round shape of the tip, $l$ is estimated as:

$$l = c_i 0.008 \alpha_{tip}$$  \hspace{1cm} (4.45)

where $\alpha_{tip}$ is the angle of attack of the tip region to the incoming flow. For $\alpha'_{tip}$ between 0 and 2 degrees, $l$ becomes:

$$l = c_i \left( 0.0230 + 0.0169 \alpha'_{tip} \right),$$  \hspace{1cm} (4.47)

while for $\alpha'_{tip}$ larger than 2 degrees, $l$ is:

$$l = c_i \left( 0.0378 + 0.0095 \alpha'_{tip} \right).$$  \hspace{1cm} (4.48)

However, it must be noted that, unfortunately, $\alpha_{tip}$ is not a reliable output of standard aeroelastic models and the impossibility to accurately determine $\alpha_{tip}$ weakens the formulation of the tip vortex noise.

### Trailing-Edge Bluntness – Vortex Shedding

Lastly, wind turbine blades are often characterized by a finite height of the trailing edge, which generates noise as a result of vortex shedding. The frequency and amplitude of this noise source depends on the geometry of the trailing edge and is typically characterized by a tonal nature. Adopting flatback and truncated airfoils far outboard along the blade may strengthen this noise source. When this noise source is activated, the user is asked to provide the distribution along the blade span of the blunt thickness of the trailing edge, $h$, and the solid angle between the suction and pressure sides of the airfoil, $\Psi$ (see Section 4.5.4). $h$ and $\Psi$ are inputs to the equation:

$$SPL_{TEB-VS} = 10 \log_{10} \left( \frac{\delta^5 M^5 d D_h}{r_c^2} \right) + G_4 \left( \frac{h}{\delta_{avg}} \Psi \right) + G_5 \left( \frac{h}{\delta_{avg}}^{-}, \Psi, \frac{St''}{St'_{peak}} \right).$$  \hspace{1cm} (4.49)
In the equation, $\delta^*_{\text{avg}}$ is the average displacement thickness for both sides of the airfoil. Note that this noise source is very sensitive to $h$ and $\Psi$, which, therefore, should be estimated accurately.

**Directivity**

The position of one or more observers is specified by the user, as described in Section 4.5.7. The directivity from the BPM model is adopted in this implementation ([aa-BPM89]). The directivity term, $D$, corrects the SPL depending on the relative position of the observer to the emitter. The position is described by the spanwise directivity angle, $\Phi_e$, and by the chordwise directivity angle, $\Theta_e$, which are schematically represented in Fig. 4.11 and defined as:

\[
\Phi_e = \text{atan} \left( \frac{z_e}{y_e} \right) \\
\Theta_e = \text{atan} \left( \frac{y_e \cdot \cos (\Phi_e) + z_e \cdot \sin (\Phi_e)}{x_e} \right)
\]

(4.50) (4.51)

Fig. 4.11: Angles used in the directivity function ([aa-BPM89][aa-MM03])

The reference axis is located at each blade node and $x_e$ is aligned with the chord, $y_e$ is aligned with the span pointing to the blade tip, and $z_e$ is aligned toward the airfoil suction side. Note that in OpenFAST the local airfoil-oriented reference system is used, and a rotation is applied.

Given the angles $\Theta_e$ and $\Phi_e$, at high frequency, $D$ for the trailing edge takes the expression:

\[
D_{h-TE} (\Theta_e, \Phi_e) = \frac{2 \sin^2 \left( \frac{\Theta_e}{2} \right) \sin^2 \Phi_e}{(1 + M \cos \Theta_e) (1 + (M - M_c) \cos \Theta_e)^2}
\]

(4.52)

where $M_c$ represents the Mach number past the trailing edge and that is here for simplicity assumed equal to 80% of free-stream $M$. 

4.5. Aeroacoustics Noise Model of OpenFAST
For the leading edge, and therefore for the turbulent inflow noise model, at high frequency, $\mathcal{D}$ is:

$$
\mathcal{D}_{h-LE} (\Theta_e, \Phi_e) = \frac{2 \cos^2 \left( \frac{\Theta_e}{2} \right) \sin^2 \Phi_e}{(1 + M \cos \Theta_e)^3}
$$

(4.53)

Note that this equation was not reported in the NREL Tech Report NREL/TP-5000-75731!

At low frequency, the equation is identical for both leading and trailing edges:

$$
\mathcal{D}_l (\Theta_e, \Phi_e) = \frac{\sin^2 \Theta_e \sin^2 \Phi_e}{(1 + M \cos \Theta_e)^4}.
$$

(4.54)

Each model distinguishes a different value between low and high frequency. For the TI noise model, the shift between low and high frequency is defined based on $\kappa_1$. For the TBL-TE noise, the model differences instead shift between below and above stall, where $\mathcal{D}_h$ and $\mathcal{D}_l$ are used, respectively.

### A-Weighting

The code offers the possibility to weigh the aeroacoustics outputs by A-weighting, which is an experimental coefficient that aims to take into account the sensitivity of human hearing to different frequencies. The A-weight, $A_w$, is computed as:

$$
A_w = 10 \log \left( \frac{1.562339}{(f^2 + 107.65265^2)(f^2 + 737.86223^2)^2} \right) \\
+ 10 \log \left( \frac{2.422881 \times 10^4}{(f^2 + 20.59979^2)(f^2 + 12194.22^2)^2} \right)
$$

(4.55)

The A-weighting is a function of frequency and is added to the values of sound pressure levels:

$$
SPL_{A_w} = SPL + A_w
$$

(4.56)

### 4.5.5 Model Verification

#### Reference Wind Turbine

The noise model of OpenFAST is exercised by simulating the aeroacoustics noise emissions of the IEA Wind Task 37 land-based reference wind turbine ([aa-BTD+19]). The main characteristics of the reference wind turbine are presented in Table 4.5.
Table 4.5: Main Characteristics of the IEA Wind Task 37 Land-Based Reference Wind Turbine

<table>
<thead>
<tr>
<th>Data</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind class</td>
<td>International Electrotechnical Commission 3A</td>
</tr>
<tr>
<td>Rated electrical power</td>
<td>3.37 megawatts</td>
</tr>
<tr>
<td>Rated aerodynamic power</td>
<td>3.6 megawatts</td>
</tr>
<tr>
<td>Drivetrain &amp; generator efficiency</td>
<td>93.60%</td>
</tr>
<tr>
<td>Rotor diameter</td>
<td>130 meters</td>
</tr>
<tr>
<td>Hub height</td>
<td>110 meters</td>
</tr>
<tr>
<td>Cut-in wind speed</td>
<td>4 meters/second</td>
</tr>
<tr>
<td>Cut-out wind speed</td>
<td>25 meters/second</td>
</tr>
<tr>
<td>Rotor cone angle</td>
<td>3 degrees</td>
</tr>
<tr>
<td>Nacelle tilt angle</td>
<td>5 degrees</td>
</tr>
<tr>
<td>Max blade tip speed</td>
<td>80 meters/second</td>
</tr>
<tr>
<td>Rated tip-speed ratio</td>
<td>8.16</td>
</tr>
<tr>
<td>Maximum aerodynamic Cp</td>
<td>0.481</td>
</tr>
<tr>
<td>Rated rotor speed</td>
<td>11.75 revolutions per minute</td>
</tr>
</tbody>
</table>

The OpenFAST model of the wind turbine is available at https://github.com/OpenFAST/r-test and is optionally coupled to the Reference OpenSource Controller.²

**Code-to-Code Comparison**

A detailed code-to-code comparison was conducted to verify the implementation of the noise models linked to OpenFAST with the implementation available at the Wind Energy Institute of the Technical University of Munich, Germany. The latter is described in Sucameli ([aa-SBCB18]) and is implemented in the wind turbine design framework Cp-Max, which adopts the multibody-based aeroservoelastic solver Cp-Lambda.

The comparison is conducted for the main noise sources—turbulent inflow and the TBL-TE noise—for both the single airfoil profile and full turbine. This helped resolve a few implementation mistakes and small inconsistencies. The comparison is performed with a steady wind of 8 meters per second (m/s), no shear, a rated pitch angle of 1.17 degrees (deg), and a fixed rotor speed of 10.04 revolutions per minute (rpm). A fixed value of 0.1 is assumed for the incident turbulent intensity, $I_1$.

Fig. 4.12 shows the predictions in terms of SPL for the Amiet model with the angle-of-attack correction from OpenFAST, the Simplified Guidati model generated by OpenFAST, and the Amiet model from Cp-Max.

The two implementations of the turbulent inflow Amiet model return a perfect match between OpenFAST and Cp-Max. The chosen scenario sees the blade operating at optimal angles of attack and, therefore, the effect of the angle of attack correction is negligible. The plots also show the great difference between the Amiet model and the Simplified Guidati model. It may be useful to keep in mind that the Simplified Guidati model has, in the past, been corrected with a factor of +10 dB, which is applied here.

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² https://github.com/NREL/ROSCO

4.5. Aeroacoustics Noise Model of OpenFAST 97
Fig. 4.12: Code-to-code comparison for the TI models
For the same inflow and rotor conditions, the BPM and TNO TBL-TE noise models are compared in Fig. 4.13. The match is again satisfactory, although slightly larger differences emerge that are attributed to differences in the angles of attack between the two aeroelastic solvers and in different integration schemes in the TNO formulations.

The last comparison looked at the directivity models and the overall sound pressure levels at various observer locations. Simulations are run distributing 200 observers in a horizontal square of 500 meters (m) by 500 m (see Fig. 4.14). The noise is computed from the Amiet and the BPM turbulent boundary layer-trailing edge models. The code-to-code comparison returns similar predictions between OpenFAST and Cp-Max. The comparison is shown in Fig. 4.15.

The main conclusion of this code-to-code comparison is that, to the best of authors’ knowledge, the models are now implemented correctly and generate similar SPL and overall SPL levels for any arbitrary observer. Nonetheless, it is clear that all of the presented models are imperfect, and improvements could be made both at the theoretical implementation levels.
Fig. 4.14: Location and numbering of the observers
Fig. 4.15: Comparison of overall sound pressure levels for the observers distributed, as shown in the previous figure.
Model Usage

The aeroacoustics model of OpenFAST has four options for the outputs:

1. Overall sound pressure level (dB/A-weighted decibels [dBA])—one value per time step per observer is generated.
2. Total sound pressure level spectra (dB/dBA)—one spectrum per time step per observer is generated between 10 Hz and 20 kHz.
3. Mechanism-dependent sound pressure level spectra (dB/dBA)—one spectrum per active noise mechanism per time step per observer is generated between 10 Hz and 20 kHz.
4. Overall sound pressure level (dB/A-weighted decibels [dBA])—one value per blade per node per time step per observer is generated.

The overall SPL from the first option can be used to plot directivity maps of the noise. An example, which was generated using a Python script, is shown in Fig. 4.16. The noise map, which shows the overall SPL averaged over 1 rotor revolution, is generated for a steady wind speed of 8 m/s, a fixed rotor speed of 10.04 rpm, and a 1.17-deg pitch angle. In a horizontal circle of 500 m in diameter, 1681 observers are placed at a 2-m height. Only the Simplified Guidati and the BPM TBL-TE noise models are activated.

Fig. 4.16: Map of the overall SPL of the reference wind turbine at a 2-m height from Simplified Guidati and BPM TBL-TE noise models. The wind turbine is located at x=0, y=0. A steady wind of 8 m/s blows from left (-x) to right (+x).

---

3 https://github.com/OpenFAST/python-toolbox
The second output can be used to generate SPL spectra. These spectra can be computed for various observers and optionally A-weighted to account for human hearing. Fig. 4.17 shows the total SPL spectra computed for the same rotor conditions of the previous example. The A-weight greatly reduces the curve at frequency below 1,000 Hz while slightly increasing those between 1 kHz and 8 kHz.

![Comparison between absolute and A-weighted SPL](image)

Fig. 4.17: Comparison between absolute and A-weighted SPL

The third output distinguishes the SPL spectrum per mechanism. Fig. 4.18 shows the various SPL spectra estimated by each noise model for the same rotor conditions reported earlier. The total spectrum is visibly dominated by the turbulent inflow, TBL-TE, and trailing-edge bluntness noise mechanisms. Notably, the latter is extremely sensitive to its inputs, $\Psi$ and $h$. The reference wind turbine is a purely numerical model, and these quantities have been arbitrarily set. Users should pay attention to these inputs when calling the trailing-edge bluntness model. Consistent with literature, the laminar boundary layer-vortex shedding and tip vortex noise mechanisms have negative dB values and are, therefore, not visible. Notably, these spectra are not A-weighted, but users can activate the flag and obtain A-weighted spectra.

Finally, the fourth output can be used to visualize the noise emission across the rotor. Fig. 4.19 shows the noise generation of the rotor as seen from an observer located 175 meters downwind at a height of 2 meters. The map is generated by plotting the overall SPL generated by one blade during one rotor revolution. The plot shows that higher noise is observed when the blade is descending (the rotor from behind is seen rotating counterclockwise). This effect, which matches the results shown in [aa-MM03], is explained by the asymmetry of (4.51). Noise is indeed higher when the observer faces the leading edge of an airfoil (high $\Theta_e$), than when it faces the trailing edge (low $\Theta_e$).
Fig. 4.18: Nonweighted SPL spectra of the various noise mechanisms
Fig. 4.19: Map of the overall SPL of the rotor of the reference wind turbine from Simplified Guidati and BPM TBL-TE noise models. The observer is located 175 meters downwind at a height of 2 meters.
4.5.6 Conclusions

This document describes a set of frequency-based aeroacoustics models coupled to the open-source aeroservoelastic solver OpenFAST. The goal of these models is to predict the aeroacoustics emissions of wind turbine rotors. The document shows a code-to-code comparison between the models coupled to OpenFAST and the models implemented at the Technical University of Munich and coupled to the aeroservoelastic solver Cp-Lambda. The comparison is performed simulating the aeroacoustics emissions of the IEA Wind Task 37 land-based reference wind turbine. The results show a good agreement between the two implementations. The same turbine model is later used to exercise the aeroacoustics model showcasing its capabilities. Finally, the appendices describe the entries of the input files of OpenFAST to run the aeroacoustics analysis.

Future work will focus on the validation of the aeroacoustics models. In parallel, propagation models will be investigated and implemented. Finally, attention will be dedicated to infrasound noise and to the time-domain models that can simulate it.

4.5.7 Using the Aeroacoustics Model in AeroDyn

A live version of this documentation is available at https://openfast.readthedocs.io/. To run the aeroacoustics model, the flag CompAA needs to be set to True at line 13 of the AeroDyn15 main input file in the inputs block General Options. When the flag is set to True, the following line must include the name of the file containing the inputs to the aeroacoustics model, which is discussed in Section 4.5.7.

```
------ AERODYN v15.03.\* INPUT FILE -----------------------------------------------
IEA Wind Task 37 land-based reference wind turbine
====== General Options ===================================================
False Echo - Echo the input to "<rootname>.AD.ech"? (flag) 
"default" DT_AA - Time interval for aerodynamic calculations {or "default"}
\(\rightarrow\) (s)
1 WakeMod - Type of wake/induction model (switch) {0=none, 1=BEMT}
2 AFAeroMod - Type of blade airfoil aerodynamics model (switch)
0 TwrPotent - Type tower influence on wind around the tower (switch)
False TwrShadow - Calculate tower influence on wind (flag)
False TwrAero - Calculate tower aerodynamic loads? (flag)
False FrozenWake - Assume frozen wake during linearization? (flag)
False CavitCheck - Perform cavitation check? (flag)
True CompAA - Flag to compute AeroAcoustics calculation
"AeroAcousticsInput.dat" AA_InputFile
====== Environmental Conditions =========================================
1.225. AirDens - Air density (kg/m^3)
```

Main Input File

The aeroacoustics main input file comprises a series of inputs and flags that should be set appropriately depending on the analysis that should be run. These are split into the subfields General Options, Aeroacoustics Models, Observer Input, and Outputs.

Starting from the General Options, these are:

- **Echo** – True/False: option to rewrite the input file with the correct template
- **DT_AA** – Float: time step of the aeroacoustics computations. Only multiples of the time step DTAero of AeroDyn can be used. If set to default, the time step DTAero is adopted.
- **AAStart** – Float: time after which the AeroAcoustics module is run.
• **BldPrcnt** – Float: percentage value of blade span measured from blade tip that contributes to the noise emissions; 100% corresponds to the entire blade from tip to root.

The field **Aeroacoustics Models** lists all the flags for the actual noise models:

• **TIMod** – Integer 0/1/2: flag to set the turbulent inflow noise model; 0 turns it off, 1 corresponds to the Amiet model discussed in Section 4.5.4, and 2 corresponds to the Simplified Guidati model presented in Section 4.5.4.

• **TICalcMeth** – Integer 1/2: flag to set the calculation method for the incident turbulence intensity. When set to 1, incident turbulence intensity is defined in a user-defined grid; see Section 4.5.7. When set to 2, incident turbulence intensity is estimated from the time history of the incident flow.

• **TICalcTabFile** – String: name of the text file with the user-defined turbulence intensity grid; see Section 4.5.7.

• **Lturb** – Float: value of \( L_{turb} \) used to estimate the turbulent lengthscale used in the Amiet model.

• **TBLTEMod** – Integer 0/1/2: flag to set the TBL-TE noise model; 0 turns off the model, 1 uses the Brooks-Pope-Marcolini (BPM) airfoil noise model (see Section 4.5.4), and 2 uses the TNO model described in Section 4.5.4.

• **BLMod** – Integer 1/2: flag to set the calculation method for the boundary layer characteristics; 1 uses the simplified equations from the BPM model, 2 loads the files as described in Section 4.5.7. Only used if **TBLTEMod** is different than zero.

• **TripMod** – Integer 0/1/2: if BLMod is set to 1, different semiempirical parameters are used for a nontripped boundary layer (**TRipMod=0**), heavily tripped boundary layer (**TRipMod=1**), or lightly tripped boundary layer (**TRipMod=2**); 2 is typically used for operational wind turbines, whereas 1 is often used for wind tunnel airfoil models.

• **LamMod** – Integer 0/1: flag to activate the laminar boundary layer – vortex shedding model, presented in Section 4.5.4.

• **TipMod** – Integer 0/1: flag to activate the tip vortex model, presented in Section 4.5.4.

• **RoundedTip** – True/False: if TipMod=1, this flag switches between a round tip (True) and a square tip (False), see Section 4.5.4.

• **Alprat** – Float: value of the slope of the lift coefficient curve at blade tip; see Section 4.5.4.

• **BluntMod** – Integer 0/1: flag to activate (**BluntMod=1**) the trailing-edge bluntness – vortex shedding model, see Section 4.5.4. If the flag is set to 1, the trailing-edge geometry must be specified in the files as described in Section 4.5.7.

The field **Observer Locations** contains the path to the file where the number of observers (NrObsLoc) and the respective locations are specified; see Section 4.5.7.

Finally, the set **Outputs** contains a few options for the output data:

• **AWeighting** – True/False: flag to set whether the sound pressure levels are reported with (True) or without (False) the A-weighting correction; see Section 4.5.5.

• **NAAOutFile** – Integer 1/2/3: flag to set the desired output file. When set to 1, a value of overall sound pressure level at every DT\_AA time step per observer is printed to file. When set to 2, the first output is accompanied by a second file where the total sound pressure level spectrum is printed per time step per observer. When set to 3, the two first outputs are accompanied by a third file where the sound pressure level spectrum per noise mechanism is printed per time step per observer. When set to 4, a fourth file is generated with the values of overall sound pressure levels per node, per blade, per observer, and per time step.

• The following line contains the file name used to store the outputs. The file name is attached with a 1, 2, 3, and 4 flag based on the **NAAOutFile** options.

The file must be closed by an END command.

---

**4.5. Aeroacoustics Noise Model of OpenFAST**

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--- AeroAcoustics Module v1.00.* INPUT FILE -------------------------------

IEA task 37 RWT turbine -- https://github.com/IEAWindTask37/IEA-3.4-130-RWT

====== General Options

---

False  Echo - Echo the input to "<rootname>.AD.ech"? (flag)
0.1  DT_AA - Time interval for aeroacoustics calculations (s), must be a multiple of DT_Aero from AeroDyn15 (or "default")
0  AAStart - Time after which the AeroAcoustics module is run (s)
70  BldPrcnt - Percentage of the blade span, starting from the tip, that will contribute to the overall noise levels. (float)

====== Aeroacoustic Models

---

2  TIMod - Turbulent Inflow noise model {0: none, 1: Amiet 2: Amiet + Simplified Guidati} (switch)
1  TICalcMeth - Method to estimate turbulence intensity incident to the profile {1: given table, 2: computed on the fly} (switch) [Only used if TIMod!=0]
"TIgrid_InVerify.txt"  TICalcTabFile - Name of the file containing the table for incident turbulence intensity (-) [Only used if TICalcMeth == 1]
0.5  SurfRoughness- Surface roughness value used to estimate the turbulent length scale in Amiet model (m)
1  TBLTEMod - Turbulent Boundary Layer-Trailing Edge noise calculation {0: none, 1:BPM, 2: TNO} (switch)
1  BLMod - Calculation method for boundary layer properties, {1:BPM, 2: Pretabulated} (switch)
1  TripMod - Boundary layer trip model {0:no trip, 1: heavy trip, 2: light trip} (switch) [Only used if BLMod=1]
0  LamMod - Laminar boundary layer noise model {0:none, 1: BPM} (switch)
0  TipMod - Tip vortex noise model {0:none, 1: BPM} (switch)
1.0  Alprat - Tip lift curve slope (Default = 1.0) [Only used if TipMod=1]
0  BluntMod - Trailing-edge-bluntness - Vortex-shedding model {0:none, 1:BPM} (switch)
"AABlade1.dat"  AABlFile(1) - Name of file containing distributed aerodynamic properties for Blade #1 (-)
"AABlade1.dat"  AABlFile(2) - Name of file containing distributed aerodynamic properties for Blade #2 (-)
"AABlade1.dat"  AABlFile(3) - Name of file containing distributed aerodynamic properties for Blade #3 (-)

====== Observer Input

---

"AA_ObserverLocations.dat"  ObserverLocations - Name of file containing all observer locations X Y Z (-)

====== Outputs

---

False  AWeighting - A-weighting Flag (flag)
3  NrOutFile - Number of Output files. 1 for Time Dependent Overall SPL, 2 for both 1 and Frequency and Time Dependent SPL as well, or 3 for both 1 and Acoustics mechanism dependent, 4 for 1-3 and the overall sound pressure levels per blade per node per observer
"IEA_LB_RWT-AeroAcoustics_"  AAOutFile - No Extension needed the resulting file will have .out Name of file containing END of input file (the word "END" must appear in the first 3 columns of this last OutList line)
Boundary Layer Inputs and Trailing Edge Geometry

When the flag BLMod is set equal to 2, pretabulated properties of the boundary layer must be provided and are used by the turbulent boundary layer–trailing-edge noise models. The file name is to be specified in the field BL_file among the inputs of the file with the airfoil polar coefficients. One airfoil file must be specified per aerodynamic station.

The file, in this example named AF20_BL.txt, contains 8 inputs, which are tabulated for a given number of Reynolds numbers, ReListBL, and a given number of angles of attack, aoaListBL. The inputs, which are defined nondimensionally and must be provided for the suction and pressure side of the airfoil above and below the trailing edge, are:

- $Ue_{Vinf}$ – flow velocity at the top of the boundary layer
- $Dstar$ – $\delta^*$, boundary layer displacement thickness
- $Delta$ – $\delta$, nominal boundary layer thickness
- $Cf$ – friction coefficient.

In the following example, the file was generated thanks to a Python script that runs the boundary layer solver, XFoil. Notably, XFoil, by default, does not return $\delta$, but the boundary layer momentum thickness, $\theta$. $\delta$ can be reconstructed using the expression from [aa-DG87]:

$$\delta = \theta \bullet \left( 3.15 + \frac{1.72}{H - 1} \right) + \delta^*$$

(4.57)

where $H$ is the kinematic shape factor, which is also among the standard outputs of XFoil. Because it is usually impossible to obtain these values for the whole ranges of Reynolds numbers and angles of attack, the code is set to adopt the last available values and print to screen a warning.

When the flag BluntMod is set to 1, the detailed geometry of the trailing edge must also be defined along the span. Two inputs must be provided, namely the angle, $\Psi$ between the suction and pressure sides of the profile, right before the trailing-edge point, and the height, $h$, of the trailing edge. $\Psi$ must be defined in degrees, while $h$ is in meters. Note that the BPM trailing-edge bluntness model is very sensitive to these two parameters, which, however, are often not easy to determine for real blades. Fig. 4.20 shows the two inputs.

---

4 https://github.com/OpenFAST/python-toolbox
One value of $\Psi$ and one value of $h$ per file must be defined. These values are not used if the flag **BluntMod** is set to 0.

```
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### 4.5. Aeroacoustics Noise Model of OpenFAST

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4.5. Aeroacoustics Noise Model of OpenFAST
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Observer Positions

The number and position of observers is set in the file ObserverLocations, which is explained in Section 4.5.7. The positions must be specified in the OpenFAST global inertial frame coordinate system, which is located at the tower base and has the x-axis pointing downwind, the y-axis pointing laterally, and the z-axis pointing vertically upward. A scheme of the coordinate system for the observers is shown in Fig. 4.21.

Fig. 4.21: Reference system for the observers

The International Energy Agency Wind Task 37 land-based reference wind turbine, which is shown in Table 4.5, has a hub height of 110 meters and a rotor radius of 65 meters, and has the International Electrotechnical Commission 61400-11 standards compliant observer located at:

\[
\begin{align*}
    x &= 175 \text{ [m]} \\
    y &= 0 \text{ [m]} \\
    z &= 0 \text{ [m]}
\end{align*}
\]

An example of a file listing four observers located at a 2-meter height is shown here:
Turbulence Grid

When the flag `TICalcMeth` is set equal to 1, the grid of turbulence intensity of the wind $T_I$ must be defined by the user. This is done by creating a file called `TIGrid_In.txt`, which mimics a TurbSim output file and contains a grid of turbulence intensity, which is defined as a fraction value. The file defines a grid centered at hub height and oriented with the OpenFAST global inertial frame coordinate system; see Fig. 4.21. A user-defined number of lateral and vertical points equally spaced by a user-defined number of meters must be specified. Note that an average wind speed must be defined to convert the turbulence intensity of the wind to the incident turbulent intensity $I_1$. An example file for a 160 (lateral) by 180 (vertical) meters grid looks like the following:

```
Average Inflow Wind Speed
8.0
Total Grid points In Y (lateral), Starts from - radius goes to + radius+
4
Total Grid points In Z (vertical), Starts from bottom tip (hub-radius)
3
Grid spacing In Y (lateral)
40
Grid spacing In Z (vertical)
60
0.1200 0.1200 0.1200 0.1200
0.1100 0.1100 0.1100 0.1100
0.1000 0.1000 0.1000 0.1000
```
anisotropic composite material couplings (using full $6 \times 6$ mass and stiffness matrices, including bend-twist coupling); and a reference axis that permits blades that are not straight (supporting built-in curve, sweep, and sectional offsets). The GEBT beam equations are discretized in space with Legendre spectral finite elements (LSFEs). LSFEs are $p$-type elements that combine the accuracy of global spectral methods with the geometric modeling flexibility of the $h$-type finite elements (FEs) [Pat84]. For smooth solutions, LSFEs have exponential convergence rates compared to low-order elements that have algebraic convergence [SG03][WS13]. Two spatial numerical integration schemes are implemented for the finite element inner products: reduced Gauss quadrature and trapezoidal-rule integration. Trapezoidal-rule integration is appropriate when a large number of sectional properties are specified along the beam axis, for example, in a long wind turbine blade with material properties that vary dramatically over the length. Time integration of the BeamDyn equations of motion is achieved through the implicit generalized-$\alpha$ solver, with user-specified numerical damping. The combined GEBT-LSFE approach permits users to model a long, flexible, composite wind turbine blade with a single high-order element. Given the theoretical foundation and powerful numerical tools introduced above, BeamDyn can solve the complicated nonlinear composite beam problem in an efficient manner. For example, it was recently shown that a grid-independent dynamic solution of a 50-m composite wind turbine blade and with dozens of cross-section stations could be achieved with a single $7^\text{th}$-order LSFE [WSJJ16].

When coupled with FAST, loads and responses are transferred between BeamDyn, ElastoDyn, ServoDyn, and AeroDyn via the FAST driver program (glue code) to enable aero-elasto-servo interaction at each coupling time step. There is a separate instance of BeamDyn for each blade. At the root node, the inputs to BeamDyn are the six displacements (three translations and three rotations), six velocities, and six accelerations; the root node outputs from BeamDyn are the six reaction loads (three translational forces and three moments). BeamDyn also outputs the blade displacements, velocities, and accelerations along the beam length, which are used by AeroDyn to calculate the local aerodynamic loads (distributed along the length) that are used as inputs for BeamDyn. In addition, BeamDyn can calculate member internal reaction loads, as requested by the user. Please refer to Figure [fig:FlowChart] for the coupled interactions between BeamDyn and other modules in FAST. When coupled to FAST, BeamDyn replaces the more simplified blade structural model of ElastoDyn that is still available as an option, but is only applicable to straight isotropic blades dominated by bending. When uncoupled from FAST, the root motion (boundary condition) and applied loads are specified via a stand-alone BeamDyn driver code.

The BeamDyn input file defines the blade geometry; cross-sectional material mass, stiffness, and damping properties; FE resolution; and other simulation- and output-control parameters. The blade geometry is defined through a curvilinear blade reference axis by a series of key points in three-dimensional (3D) space along with the initial twist angles at these points. Each member contains at least three key points for the cubic spline fit implemented in BeamDyn; each member is discretized with a single LSFE with a parameter defining the order of the element. Note that the number of key points defining the member and the order ($N$) of the LSFE are independent. LSFE nodes, which are located at the $N + 1$ Gauss-Legendre-Lobatto points, are not evenly spaced along the element; node locations are generated by the module based on the mesh information. Blade properties are specified in a non-dimensional coordinate ranging from 0.0 to 1.0 along the blade reference axis and are linearly interpolated between two stations if needed by the spatial integration method. The BeamDyn applied loads can be either distributed loads specified at quadrature points, concentrated loads specified at FE nodes, or a combination of the two. When BeamDyn is coupled to FAST, the blade analysis node discretization may be independent between BeamDyn and AeroDyn.

This document is organized as follows. Section Running BeamDyn details how to obtain the BeamDyn and FAST software archives and run either the stand-alone version of BeamDyn or BeamDyn coupled to FAST. Section Input Files describes the BeamDyn input files. Section Output Files discusses the output files generated by BeamDyn. Section BeamDyn Theory summarizes the BeamDyn theory. Section Future Work outlines potential future work. Example input files are shown in Appendix Section 4.6.7. A summary of available output channels is found in Appendix BeamDyn List of Output Channels.
Fig. 4.22: Coupled interaction between BeamDyn and FAST
4.6.2 Running BeamDyn

This section discusses how to obtain and execute BeamDyn from a personal computer. Both the stand-alone version and the FAST-coupled version of the software are considered.

Downloading the BeamDyn Software

There are two forms of the BeamDyn software to choose from: stand-alone and coupled to the FAST simulator. Although the user may not necessarily need both forms, he/she would likely need to be familiar with and run the stand-alone model if building a model of the blade from scratch. The stand-alone version is also helpful for model troubleshooting, even if the goal is to conduct aero-hydro-servo-elastic simulations of onshore/offshore wind turbines within FAST.

Stand-Alone BeamDyn Archive

Users can download the stand-alone BeamDyn archive from our Web server at https://nwtc.nrel.gov/BeamDyn. The file has a name similar to BD_v1.00.00a.exe, but may have a different version number. The user can then download the self-extracting archive (.exe) to expand the archive into a folder he/she specifies.

The archive contains the bin, CertTest, Compiling, Docs, and Source folders. The bin folder includes the main executable file, BeamDyn_Driver.exe, which is used to execute the stand-alone BeamDyn program. The CertTest folder contains a collection of sample BeamDyn input files and driver input files that can be used as templates for the user’s own models. This document may be found in the Docs folder. The Compiling folder contains files for compiling the stand-alone BeamDyn_v1.00.00.exe file with either Visual Studio or gFortran. The Fortran source code is located in the Source folder.

FAST Archive

Download the FAST archive, which includes BeamDyn, from our Web server at https://nwtc.nrel.gov/FAST8. The file has a name similar to FAST_v8.12.00.exe, but may have a different version number. Run the downloaded self-extracting archive (.exe) to expand the archive into a user-specified folder. The FAST executable file is located in the archive’s bin folder. An example model using the NREL 5-MW reference turbine is located in the CertTest folder.

Running BeamDyn

Running the Stand-Alone BeamDyn Program

The stand-alone BeamDyn program, BeamDyn_Driver.exe, simulates static and dynamic responses of the user’s input model, without coupling to FAST. Unlike the coupled version, the stand-alone software requires the use of a driver file in addition to the primary and blade BeamDyn input files. This driver file specifies inputs normally provided to BeamDyn by FAST, including motions of the blade root and externally applied loads. Both the BeamDyn summary file and the results output file are available when using the stand-alone BeamDyn (see Section Output Files for more information regarding the BeamDyn output files).

Run the stand-alone BeamDyn software from a DOS command prompt by typing, for example:

```plaintext
>BeamDyn_Driver.exe Dvr_5MW_Dynamic.inp
```

where, Dvr_5MW_Dynamic.inp is the name of the BeamDyn driver input file, as described in Section BeamDyn Driver Input File.
Running BeamDyn Coupled to FAST

Run the coupled FAST software from a DOS command prompt by typing, for example:

```bash
>FAST_Win32.exe Test26.fst
```

where `Test26.fst` is the name of the primary FAST input file. This input file has a feature switch to enable or disable the BeamDyn capabilities within FAST, and a corresponding reference to the BeamDyn input file. See the documentation supplied with FAST for further information.

4.6.3 Input Files

Users specify the blade model parameters; including its geometry, cross-sectional properties, and FE and output control parameters; via a primary BeamDyn input file and a blade property input file. When used in stand-alone mode, an additional driver input file is required. This driver file specifies inputs normally provided to BeamDyn by FAST, including simulation range, root motions, and externally applied loads.

No lines should be added or removed from the input files, except in tables where the number of rows is specified.

Units

BeamDyn uses the SI system (kg, m, s, N). Angles are assumed to be in radians unless otherwise specified.

BeamDyn Driver Input File

The driver input file is needed only for the stand-alone version of BeamDyn. It contains inputs that are normally set by FAST and that are necessary to control the simulation for uncoupled models.

The driver input file begins with two lines of header information, which is for the user but is not used by the software. If BeamDyn is run in the stand-alone mode, the results output file will be prefixed with the same name of this driver input file.

A sample BeamDyn driver input file is given in Section 4.6.7.

Simulation Control Parameters

`DynamicSolve` is a logical variable that specifies if BeamDyn should use dynamic analysis (`DynamicSolve = true`) or static analysis (`DynamicSolve = false`). `t_initial` and `t_final` specify the starting time of the simulation and ending time of the simulation, respectively. `dt` specifies the time step size.

Gravity Parameters

`Gx`, `Gy`, and `Gz` specify the components of gravity vector along `X`, `Y`, and `Z` directions in the global coordinate system, respectively. In FAST, this is normally 0, 0, and -9.80665.
Inertial Frame Parameters

This section defines the relation between two inertial frames, the global coordinate system and initial blade reference coordinate system. GlbPos(1), GlbPos(2), and GlbPos(3) specify three components of the initial global position vector along X, Y, and Z directions resolved in the global coordinate system, see Figure Fig. 4.23. And the following $3 \times 3$ direction cosine matrix (GlbDCM) relates the rotations from the global coordinate system to the initial blade reference coordinate system.

![Floating blade reference frame at instant t](image)

Fig. 4.23: Global and blade coordinate systems in BeamDyn.

Blade Floating Reference Frame Parameters

This section specifies the parameters that define the blade floating reference frame, which is a body-attached floating frame; the blade root is cantilevered at the origin of this frame. Based on the driver input file, the floating blade reference frame is assumed to be in a constant rigid-body rotation mode about the origin of the global coordinate system, that is,

$$v_{rt} = \omega_r \times r_t$$  \hspace{1cm} (4.58)

where $v_{rt}$ is the root (origin of the floating blade reference frame) translational velocity vector; $\omega_r$ is the constant root (origin of the floating blade reference frame) angular velocity vector; and $r_t$ is the global position vector introduced in the previous section at instant $t$, see Fig. 4.23. The floating blade reference frame coincides with the initial floating blade reference frame at the beginning $t = 0$. RootVel(4), RootVel(5), and RootVel(6) specify the three components of the constant root angular velocity vector about X, Y, and Z axises in global coordinate system, respectively. RootVel(1), RootVel(2), and RootVel(3), which are the three components of the root translational velocity vector along X, Y, and Z directions in global coordinate system, respectively, are calculated based on Eq. (4.58).

BeamDyn can handle more complicated root motions by changing, for example, the BD_InputSolve subroutine in the Driver_Beam.f90 (requiring a recompile of stand-alone BeamDyn).
The blade is initialized in the rigid-body motion mode, i.e., based on the root velocity information defined in this section and the position information defined in the previous section, the motion of other points along the blade are initialized as

\[
\begin{align*}
\mathbf{a}_0 &= \omega_r \times (\omega_r \times (\mathbf{r}_0 + \mathbf{P})) \\
\mathbf{v}_0 &= \mathbf{v}_r + \omega_r \times \mathbf{P} \\
\omega_0 &= \omega_r
\end{align*}
\]

where \( \mathbf{a}_0 \) is the initial translational acceleration vector along the blade; \( \mathbf{v}_0 \) and \( \omega_0 \) the initial translational and angular velocity vectors along the blade, respectively; and \( \mathbf{P} \) is the position vector along the blade relative to the root. Note that these equations are actually implemented with a call to the NWTC Library’s mesh mapping routines.

**Applied Load**

This section defines the applied loads, including distributed, point (lumped), and tip-concentrated loads, for the stand-alone analysis.

The first six entries \( \text{DistrLoad}(i), i \in [1,6], \) specify three components of uniformly distributed force vector and three components of uniformly distributed moment vector in the global coordinate systems, respectively.

The following six entries \( \text{TipLoad}(i), i \in [1,6], \) specify three components of concentrated tip force vector and three components of concentrated tip moment vector in the global coordinate system, respectively.

\( \text{NumPointLoads} \) defines how many point loads along the blade will be applied. The table following this input contains two header lines with seven columns and \( \text{NumPointLoads} \) rows. The first column is the non-dimensional distance along the local blade reference axis, ranging from \([0.0, 1.0]\). The next three columns, \( F_x, F_y, \) and \( F_z \) specify three components of point-force vector. The remaining three columns, \( M_x, M_y, \) and \( M_z \) specify three components of a moment vector.

The distributed load defined in this section is assumed to be uniform along the blade and constant throughout the simulation. The tip load is a constant concentrated load applied at the tip of a blade.

It is noted that all the loads defined in this section are dead loads, i.e., they are not rotating with the blade following the rigid-body rotation defined in the previous section.

BeamDyn is capable of handling more complex loading cases, e.g., time-dependent loads, through customization of the source code (requiring a recompile of stand-alone BeamDyn). The user can define such loads in the \text{BD\_InputSolve} subroutine in the \text{Driver\_Beam.f90} file, which is called every time step. The following section can be modified to define the concentrated load at each FE node:

\[
\begin{align*}
\text{u\%PointLoad\%Force}(1:3,:,:) &= \text{u\%PointLoad\%Force}(1:3,:,:) + \text{DvrData\%TipLoad}(1:3) \\
\text{u\%PointLoad\%Moment}(1:3,:,:) &= \text{u\%PointLoad\%Moment}(1:3,:,:) + \text{DvrData\%TipLoad}(4:6)
\end{align*}
\]

where the first index in each array ranges from 1 to 3 for load vector components along three global directions and the second index of each array ranges from 1 to \( \text{u\%PointLoad\%NNodes} \), where the latter is the total number of FE nodes. Note that \( \text{u\%PointLoad\%Force}(1:3,:) \) and \( \text{u\%PointLoad\%Moment}(1:3,:) \) have been populated with the point-load loads read from the BeamDyn driver input file using the call to \text{Transfer\_Point\_to\_Point} earlier in the subroutine.

For example, a time-dependent sinusoidal force acting along the \( X \) direction applied at the \( 2^{nd} \) FE node can be defined as

\[
\begin{align*}
\text{u\%PointLoad\%Force}(1,2,:) &= 1.00D+03 \times \text{SIN}((2.0 \times \pi) \times t / 6.0) \\
\text{u\%PointLoad\%Moment}(1,:) &= 0.00D
\end{align*}
\]
with $1.0 \times 10^3$ being the amplitude and 6.0 being the period. Note that this particular implementation overrides the tip-load and point-loads defined in the driver input file.

Similar to the concentrated load, the distributed loads can be defined in the same subroutine

```fortran
DO i=1,u%DistrLoad%NNodes
   u%DistrLoad%Force(1:3,i) = DvrData%DistrLoad(1:3)
   u%DistrLoad%Moment(1:3,i)= DvrData%DistrLoad(4:6)
ENDDO
```

where $u%DistrLoad%NNodes$ is the number of nodes input to BeamDyn (on the quadrature points), and $DvrData%DistrLoad(:)$ is the constant uniformly distributed load BeamDyn reads from the driver input file. The user can modify $DvrData%DistrLoad(:)$ to define the loads based on need.

We note that the distributed loads are defined at the quadrature points for numerical integrations. For example, if Gauss quadrature is chosen, then the distributed loads are defined at Gauss points plus the two end points of the beam (root and tip). For trapezoidal quadrature, $p%ngp$ stores the number of trapezoidal quadrature points.

**Primary Input File**

*InputFile* is the file name of the primary BeamDyn input file. This name should be in quotations and can contain an absolute path or a relative path.

**BeamDyn Primary Input File**

The BeamDyn primary input file defines the blade geometry, LSFE-discretization and simulation options, output channels, and name of the blade input file. The geometry of the blade is defined by key-point coordinates and initial twist angles (in units of degree) in the blade local coordinate system (IEC standard blade system where $Z_r$ is along blade axis from root to tip, $X_r$ directs normally toward the suction side, and $Y_r$ directs normally toward the trailing edge).

The file is organized into several functional sections. Each section corresponds to an aspect of the BeamDyn model. A sample BeamDyn primary input file is given in Section 4.6.7.

The primary input file begins with two lines of header information, which are for the user but are not used by the software.

**Simulation Controls**

The user can set the *Echo* flag to TRUE to have BeamDyn echo the contents of the BeamDyn input file (useful for debugging errors in the input file).

The *QuasiStaticInit* flag indicates if BeamDyn should perform a quasi-static solution at initialization to better initialize its states. In general, this should be set to true for better numerical performance (it reduces startup transients).

*rhoinf* specifies the numerical damping parameter (spectral radius of the amplification matrix) in the range of $[0.0, 1.0]$ used in the generalized-$\alpha$ time integrator implemented in BeamDyn for dynamic analysis. For $rhoinf = 1.0$, no numerical damping is introduced and the generalized-$\alpha$ scheme is identical to the Newmark scheme; for $rhoinf = 0.0$, maximum numerical damping is introduced. Numerical damping may help produce numerically stable solutions.

*Quadrature* specifies the spatial numerical integration scheme. There are two options: 1) Gauss quadrature; and 2) Trapezoidal quadrature. We note that in the current version, Gauss quadrature is implemented in reduced form to improve efficiency and avoid shear locking. In the trapezoidal quadrature, only one member (FE element) can be
defined in the following GEOMETRY section of the primary input file. Trapezoidal quadrature is appropriate when the number of “blade input stations” (described below) is significantly greater than the order of the LSFE.

**Refine** specifies a refinement parameter used in trapezoidal quadrature. An integer value greater than unity will split the space between two input stations into “Refine factor” of segments. The keyword “DEFAULT” may be used to set it to 1, i.e., no refinement is needed. This entry is not used in Gauss quadrature.

**N_Fact** specifies a parameter used in the modified Newton-Raphson scheme. If N_Fact = 1 a full Newton iteration scheme is used, i.e., the global tangent stiffness matrix is computed and factorized at each iteration; if N_Fact > 1 a modified Newton iteration scheme is used, i.e., the global stiffness matrix is computed and factorized every N_Fact iterations within each time step. The keyword “DEFAULT” sets N_Fact = 5.

**DTBeam** specifies the constant time increment of the time-integration in seconds. The keyword “DEFAULT” may be used to indicate that the module should employ the time increment prescribed by the driver code (FAST/stand-alone driver program).

**load_retries** specifies the maximum number of load retries allowed. This option currently works only for static analysis. For every load retry, the applied load is halved to promote convergence of the Newton-Raphson scheme in iteration of smaller load steps as opposed to one single large load step which may cause divergence of the Newton-Raphson scheme. The keyword “DEFAULT” sets load_retries = 20.

**NRMax** specifies the maximum number of iterations per time step in the Newton-Raphson scheme. If convergence is not reached within this number of iterations, BeamDyn returns an error message and terminates the simulation. The keyword “DEFAULT” sets NRMax = 10.

**Stop_Tol** specifies a tolerance parameter used in convergence criteria of a nonlinear solution that is used for the termination of the iteration. The keyword “DEFAULT” sets Stop_Tol = 1.0E-05. Please refer to Section 4.6.5 for more details.

**tntgt_stf_fd** is a boolean that sets the flag to compute the tangent stiffness matrix using finite differencing instead of analytical differentiation. The finite differencing is performed using a central scheme. The keyword “DEFAULT” sets tngt_stf_fd = FALSE.

**tntgt_stf_comp** is a boolean that sets the flag to compare the analytical tangent stiffness matrix against the finite differenced tangent stiffness matrix. Information is written to the terminal regarding the dol where the maximum difference is observed. If tngt_stf_fd = FALSE and tngt_stf_comp = TRUE, the analytical tangent stiffness matrix is used to solve the system of equations while the finite difference tangent stiffness matrix is used only to perform the comparison of the two matrices. The keyword “DEFAULT” sets tngt_stf_comp = FALSE.

**tntgt_stf_pert** sets the perturbation size for finite differencing. The “DEFAULT” value based on experience is set to 1e-06.

**tntgt_stf_diff_tol** is the maximum allowable relative difference between the analytical and finite differenced tangent stiffness matrices. If for any entry in the matrices, the relative difference exceeds this value the simulation will terminate. The “DEFAULT” value is currently set to 1e-01.

**RotStates** is a flag that indicates if BeamDyn’s continuous states should be oriented in the rotating frame during linearization analysis when coupled to OpenFAST. If multi-blade coordinate (MBC3) analysis is performed, RotStates must be true.
**Geometry Parameter**

The blade geometry is defined by a curvilinear local blade reference axis. The blade reference axis locates the origin and orientation of each a local coordinate system where the cross-sectional 6x6 stiffness and mass matrices are defined in the BeamDyn blade input file. It should not really matter where in the cross section the 6x6 stiffness and mass matrices are defined relative to, as long as the reference axis is consistently defined and closely follows the natural geometry of the blade.

The blade beam model is composed of several *members* in contiguous series and each member is defined by at least three key points in BeamDyn. A cubic-spline-fit pre-processor implemented in BeamDyn automatically generates the member based on the key points and then interconnects the members into a blade. There is always a shared key point at adjacent members; therefore the total number of key points is related to number of members and key points in each member.

*member_total* specifies the total number of beam members used in the structure. With the LSFE discretization, a single member and a sufficiently high element order, *order_elem* below, may well be sufficient.

*kp_total* specifies the total number of key points used to define the beam members.

The following section contains *member_total* lines. Each line has two integers providing the member number (must be 1, 2, 3, etc., sequentially) and the number of key points in this member, respectively. It is noted that the number of key points in each member is not independent of the total number of key points and they should satisfy the following equality:

$$\sum_{i=1}^{member\_total} n_i - member\_total + 1 = kp\_total$$

(4.60)

where \(n_i\) is the number of key points in the \(i^{th}\) member. Because cubic splines are implemented in BeamDyn, \(n_i\) must be greater than or equal to three. Figures Fig. 4.24 and Fig. 4.25 show two cases for member and key-point definition.

![Key point](image)

**Fig. 4.24:** Member and key point definition: one member defined by four key points;

1  Member_Total  - Total number of member (-)
4  KP_Total      - Total number of key point (-)
1  4

The next section defines the key-point information, preceded by two header lines. Each key point is defined by three physical coordinates (kp_xr, kp_yr, kp_zr) in the IEC standard blade coordinate system (the blade reference coordinate system) along with a structural twist angle (*initial_twist*) in the unit of degrees. The structural twist angle is also following the IEC standard which is defined as the twist about the negative \(Z_l\) axis. The key points are entered sequentially (from the root to tip) and there should be a total of *kp_total* lines for BeamDyn to read in the information, after two header lines. Please refer to Figure Fig. 4.26 for more details on the blade geometry definition.
Fig. 4.25: Member and key point definition: two members defined by six key points.

Fig. 4.26: BeamDyn Blade Geometry - Top: Side View; Middle: Front View (Looking Downwind); Bottom: Cross Section View (Looking Toward the Tip, from the Root)
Mesh Parameter

Order_Elem specifies the order of shape functions for each finite element. Each LSFE will have Order_Elem+1 nodes located at the GLL quadrature points. All LSFEs will have the same order. With the LSFE discretization, an increase in accuracy will, in general, be better achieved by increasing Order_Elem (i.e., p-refinement) rather than increasing the number of members (i.e., h-refinement). For Gauss quadrature, Order_Elem should be greater than one.

Material Parameter

BldFile is the file name of the blade input file. This name should be in quotations and can contain an absolute path or a relative path.

Pitch Actuator Parameter

In this release, the pitch actuator implemented in BeamDyn is not available. The UsePitchAct should be set to “FALSE” in this version, whereby the input blade-pitch angle prescribed by the driver code is used to orient the blade directly. PitchJ, PitchK, and PitchC specify the pitch actuator inertial, stiffness, and damping coefficient, respectively. In future releases, specifying UsePitchAct = TRUE will enable a second-order pitch actuator, whereby the pitch angular orientation, velocity, and acceleration are determined by the actuator based on the input blade-pitch angle prescribed by the driver code.

Outputs

In this section of the primary input file, the user sets flags and switches for the desired output behavior. Specifying SumPrint = TRUE causes BeamDyn to generate a summary file with name InputFile.sum. See Section 4.6.4 for summary file details.

OutFmt parameter controls the formatting of the results within the stand-alone BeamDyn output file. It needs to be a valid Fortran format string, but BeamDyn currently does not check the validity. This input is unused when BeamDyn is used coupled to FAST.

NNodeOuts specifies the number of nodes where output can be written to a file. Currently, BeamDyn can output quantities at a maximum of nine nodes.

OutNd is a list NNodeOuts long of node numbers between 1 and the number of nodes on the output mesh, separated by any combination of commas, semicolons, spaces, and/or tabs. The nodal positions are given in the summary file, if output. For Gaussian quadrature, the number of nodes on the output mesh is the total number of FE nodes; for trapezoidal quadrature, this is the number of quadrature nodes.

The OutList block contains a list of output parameters. Enter one or more lines containing quoted strings that in turn contain one or more output parameter names. Separate output parameter names by any combination of commas, semicolons, spaces, and/or tabs. If you prefix a parameter name with a minus sign, “-”, underscores, “_”, or the characters “m” or “M”, BeamDyn will multiply the value for that channel by -1 before writing the data. The parameters are written in the order they are listed in the input file. BeamDyn allows you to use multiple lines so that you can break your list into meaningful groups and so the lines can be shorter. You may enter comments after the closing quote on any of the lines. Entering a line with the string “END” at the beginning of the line or at the beginning of a quoted string found at the beginning of the line will cause BeamDyn to quit scanning for more lines of channel names. Node-related quantities are generated for the requested nodes identified through the OutNd list above. If BeamDyn encounters an unknown/invalid channel name, it warns the users but will remove the suspect channel from the output file. Please refer to Appendix Section 4.6.7 for a complete list of possible output parameters and their names.
Nodal Outputs

In addition to the named outputs in Section 4.6.3 above, BeamDyn allows for outputting the full set blade node motions and loads (tower nodes unavailable at present). Please refer to the BeamDyn_Nodes tab in the Excel file OutListParameters.xlsx for a complete list of possible output parameters.

This section follows the END statement from normal Outputs section described above, and includes a separator description line followed by the following options.

BldNd_BIOutNd specifies which nodes to output. This is currently unused.

The OutList section controls the nodal output quantities generated by BeamDyn. In this section, the user specifies the name of the channel family to output. The output name for each channel is then created internally by BeamDyn by combining the blade number, node number, and channel family name. For example, if the user specifies TDxr as the channel family name, the output channels will be named with the convention of B/βN###TDxr where β is the blade number, and ### is the three digit node number.

Sample Nodal Outputs section

This sample includes the END statement from the regular outputs section.

```plaintext
END of input file (the word "END" must appear in the first 3 columns of this last OutList line)

--- NODE OUTPUTS -------------------------------------------
99 BldNd_BIOutNd - Blade nodes on each blade (currently unused)
OutList - The next line(s) contains a list of output parameters. (-)
See OutListParameters.xlsx, BeamDyn_Nodes tab for a listing of available output channels, (-)

"FxL" - Sectional force resultants at each node expressed in l (N)
--coordinate system local to the deflected beam (N)
"FyL" - Sectional force resultants at each node expressed in l (N)
--coordinate system local to the deflected beam (N)
"FzL" - Sectional force resultants at each node expressed in l (N)
--coordinate system local to the deflected beam (N)
"MxL" - Sectional moment resultants at each node expressed in l (N-m)
--floating coordinate system local to the deflected beam (N-m)
"MyL" - Sectional moment resultants at each node expressed in l (N-m)
--floating coordinate system local to the deflected beam (N-m)
"MzL" - Sectional moment resultants at each node expressed in l (N-m)
--floating coordinate system local to the deflected beam (N-m)
"Fxr" - Sectional force resultants at each node expressed in r (N)
--reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (N)
"Fyr" - Sectional force resultants at each node expressed in r (N)
--reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (N)
"Fzr" - Sectional force resultants at each node expressed in r (N)
--reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (N)
"Mxr" - Sectional moment resultants at each node expressed in r (N-m)
--floating reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (N-m)
"Myr" - Sectional moment resultants at each node expressed in r (N-m)
--floating reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (N-m)
```

(continues on next page)
"Mzr" - Sectional moment resultants at each node expressed in r: a floating reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (N-m)

"TDxr" - Sectional translational deflection (relative to the undeflected position) at each node expressed in r: a floating reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (m)

"TDyr" - Sectional translational deflection (relative to the undeflected position) at each node expressed in r: a floating reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (m)

"TDzr" - Sectional translational deflection (relative to the undeflected position) at each node expressed in r: a floating reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (m)

"RDxr" - Sectional angular/rotational deflection Wiener-Milenkovic parameter (relative to the undeflected orientation) at each node expressed in r: a floating reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (-)

"RDyr" - Sectional angular/rotational deflection Wiener-Milenkovic parameter (relative to the undeflected orientation) at each node expressed in r: a floating reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (-)

"RDzr" - Sectional angular/rotational deflection Wiener-Milenkovic parameter (relative to the undeflected orientation) at each node expressed in r: a floating reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (-)

"AbsXg" - Node position in X (global coordinate) g: the global inertial frame coordinate system; when coupled to FAST, this is equivalent to FAST’s global inertial frame (i) coordinate system (m)

"AbsYg" - Node position in Y (global coordinate) g: the global inertial frame coordinate system; when coupled to FAST, this is equivalent to FAST’s global inertial frame (i) coordinate system (m)

"AbsZg" - Node position in Z (global coordinate) g: the global inertial frame coordinate system; when coupled to FAST, this is equivalent to FAST’s global inertial frame (i) coordinate system (m)

"AbsXr" - Node position in X (relative to root) r: a floating reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (m)

"AbsYr" - Node position in Y (relative to root) r: a floating reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (m)

"AbsZr" - Node position in Z (relative to root) r: a floating reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (m)

"TVxg" - Sectional translational velocities (absolute) g: the global inertial frame coordinate system; when coupled to FAST, this is equivalent to FAST’s global inertial frame (i) coordinate system (m/s)

"TVyg" - Sectional translational velocities (absolute) g: the global inertial frame coordinate system; when coupled to FAST, this is equivalent to FAST’s global inertial frame (i) coordinate system (m/s)

"TVzg" - Sectional translational velocities (absolute) g: the global inertial frame coordinate system; when coupled to FAST, this is equivalent to FAST’s global inertial frame (i) coordinate system (m/s)
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TVx1l</td>
<td>Sectional translational velocities (absolute) l: a floating coordinate system local to the deflected beam (m/s)</td>
</tr>
<tr>
<td>TVy1l</td>
<td>Sectional translational velocities (absolute) l: a floating coordinate system local to the deflected beam (m/s)</td>
</tr>
<tr>
<td>TVz1l</td>
<td>Sectional translational velocities (absolute) l: a floating coordinate system local to the deflected beam (m/s)</td>
</tr>
<tr>
<td>TVxrl</td>
<td>Sectional translational velocities (absolute) r: a floating coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (m/s)</td>
</tr>
<tr>
<td>TVyrl</td>
<td>Sectional translational velocities (absolute) r: a floating coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (m/s)</td>
</tr>
<tr>
<td>TVzrl</td>
<td>Sectional translational velocities (absolute) r: a floating coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (m/s)</td>
</tr>
<tr>
<td>RVxg</td>
<td>Sectional angular/rotational velocities (absolute) g: the global inertial frame coordinate system; when coupled to FAST, this is equivalent to FAST’s global inertial frame (i) coordinate system (deg/s)</td>
</tr>
<tr>
<td>RVyg</td>
<td>Sectional angular/rotational velocities (absolute) g: the global inertial frame coordinate system; when coupled to FAST, this is equivalent to FAST’s global inertial frame (i) coordinate system (deg/s)</td>
</tr>
<tr>
<td>RVzg</td>
<td>Sectional angular/rotational velocities (absolute) g: the global inertial frame coordinate system; when coupled to FAST, this is equivalent to FAST’s global inertial frame (i) coordinate system (deg/s)</td>
</tr>
<tr>
<td>RVx1l</td>
<td>Sectional angular/rotational velocities (absolute) l: a floating coordinate system local to the deflected beam (deg/s)</td>
</tr>
<tr>
<td>RVy1l</td>
<td>Sectional angular/rotational velocities (absolute) l: a floating coordinate system local to the deflected beam (deg/s)</td>
</tr>
<tr>
<td>RVz1l</td>
<td>Sectional angular/rotational velocities (absolute) l: a floating coordinate system local to the deflected beam (deg/s)</td>
</tr>
<tr>
<td>RVxrl</td>
<td>Sectional angular/rotational velocities (absolute) r: a floating coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (deg/s)</td>
</tr>
<tr>
<td>RVyrl</td>
<td>Sectional angular/rotational velocities (absolute) r: a floating coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (deg/s)</td>
</tr>
<tr>
<td>RVzrl</td>
<td>Sectional angular/rotational velocities (absolute) r: a floating coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (deg/s)</td>
</tr>
<tr>
<td>TAx1l</td>
<td>Sectional angular/rotational velocities (absolute) l: a floating coordinate system local to the deflected beam (m/s^2)</td>
</tr>
<tr>
<td>TAY1l</td>
<td>Sectional angular/rotational velocities (absolute) l: a floating coordinate system local to the deflected beam (m/s^2)</td>
</tr>
<tr>
<td>TAZ1l</td>
<td>Sectional angular/rotational velocities (absolute) l: a floating coordinate system local to the deflected beam (m/s^2)</td>
</tr>
<tr>
<td>TAxrl</td>
<td>Sectional angular/rotational velocities (absolute) r: a floating coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (m/s^2)</td>
</tr>
<tr>
<td>TAYrl</td>
<td>Sectional angular/rotational velocities (absolute) r: a floating coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (m/s^2)</td>
</tr>
<tr>
<td>TAZrl</td>
<td>Sectional angular/rotational velocities (absolute) r: a floating coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (m/s^2)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>RAxl</td>
<td>Sectional angular/rotational velocities (absolute) l</td>
</tr>
<tr>
<td>RAyl</td>
<td>Sectional angular/rotational velocities (absolute) l</td>
</tr>
<tr>
<td>RAzl</td>
<td>Sectional angular/rotational velocities (absolute) l</td>
</tr>
<tr>
<td>RAxr</td>
<td>Sectional angular/rotational velocities (absolute) r</td>
</tr>
<tr>
<td>RAyr</td>
<td>Sectional angular/rotational velocities (absolute) r</td>
</tr>
<tr>
<td>RAZr</td>
<td>Sectional angular/rotational velocities (absolute) r</td>
</tr>
<tr>
<td>PFxL</td>
<td>Applied point forces at each node expressed in l</td>
</tr>
<tr>
<td>PFyL</td>
<td>Applied point forces at each node expressed in l</td>
</tr>
<tr>
<td>PFzL</td>
<td>Applied point forces at each node expressed in l</td>
</tr>
<tr>
<td>PMxL</td>
<td>Applied point moments at each node expressed in l</td>
</tr>
<tr>
<td>PMyL</td>
<td>Applied point moments at each node expressed in l</td>
</tr>
<tr>
<td>PMzL</td>
<td>Applied point moments at each node expressed in l</td>
</tr>
<tr>
<td>DFXL</td>
<td>Applied distributed forces at each node expressed in l</td>
</tr>
<tr>
<td>DFXL</td>
<td>Applied distributed forces at each node expressed in l</td>
</tr>
<tr>
<td>DFXL</td>
<td>Applied distributed forces at each node expressed in l</td>
</tr>
<tr>
<td>DMxL</td>
<td>Applied distributed moments at each node expressed in l</td>
</tr>
<tr>
<td>DMYL</td>
<td>Applied distributed moments at each node expressed in l</td>
</tr>
<tr>
<td>DMZL</td>
<td>Applied distributed moments at each node expressed in l</td>
</tr>
<tr>
<td>DFxR</td>
<td>Applied distributed forces at each node expressed in r</td>
</tr>
<tr>
<td>DFXR</td>
<td>Applied distributed forces at each node expressed in r</td>
</tr>
<tr>
<td>DFXR</td>
<td>Applied distributed forces at each node expressed in r</td>
</tr>
<tr>
<td>DMxR</td>
<td>Applied distributed moments at each node expressed in r</td>
</tr>
<tr>
<td>DMYR</td>
<td>Applied distributed moments at each node expressed in r</td>
</tr>
<tr>
<td>DMZR</td>
<td>Applied distributed moments at each node expressed in r</td>
</tr>
</tbody>
</table>
DMzR - Applied distributed forces at each node expressed in a floating reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (N-m/m).

FFbxl - Gyroscopic force x in a floating coordinate system local to the deflected beam (N)

FFbyl - Gyroscopic force y in a floating coordinate system local to the deflected beam (N)

FFbzl - Gyroscopic force z in a floating coordinate system local to the deflected beam (N)

FFbxr - Gyroscopic force x in a floating reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (N)

FFbyr - Gyroscopic force y in a floating reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (N)

FFbzd - Gyroscopic force z in a floating reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (N)

MFbxl - Gyroscopic moment about x in a floating coordinate system local to the deflected beam (N-m)

MFbyl - Gyroscopic moment about y in a floating coordinate system local to the deflected beam (N-m)

MFbzl - Gyroscopic moment about z in a floating coordinate system local to the deflected beam (N-m)

MFbxr - Gyroscopic moment about x in a floating reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (N-m)

MFbyr - Gyroscopic moment about y in a floating reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (N-m)

MFbzr - Gyroscopic moment about z in a floating reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (N-m)

FFcxl - Elastic restoring force in a floating coordinate system local to the deflected beam (N)

FFcly - Elastic restoring force in a floating coordinate system local to the deflected beam (N)

FFczl - Elastic restoring force in a floating coordinate system local to the deflected beam (N)

FFcxl - Elastic restoring force in a floating coordinate system local to the deflected beam (N)

MFcxl - Elastic restoring force in a floating coordinate system local to the deflected beam (N-m)

MFcly - Elastic restoring force in a floating coordinate system local to the deflected beam (N-m)

MFczl - Elastic restoring force in a floating coordinate system local to the deflected beam (N-m)

MFcxl - Elastic restoring force in a floating coordinate system local to the deflected beam (N-m)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFcyr</td>
<td>Elastic restoring moment $F_c$ about $y$ r: a floating reference coordinate</td>
</tr>
<tr>
<td>MFczr</td>
<td>Elastic restoring moment $F_c$ about $z$ r: a floating reference coordinate</td>
</tr>
<tr>
<td>FFdxl</td>
<td>Elastic restoring force $F_d$ about $x$ 1: a floating coordinate system local</td>
</tr>
<tr>
<td>FFdyl</td>
<td>Elastic restoring force $F_d$ about $y$ 1: a floating coordinate system local</td>
</tr>
<tr>
<td>FFdzl</td>
<td>Elastic restoring force $F_d$ about $z$ 1: a floating coordinate system local</td>
</tr>
<tr>
<td>FFdxr</td>
<td>Elastic restoring force $F_d$ about $x$ r: a floating reference coordinate</td>
</tr>
<tr>
<td>FFdyr</td>
<td>Elastic restoring force $F_d$ about $y$ r: a floating reference coordinate</td>
</tr>
<tr>
<td>FFdzr</td>
<td>Elastic restoring force $F_d$ about $z$ r: a floating reference coordinate</td>
</tr>
<tr>
<td>MFdxl</td>
<td>Elastic restoring moment $F_d$ about $x$ 1: a floating coordinate system local</td>
</tr>
<tr>
<td>MFdyl</td>
<td>Elastic restoring moment $F_d$ about $y$ 1: a floating coordinate system local</td>
</tr>
<tr>
<td>MFdzl</td>
<td>Elastic restoring moment $F_d$ about $z$ 1: a floating coordinate system local</td>
</tr>
<tr>
<td>MFdxr</td>
<td>Elastic restoring moment $F_d$ about $x$ r: a floating reference coordinate</td>
</tr>
<tr>
<td>MFdyr</td>
<td>Elastic restoring moment $F_d$ about $y$ r: a floating reference coordinate</td>
</tr>
<tr>
<td>MFdzr</td>
<td>Elastic restoring moment $F_d$ about $z$ r: a floating reference coordinate</td>
</tr>
<tr>
<td>FFgxl</td>
<td>Gravity force $x$ 1: a floating coordinate system local to the deflected beam</td>
</tr>
<tr>
<td>FFgyl</td>
<td>Gravity force $y$ 1: a floating coordinate system local to the deflected beam</td>
</tr>
<tr>
<td>FFgzl</td>
<td>Gravity force $z$ 1: a floating coordinate system local to the deflected beam</td>
</tr>
<tr>
<td>FFgxr</td>
<td>Gravity force $x$ r: a floating reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (N)</td>
</tr>
<tr>
<td>FFgyr</td>
<td>Gravity force $y$ r: a floating reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (N)</td>
</tr>
<tr>
<td>FFgzr</td>
<td>Gravity force $z$ r: a floating reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system (N)</td>
</tr>
<tr>
<td>MFgxl</td>
<td>Gravity moment about $x$ 1: a floating coordinate system local to the deflected beam (N-m)</td>
</tr>
<tr>
<td>MFgyl</td>
<td>Gravity moment about $y$ 1: a floating coordinate system local to the deflected beam (N-m)</td>
</tr>
<tr>
<td>MFgzl</td>
<td>Gravity moment about $z$ 1: a floating coordinate system local to the deflected beam (N-m)</td>
</tr>
<tr>
<td>Code</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>MFx</td>
<td>Gravity moment about x: a floating reference coordinate system</td>
</tr>
<tr>
<td>MFy</td>
<td>Gravity moment about y: a floating reference coordinate system</td>
</tr>
<tr>
<td>MFz</td>
<td>Gravity moment about z: a floating reference coordinate system</td>
</tr>
<tr>
<td>FFx</td>
<td>Inertial force x: a floating coordinate system local to the deflected beam</td>
</tr>
<tr>
<td>FFy</td>
<td>Inertial force y: a floating coordinate system local to the deflected beam</td>
</tr>
<tr>
<td>FFz</td>
<td>Inertial force z: a floating coordinate system local to the deflected beam</td>
</tr>
<tr>
<td>MFx</td>
<td>Inertial moment about x: a floating reference coordinate system</td>
</tr>
<tr>
<td>MFy</td>
<td>Inertial moment about y: a floating reference coordinate system</td>
</tr>
<tr>
<td>MFz</td>
<td>Inertial moment about z: a floating reference coordinate system</td>
</tr>
</tbody>
</table>

END of input file (the word "END" must appear in the first 3 columns of this last OutList line)
Blade Input File

The blade input file defines the cross-sectional properties at various stations along a blade and six damping coefficients for the whole blade. A sample BeamDyn blade input file is given in Section 4.6.7. The blade input file begins with two lines of header information, which is for the user but is not used by the software.

Blade Parameters

Station_Total specifies the number of cross-sectional stations along the blade axis used in the analysis.

Damp_Type specifies if structural damping is considered in the analysis. If Damp_Type = 0, then no damping is considered in the analysis and the six damping coefficients in the next section will be ignored. If Damp_Type = 1, structural damping will be included in the analysis.

Damping Coefficient

This section specifies six damping coefficients, $\mu_{ii}$ with $i \in [1, 6]$, for six DOFs (three translations and three rotations). Viscous damping is implemented in BeamDyn where the damping forces are proportional to the strain rate. These are stiffness-proportional damping coefficients, whereby the $6 \times 6$ damping matrix at each cross section is scaled from the $6 \times 6$ stiffness matrix by these diagonal entries of a $6 \times 6$ scaling matrix:

$$\mathcal{F}_{\text{Damp}} = \mu \mathcal{S} \ddot{\xi}$$

(4.61)

where $\mathcal{F}_{\text{Damp}}$ is the damping force, $\mathcal{S}$ is the $6 \times 6$ cross-sectional stiffness matrix, $\ddot{\xi}$ is the strain rate, and $\mu$ is the damping coefficient matrix defined as

$$\mu = \begin{bmatrix} \mu_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & \mu_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & \mu_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & \mu_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \mu_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & \mu_{66} \end{bmatrix}$$

(4.62)

Distributed Properties

This section specifies the cross-sectional properties at each of the Station_Total stations. For each station, a non-dimensional parameter $\eta$ specifies the station location along the local blade reference axis ranging from $[0.0, 1.0]$. The first and last station parameters must be set to 0.0 (for the blade root) and 1.0 (for the blade tip), respectively.

Following the station location parameter $\eta$, there are two $6 \times 6$ matrices providing the structural and inertial properties for this cross-section. First is the stiffness matrix and then the mass matrix. We note that these matrices are defined in a local coordinate system along the blade axis with $Z_l$ directing toward the unit tangent vector of the blade reference axis. For a cross-section without coupling effects, for example, the stiffness matrix is given as follows:

$$\begin{bmatrix} K_{\text{ShrFlp}} & 0 & 0 & 0 & 0 & 0 \\ 0 & K_{\text{ShrEdg}} & 0 & 0 & 0 & 0 \\ 0 & 0 & E A & 0 & 0 & 0 \\ 0 & 0 & 0 & E I_{\text{Edg}} & 0 & 0 \\ 0 & 0 & 0 & 0 & E I_{\text{Flp}} & 0 \\ 0 & 0 & 0 & 0 & 0 & G J \end{bmatrix}$$

(4.63)

where $K_{\text{ShrEdg}}$ and $K_{\text{ShrFlp}}$ are the edge and flap shear stiffnesses, respectively; $E A$ is the extension stiffness; $E I_{\text{Edg}}$ and $E I_{\text{Flp}}$ are the edge and flap stiffnesses, respectively; and $G J$ is the torsional stiffness. It is pointed out that
for a generic cross-section, the sectional property matrices can be derived from a sectional analysis tool, e.g. VABS, BECAS, or NuMAD/BPE.

A generalized sectional mass matrix is given by:

\[
\begin{bmatrix}
m & 0 & 0 & 0 & 0 & -mY_{cm} \\
0 & m & 0 & 0 & 0 & mX_{cm} \\
0 & 0 & m & mY_{cm} & -mX_{cm} & 0 \\
0 & 0 & mY_{cm} & i_{Edg} & -i_{cp} & 0 \\
0 & 0 & -mX_{cm} & -i_{cp} & i_{Flp} & 0 \\
-mY_{cm} & mX_{cm} & 0 & 0 & 0 & i_{plr}
\end{bmatrix}
\]  

(4.64)

where \( m \) is the mass density per unit span; \( X_{cm} \) and \( Y_{cm} \) are the local coordinates of the sectional center of mass, respectively; \( i_{Edg} \) and \( i_{Flp} \) are the edge and flap mass moments of inertia per unit span, respectively; \( i_{plr} \) is the polar moment of inertia per unit span; and \( i_{cp} \) is the sectional cross-product of inertia per unit span. We note that for beam structure, the \( i_{plr} \) is given as (although this relationship is not checked by BeamDyn)

\[
i_{plr} = i_{Edg} + i_{Flp}
\]  

(4.65)

### 4.6.4 Output Files

BeamDyn produces three types of output files, depending on the options selected: an echo file, a summary file, and a time-series results file. The following sections detail the purpose and contents of these files.

#### Echo File

If the user sets the Echo flag to TRUE in the BeamDyn primary input file, the contents of this file will be echoed to a file with the naming convention \( \text{InputFile.ech} \). The echo file is helpful for debugging the input files. The contents of an echo file will be truncated if BeamDyn encounters an error while parsing an input file. The error usually corresponds to the line after the last successfully echoed line.

#### Summary File

In stand-alone mode, BeamDyn generates a summary file with the naming convention \( \text{InputFile.sum} \) if the SumPrint parameter is set to TRUE. When coupled to FAST, the summary file is named \( \text{InputFile.BD.sum} \). This file summarizes key information about the simulation, including:

- Blade mass.
- Blade length.
- Blade center of mass.
- Initial global position vector in BD coordinate system.
- Initial global rotation tensor in BD coordinate system.
- Analysis type.
- Numerical damping coefficients.
- Time step size.
- Maximum number of iterations in the Newton-Raphson solution.
- Convergence parameter in the stopping criterion.
- Factorization frequency in the Newton-Raphson solution.
• Numerical integration (quadrature) method.
• FE mesh refinement factor used in trapezoidal quadrature.
• Number of elements.
• Number of FE nodes.
• Initial position vectors of FE nodes in BD coordinate system.
• Initial rotation vectors of FE nodes in BD coordinate system.
  • Quadrature point position vectors in BD coordinate system. For Gauss quadrature, the physical coordinates of Gauss points are listed. For trapezoidal quadrature, the physical coordinates of the quadrature points are listed.
  • Sectional stiffness and mass matrices at quadrature points in local blade reference coordinate system. These are the data being used in calculations at quadrature points and they can be different from the section in Blade Input File since BeamDyn linearly interpolates the sectional properties into quadrature points based on need.
• Initial displacement vectors of FE nodes in BD coordinate system.
• Initial rotational displacement vectors of FE nodes in BD coordinate system.
• Initial translational velocity vectors of FE nodes in BD coordinate system.
• Initial angular velocity vectors of FE nodes in BD coordinate system.
• Requested output information.

All of these quantities are output in this file in the BD coordinate system, the one being used internally in BeamDyn calculations. The initial blade reference coordinate system, denoted by a subscript $r_0$ that follows the IEC standard, is related to the internal BD coordinate system by Table 4.6 in Section 4.6.5.

Results File

The BeamDyn time-series results are written to a text-based file with the naming convention $\text{DriverInputFile.out}$ where $\text{DriverInputFile}$ is the name of the driver input file when BeamDyn is run in the stand-alone mode. If BeamDyn is coupled to FAST, then FAST will generate a master results file that includes the BeamDyn results. The results in $\text{DriverInputFile.out}$ are in table format, where each column is a data channel (the first column always being the simulation time), and each row corresponds to a simulation time step. The data channel are specified in the OUTPUT section of the primary input file. The column format of the BeamDyn-generated file is specified using the $\text{OutFmt}$ parameters of the primary input file.

4.6.5 BeamDyn Theory

This section focuses on the theory behind the BeamDyn module. The theoretical foundation, numerical tools, and some special handling in the implementation will be introduced. References will be provided in each section detailing the theories and numerical tools.

In this chapter, matrix notation is used to denote vectorial or vectorial-like quantities. For example, an underline denotes a vector $\underline{u}$, an over bar denotes unit vector $\bar{n}$, and a double underline denotes a tensor $\underline{\Delta}$. Note that sometimes the underlines only denote the dimension of the corresponding matrix.
Coordinate Systems

Fig. 4.26 (in Section 4.6.3) and Fig. 4.27 show the coordinate system used in BeamDyn.

Global Coordinate System

The global coordinate system is denoted as X, Y, and Z in Fig. 4.27. This is an inertial frame and in FAST its origin is usually placed at the bottom of the tower as shown.

BD Coordinate System

The BD coordinate system is denoted as $x_1$, $x_2$, and $x_3$ respectively in Fig. 4.27. This is an inertial frame used internally in BeamDyn (i.e., doesn’t rotate with the rotor) and its origin is placed at the initial position of the blade root point.

Blade Reference Coordinate System

The blade reference coordinate system is denoted as $X_r$, $Y_r$, and $Z_r$ in Fig. 4.27 at initialization ($t = 0$). The blade reference coordinate system is a floating frame that attaches at the blade root and is rotating with the blade. Its origin is at the blade root and the directions of axes following the IEC standard, i.e., $Z_r$ is pointing along the blade axis from root to tip; $Y_r$ pointing nominally towards the trailing edge of the blade and parallel with the chord line at the zero-twist blade station; and $X_r$ is orthogonal with the $Y_r$ and $Z_r$ axes, such that they form a right-handed coordinate system (pointing nominally downwind). We note that the initial blade reference coordinate system, denoted by subscript $r0$, coincides with the BD coordinate system, which is used internally in BeamDyn and introduced in the previous section. The axis convention relations between the initial blade reference coordinate system and the BD coordinate system can be found in Table 4.6.

Table 4.6: Transformation between blade coordinate system and BD coordinate system.

<table>
<thead>
<tr>
<th>Blade Frame</th>
<th>$X_{r0}$</th>
<th>$Y_{r0}$</th>
<th>$Z_{r0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BD Frame</td>
<td>$x_2$</td>
<td>$x_3$</td>
<td>$x_1$</td>
</tr>
</tbody>
</table>

Local blade coordinate system

The local blade coordinate system is used for some input and output quantities, for example, the cross-sectional mass and stiffness matrices and the the sectional force and moment resultants. This coordinate system is different from the blade reference coordinate system in that its $Z_l$ axis is always tangent to the blade axis as the blade deflects. Note that a subscript $l$ denotes the local blade coordinate system.
Fig. 4.27: Global, blade reference, and internal coordinate systems in BeamDyn. Illustration by Al Hicks, NREL.
Geometrically Exact Beam Theory

The theoretical foundation of BeamDyn is the geometrically exact beam theory. This theory features the capability of beams that are initially curved and twisted and subjected to large displacement and rotations. Along with a proper two-dimensional (2D) cross-sectional analysis, the coupling effects between all six DOFs, including extension, bending, shear, and torsion, can be captured by GEBT as well. The term, “geometrically exact” refer to the fact that there is no approximation made on the geometries, including both initial and deformed geometries, in formulating the equations [Hod06].

The governing equations of motion for geometrically exact beam theory can be written as [Bau10]

\[
\begin{align*}
\dot{h} - F' &= f \\
\dot{g} + \dot{u} h - M' + (\tilde{x}'_0 + \tilde{u}')^T F &= m
\end{align*}
\] (4.66)

where \( h \) and \( g \) are the linear and angular momenta resolved in the inertial coordinate system, respectively; \( F \) and \( M \) are the beam’s sectional force and moment resultants, respectively; \( u \) is the one-dimensional (1D) displacement of a point on the reference line; \( x'_0 \) is the position vector of a point along the beam’s reference line; and \( f \) and \( m \) are the distributed force and moment applied to the beam structure. The notation \( (\cdot)' \) indicates a derivative with respect to beam axis \( x_1 \) and \( \dot{\cdot} \) indicates a derivative with respect to time. The tilde operator \( (\tilde{\cdot}) \) defines a skew-symmetric tensor corresponding to the given vector. In the literature, it is also termed as “cross-product matrix”. For example,

\[
\tilde{n} = \begin{bmatrix}
0 & -n_3 & n_2 \\
n_3 & 0 & -n_1 \\
-n_2 & n_1 & 0
\end{bmatrix}
\]

The constitutive equations relate the velocities to the momenta and the 1D strain measures to the sectional resultants as

\[
\begin{bmatrix}
h \\
g
\end{bmatrix} = M \begin{bmatrix}
\dot{u} \\
\omega
\end{bmatrix}
\] (4.67)

\[
\begin{bmatrix}
F \\
M
\end{bmatrix} = \zeta \begin{bmatrix}
\xi \\
\kappa
\end{bmatrix}
\]

where \( M \) and \( \zeta \) are the \( 6 \times 6 \) sectional mass and stiffness matrices, respectively (note that they are not really tensors); \( \xi \) and \( \kappa \) are the 1D strains and curvatures, respectively; and, \( \omega \) is the angular velocity vector that is defined by the rotation tensor \( R \) as \( \omega = axial(R, R^T) \). The axial vector \( a \) associated with a second-order tensor \( A \) is denoted \( a = axial(A) \) and its components are defined as

\[
a = axial(A) = \begin{bmatrix}
a_1 \\
a_2 \\
a_3
\end{bmatrix} = \frac{1}{2} \begin{bmatrix}
A_{32} - A_{23} \\
A_{13} - A_{31} \\
A_{21} - A_{12}
\end{bmatrix}
\] (4.68)

The 1D strain measures are defined as

\[
\begin{bmatrix}
\xi \\
\kappa
\end{bmatrix} = \begin{bmatrix}
x'_0 + y' - (R \cdot \tilde{r}_1) \\
\kappa
\end{bmatrix}
\] (4.69)

where \( k = axial((RR_0)'(RR_0)^T) \) is the sectional curvature vector resolved in the inertial basis; \( R_0 \) is the initial rotation tensor; and \( \tilde{r}_1 \) is the unit vector along \( x_1 \) direction in the inertial basis. These three sets of equations, including equations of motion Eq. (4.66), constitutive equations Eq. (4.67), and kinematical equations Eq. (4.69), provide a full mathematical description of the beam elasticity problems.
Numerical Implementation with Legendre Spectral Finite Elements

For a displacement-based finite element implementation, there are six degree-of-freedoms at each node: three displacement components and three rotation components. Here we use \( \hat{q} \) to denote the elemental displacement array as \( \hat{q} = [u^T \; \phi^T] \) where \( u \) is the displacement and \( \phi \) is the rotation-parameter vector. The acceleration array can thus be defined as \( a = [\ddot{u}^T \; \ddot{\phi}^T] \). For nonlinear finite-element analysis, the discretized and incremental forms of displacement, velocity, and acceleration are written as

\[
q(x) = N \hat{q} \quad \Delta q^T = [\Delta u^T \; \Delta \phi^T] \\
u(x) = N \ddot{\hat{u}} \quad \Delta \dot{u}^T = [\Delta \ddot{u}^T \; \Delta \ddot{\phi}^T] \\
a(x) = N \dddot{\hat{a}} \quad \Delta \dddot{\hat{a}}^T = [\Delta \dddot{u}^T \; \Delta \dddot{\phi}^T]
\]

(4.70)

where \( N \) is the shape function matrix and \( \hat{\cdot} \) denotes a column matrix of nodal values.

The displacement fields in an element are approximated as

\[
u(\xi) = h^k(\xi) v^k \\
u'(\xi) = h^k(\xi) \dot{v}^k
\]

(4.71)

where \( h^k(\xi) \), the component of shape function matrix \( N \), is the \( p^{th} \)-order polynomial Lagrangian-interpolant shape function of node \( k \), \( k = \{1, 2, \ldots, p + 1\} \), \( v^k \) is the \( k^{th} \) nodal value, and \( \xi \in [-1, 1] \) is the element natural coordinate. However, as discussed in [BEH08], the 3D rotation field cannot simply be interpolated as the displacement field in the form of

\[
c(\xi) = h^k(\xi) c^k \\
c'(\xi) = h^k(\xi) \dot{c}^k
\]

(4.72)

where \( c \) is the rotation field in an element and \( c^k \) is the nodal value at the \( k^{th} \) node, for three reasons:

1) rotations do not form a linear space so that they must be “composed” rather than added;

2) a rescaling operation is needed to eliminate the singularity existing in the vectorial rotation parameters;

3) the rotation field lacks objectivity, which, as defined by [JelenicC99], refers to the invariance of strain measures computed through interpolation to the addition of a rigid-body motion.

Therefore, we adopt the more robust interpolation approach proposed by [JelenicC99] to deal with the finite rotations. Our approach is described as follows

**Step 1:** Compute the nodal relative rotations, \( \hat{c}^k \), by removing the reference rotation, \( \hat{c}^1 \), from the finite rotation at each node, \( \hat{c}^k = (\hat{c}^1 - \hat{c}_r) \). It is noted that the minus sign on \( \hat{c}^1 \) denotes that the relative rotation is calculated by removing the reference rotation from each node. The composition in that equation is an equivalent of \( R(\hat{c}^k) = R^T(\hat{c}^1) R(\hat{c}_r) \).

**Step 2:** Interpolate the relative-rotation field: \( c(\xi) = h^k(\xi) \hat{c}^k \) and \( c'(\xi) = h^k(\xi) \dot{\hat{c}}^k \). Find the curvature field \( \kappa(\xi) = \frac{\partial}{\partial \xi} H(\xi) c' \) where \( H \) is the tangent tensor that relates the curvature vector \( k \) and rotation vector \( c \) as

\[
k = H c'
\]

(4.73)

**Step 3:** Restore the rigid-body rotation removed in Step 1: \( c(\xi) = \hat{c}^1 + \kappa(\xi) \).

Note that the relative-rotation field can be computed with respect to any of the nodes of the element; we choose node 1 as the reference node for convenience. In the LSFE approach, shape functions (i.e., those composing \( N \)) are \( p^{th} \)-order Lagrangian interpolants, where nodes are located at the \( p + 1 \) Gauss-Lobatto-Legendre (GLL) points in the \([-1, 1]\) element natural-coordinate domain. Fig. 4.28 shows representative LSFE basis functions for fourth- and eighth-order elements. Note that nodes are clustered near element endpoints. More details on the LSFE and its applications can be found in References [Pat84][RP87][SG03][SG04].
Fig. 4.28: Representative $p + 1$ Lagrangian-interpolant shape functions in the element natural coordinates for a fourth-order LSFEs, where nodes are located at the Gauss-Lobatto-Legendre points.

Fig. 4.29: Representative $p + 1$ Lagrangian-interpolant shape functions in the element natural coordinates for an eighth-order LSFEs, where nodes are located at the Gauss-Lobatto-Legendre points.
Wiener-Milenković Rotation Parameter

In BeamDyn, the 3D rotations are represented as Wiener-Milenković parameters defined in the following equation:

\[ \xi = 4 \tan \left( \frac{\phi}{4} \right) \hat{n} \]  

(4.74)

where \( \phi \) is the rotation angle and \( \hat{n} \) is the unit vector of the rotation axis. It can be observed that the valid range for this parameter is \(|\phi| < 2\pi\). The singularities existing at integer multiples of \(\pm 2\pi\) can be removed by a rescaling operation at \(\pi\) as:

\[ \xi = \begin{cases} 
(4q_0p + p_0q + \dot{p}q)/(\Delta_1 + \Delta_2), & \text{if } \Delta_2 \geq 0 \\
-4(q_0p + p_0q + \dot{p}q)/(\Delta_1 - \Delta_2), & \text{if } \Delta_2 < 0 
\end{cases} \]  

(4.75)

where \( p, q \), and \( \xi \) are the vectorial parameterization of three finite rotations such that \( R(\xi) = R(p)R(q) \), \( p_0 = 2 - p^T \hat{p}/\hat{8} \), \( q_0 = 2 - q^T \hat{q}/\hat{8} \), \( \Delta_1 = (4 - p_0)(4 - q_0) \), and \( \Delta_2 = p_0q_0 - p^T \hat{p} \). It is noted that the rescaling operation could cause a discontinuity of the interpolated rotation field; therefore a more robust interpolation algorithm has been introduced in Section Numerical Implementation with Legendre Spectral Finite Elements where the rescaling-independent relative-rotation field is interpolated.

The rotation tensor expressed in terms of Wiener-Milenković parameters is

\[ R(\xi) = \frac{1}{(4 - c_0)^2} \begin{bmatrix} c_0^2 + c_2^2 - c_3^2 & 2(c_1c_2 - c_0c_3) & 2(c_1c_3 + c_0c_2) \\ 2(c_1c_2 + c_0c_3) & c_0^2 - c_1^2 - c_3^2 & 2(c_2c_3 - c_0c_1) \\ 2(c_1c_3 - c_0c_2) & 2(c_2c_3 + c_0c_1) & c_0^2 - c_1^2 + c_3^2 \end{bmatrix} \]  

(4.76)

where \( \xi = [c_1 \ c_2 \ c_3]^T \) is the Wiener-Milenković parameter and \( c_0 = 2 - \frac{1}{\hat{8}} \xi^T \xi \). The relation between rotation tensor and direction cosine matrix (DCM) is

\[ R = (DCM)^T \]  

(4.77)

Interested users are referred to [BEH08] and [WYS13] for more details on the rotation parameter and its implementation with GEBT.

Linearization Process

The nonlinear governing equations introduced in the previous section are solved by Newton-Raphson method, where a linearization process is needed. The linearization of each term in the governing equations are presented in this section.

According to [Bau10], the linearized governing equations in Eq. (4.66) are in the form of

\[ \dot{\bar{M}}\Delta\ddot{\hat{u}} + \bar{G}\Delta\ddot{\hat{v}} + \bar{K}\Delta\ddot{\hat{w}} = \bar{F}^{ext} - \bar{F} \]  

(4.78)

where the \( \bar{M}, \bar{G}, \) and \( \bar{K} \) are the elemental mass, gyroscopic, and stiffness matrices, respectively; \( \bar{F} \) and \( \bar{F}^{ext} \) are the elemental forces and externally applied loads, respectively. They are defined for an element of length \( l \) along \( x_1 \) as follows

\[
\bar{M} = \int_{0}^{l} N^T M N dx_1
\]

\[
\bar{G} = \int_{0}^{l} N^T G N dx_1
\]

\[
\bar{K} = \int_{0}^{l} \left[ N^T (K + Q) N + N^T P N' + N^T C N' + N^T Q N' + N^T C N' + N^T Q N' dx_1
\]

\[
\bar{F} = \int_{0}^{l} \left( N^T F + N^T F D + N^T F C \right) dx_1
\]

\[
\bar{F}^{ext} = \int_{0}^{l} N^T F^{ext} dx_1
\]


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where $\mathbf{F}^\text{ext}$ is the applied load vector. The new matrix notations in Eqs. (4.79) to are briefly introduced here. $\mathbf{F}^C$ and $\mathbf{F}^D$ are elastic forces obtained from Eq. (4.66) as

$$
\mathbf{F}^C = \begin{bmatrix} F \end{bmatrix} = \mathbf{C} \begin{bmatrix} \epsilon \end{bmatrix}
$$

$$
\mathbf{F}^D = \begin{bmatrix} (\ddot{x}_0 + \ddot{u})^T \end{bmatrix} \begin{bmatrix} 0 \end{bmatrix} \mathbf{F}^C = \mathbf{K} \mathbf{F}^C
$$

where $\mathbf{0}$ denotes a $3 \times 3$ null matrix. The $\mathbf{G}^I, \mathbf{K}^I, \mathbf{O}, \mathbf{P}, \mathbf{Q}$, and $\mathbf{F}^I$ in Eqs. (4.79) are defined as

$$
\mathbf{G}^I = \begin{bmatrix} 0 \end{bmatrix} \begin{bmatrix} \ddot{m} \eta + \ddot{\eta} \ddot{m} \end{bmatrix}
$$

$$
\mathbf{K}^I = \begin{bmatrix} 0 \end{bmatrix} \begin{bmatrix} \ddot{m} \eta + \ddot{\eta} \ddot{m} \end{bmatrix}
$$

$$
\mathbf{O} = \begin{bmatrix} 0 \end{bmatrix} \begin{bmatrix} C_{11} \dddot{E}_1 - \dddot{F} \end{bmatrix}
$$

$$
\mathbf{P} = \begin{bmatrix} \dddot{F} + (C_{11} \dddot{E}_1)^T \end{bmatrix} \begin{bmatrix} 0 \end{bmatrix} \begin{bmatrix} 0 \end{bmatrix}
$$

$$
\mathbf{Q} = \mathbf{Y} \mathbf{O}
$$

$$
\mathbf{F}^I = \begin{bmatrix} \dddot{m} \dddot{u} + (\dddot{\omega} + \dddot{\omega} \dddot{m} \eta) \end{bmatrix}
$$

where $m$ is the mass density per unit length, $\eta$ is the location of the sectional center of mass, $\bar{\omega}$ is the moment of inertia tensor, and the following notations were introduced to simplify the above expressions

$$
\dddot{E}_1 = \dddot{x}_0 + \dddot{u}
$$

$$
\mathbf{C} = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix}
$$

**Damping Forces and Linearization**

A viscous damping model has been implemented into BeamDyn to account for the structural damping effect. The damping force is defined as

$$
\mathbf{f}_d = \mu \mathbf{C} \begin{bmatrix} \epsilon \end{bmatrix}
$$

where $\mu$ is a user-defined damping-coefficient diagonal matrix. The damping force can be recast in two separate parts, like $\mathbf{F}^C$ and $\mathbf{F}^D$ in the elastic force, as

$$
\mathbf{F}^C_d = \begin{bmatrix} F_d \end{bmatrix}
$$

$$
\mathbf{F}^D_d = \begin{bmatrix} (\dddot{x}_0 + \dddot{u})^T F_d \end{bmatrix}
$$

The linearization of the structural damping forces are as follows:

$$
\Delta \mathbf{F}^C_d = \mathbf{S} \begin{bmatrix} \Delta u' \end{bmatrix} + \mathbf{Q} \begin{bmatrix} \Delta u \end{bmatrix} + \mathbf{G} \begin{bmatrix} \Delta u \end{bmatrix} + \mathbf{C} \begin{bmatrix} \Delta u' \end{bmatrix} + \mu \mathbf{C} \begin{bmatrix} \Delta u' \end{bmatrix}
$$

$$
\Delta \mathbf{F}^D_d = \mathbf{P} \begin{bmatrix} \Delta u' \end{bmatrix} + \mathbf{Q} \begin{bmatrix} \Delta u \end{bmatrix} + \mathbf{K} \begin{bmatrix} \Delta u \end{bmatrix} + \mathbf{Y} \begin{bmatrix} \Delta u' \end{bmatrix}
$$
where the newly introduced matrices are defined as

\[
S_d = \mu C \begin{bmatrix}
\tilde{\omega}^T & 0 \\
0 & \tilde{\omega}^T
\end{bmatrix}
\]

\[
Q_d = \begin{bmatrix}
0 & \mu C_{11} (\dot{t} - \tilde{\omega} \tilde{E}_1) - \tilde{F}_d \\
0 & \mu C_{11} (\dot{t} - \tilde{\omega} \tilde{E}_1) - \tilde{M}_d
\end{bmatrix}
\]

\[
G_d = \begin{bmatrix}
0 & C_{11} \tilde{t} \tilde{E}_1 \\
0 & C_{12} \tilde{t} \tilde{E}_1
\end{bmatrix}
\]

\[
P_d = \begin{bmatrix}
\tilde{F}_d + \tilde{E}_1 \tilde{t} \mu C_{11} \tilde{E}_1^T & \tilde{E}_1^T \mu C_{12} \tilde{E}_1^T
\end{bmatrix}
\]

\[
Q_d = \begin{bmatrix}
0 & 0 \\
0 & \tilde{E}_1 \tilde{t} Q_{12}
\end{bmatrix}
\]

\[
G_d = \begin{bmatrix}
0 & 0 \\
0 & \tilde{E}_1 \tilde{t} G_{12}
\end{bmatrix}
\]

\[
P_d = \begin{bmatrix}
0 & 0 \\
0 & \tilde{E}_1 \tilde{t} \mu C_{11} \tilde{E}_1^T & \tilde{E}_1 \tilde{t} \mu C_{12} \tilde{E}_1^T
\end{bmatrix}
\]

where \(Q_{12}\) and \(G_{12}\) are the 3 × 3 sub matrices of \(Q\) and \(G\) as \(C_{12}\) in Eq. (4.82).

**Convergence Criterion and Generalized-\(\alpha\) Time Integrator**

The system of nonlinear equations in Eqs. (4.66) are solved using the Newton-Raphson method with the linearized form in Eq. (4.78). In the present implementation, an energy-like stopping criterion has been chosen, which is calculated as

\[
|\Delta U^{(i)}(\Delta t) R + (t + \Delta t) F^{(i-1)}| \leq |\epsilon_E (\Delta U^{(1)}(t + \Delta t) R - t F)|
\]

where \(\cdot\) denotes the absolute value, \(\Delta U\) is the incremental displacement vector, \(R\) is the vector of externally applied nodal point loads, \(F\) is the vector of nodal point forces corresponding to the internal element stresses, and \(\epsilon_E\) is the user-defined energy tolerance. The superscript on the left side of a variable denotes the time-step number (in a dynamic analysis), while the one on the right side denotes the Newton-Raphson iteration number. As pointed out by [BC80], this criterion provides a measure of when both the displacements and the forces are near their equilibrium values.

Time integration is performed using the generalized-\(\alpha\) scheme in BeamDyn, which is an unconditionally stable (for linear systems), second-order accurate algorithm. The scheme allows for users to choose integration parameters that introduce high-frequency numerical dissipation. More details regarding the generalized-\(\alpha\) method can be found in [CH93][Bau10].

**Calculation of Reaction Loads**

Since the root motion of the wind turbine blade, including displacements and rotations, translational and angular velocities, and translational and angular accelerates, are prescribed as inputs to BeamDyn either by the driver (in stand-alone mode) or by FAST glue code (in FAST-coupled mode), the reaction loads at the root are needed to satisfy equality of the governing equations. The reaction loads at the root are also the loads passing from blade to hub in a full turbine analysis.

The governing equations in Eq. (4.66) can be recast in a compact form

\[
\mathcal{F}^I - \mathcal{F}^C + \mathcal{F}^D = \mathcal{F}^{ext}
\]
with all the vectors defined in Section [sec:LinearProcess]. At the blade root, the governing equation is revised as

$$
\mathbf{F}^I - \mathbf{F}^{C'} + \mathbf{F}^D = \mathbf{F}^{ext} + \mathbf{F}^R
$$

(4.89)

where $\mathbf{F}^R = \left[ \mathbf{F}^R \ M^R \right]^T$ is the reaction force vector and it can be solved from Eq. (4.89) given that the motion fields are known at this point.

### Calculation of Blade Loads

BeamDyn can also calculate the blade loads at each finite element node along the blade axis. The governing equation in Eq. (4.88) are recast as

$$
\mathbf{F}^A + \mathbf{F}^V - \mathbf{F}^{C'} + \mathbf{F}^D = \mathbf{F}^{ext}
$$

(4.90)

where the inertial force vector $\mathbf{F}^I$ is split into $\mathbf{F}^A$ and $\mathbf{F}^V$:

$$
\mathbf{F}^A = \begin{bmatrix} \dot{\mathbf{m}} \ddot{\mathbf{u}} + \dot{\mathbf{\omega}} m \eta \\ \mathbf{m} \dddot{\mathbf{u}} + \dot{\rho} \ddot{\mathbf{u}} \end{bmatrix}
$$

$$
\mathbf{F}^V = \begin{bmatrix} \ddot{\mathbf{\omega}} m \eta \\ \ddot{\omega} \rho \mathbf{u} \end{bmatrix}
$$

(4.91)

The blade loads are thus defined as

$$
\mathbf{F}^{BF} = \mathbf{F}^V - \mathbf{F}^{C'} + \mathbf{F}^D
$$

(4.92)

We note that if structural damping is considered in the analysis, the $\mathbf{F}^C_d$ and $\mathbf{F}^D_d$ are incorporated into the internal elastic forces, $\mathbf{F}^C$ and $\mathbf{F}^D$, for calculation.

### 4.6.6 Future Work

The following list contains future work onBeamDyn software:

- Eliminating numerical problems in single precision.
- Implementing eigenvalue analysis.
- Improving input options for stand-alone version to make it more user-friendly.
- Implementing GEBT based on modal method for computational efficiency.
- Adding more options for blade cross-sectional properties inputs. For example, for general isotropic beams, engineering parameters including sectional offsets, material properties, etc will be used to generate the $6 \times 6$ matrices needed by BeamDyn.
- Writing a general guidance on modeling composite beam structures using BeamDyn, for example, how to select a time step, how to select the model discretization, how to define the blade reference axis, where to get $6 \times 6$ mass/stiffness matrices, etc.
- Extending applications in FAST to other slender structures in the wind turbine system, for example, tower, mooring lines, and shaft.
- Developing a simplified form of GEBT with only rotational DOFs (bending, torsion) for computational efficiency.
4.6.7 Appendix

BeamDyn Input Files

In this appendix we describe the BeamDyn input-file structure and provide examples for the NREL 5MW Reference Wind Turbine.

OpenFAST+BeamDyn and stand-alone BeamDyn (static and dynamic) simulations all require two files:

1) BeamDyn primary input file (NREL 5MW static example): This file includes information on the numerical-solution parameters (e.g., numerical damping, quadrature rules), and the geometric definition of the beam reference line via “members” and “key points”. This file also specifies the “blade input file.”

2) BeamDyn blade input file (NREL 5MW example):

Stand-alone BeamDyn simulation also require a driver input file; we list here examples for static and dynamic simulations:

3a) BeamDyn driver for dynamic simulations (NREL 5MW example): This file specifies the inputs for a single blade (e.g., forces, orientations, root velocity) and specifies the BeamDyn primary input file.

3b) BeamDyn driver for static simulations (NREL 5MW example): Same as above but for static analysis.

BeamDyn List of Output Channels

This is a list of all possible output parameters for the BeamDyn module. The names are grouped by meaning, but can be ordered in the OUTPUTS section of the BeamDyn primary input file as the user sees fit. \( N_\beta \), refers to output node \( \beta \), where \( \beta \) is a number in the range \([1,9]\), corresponding to entry \( \beta \) in the OutNd list. When coupled to FAST, “\( B_\alpha \)” is prefixed to each output name, where \( \alpha \) is a number in the range \([1,3]\), corresponding to the blade number. The outputs are expressed in one of the following three coordinate systems:

- \( r \): a floating reference coordinate system fixed to the root of the moving beam; when coupled to FAST for blades, this is equivalent to the IEC blade (b) coordinate system.
- \( l \): a floating coordinate system local to the deflected beam.
- \( g \): the global inertial frame coordinate system; when coupled to FAST, this is equivalent to FAST’s global inertial frame (i) coordinate system.


4.7.1 Introduction

SubDyn is a time-domain structural-dynamics module for multimember fixed-bottom substructures created by the National Renewable Energy Laboratory (NREL) through U.S. Department of Energy Wind and Water Power Program support. The module has been coupled into the FAST aero-hydro-servo-elastic computer-aided engineering (CAE) tool. Substructure types supported by SubDyn include monopiles, tripods, jackets, and other non-floating lattice-type substructures common for offshore wind installations in shallow and transitional water depths. SubDyn can also be used to model lattice support structures for land-based wind turbines.

The new SubDyn module follows the requirements of the FAST modularization framework, couples to OpenFAST, and provides new capabilities (relative to prior released versions of the software) for modeling the dynamic loading on multimember substructures. (Refer to Appendix E and the changelog.txt file that is provided in the archives for more details about changes among different versions.) SubDyn can also be driven as a standalone code to compute the mode shapes, natural frequencies, and time-domain responses of substructures under prescribed motion at the interface to the tower, uncoupled from FAST and in the absence of external loading other than gravity.
<table>
<thead>
<tr>
<th>Channel(s)</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>RootFxr, RootFyr, RootFzr</td>
<td>(N), (N), (N)</td>
<td>Root reaction forces expressed in r</td>
</tr>
<tr>
<td>RootMxr, RootMyr, RootMzr</td>
<td>(N m), (N m), (N m)</td>
<td>Root reaction moments expressed in r</td>
</tr>
<tr>
<td>TipTDxr, TipTDyr, TipTDzr</td>
<td>(m), (m), (m)</td>
<td>Tip translational deflection (relative to the undeflected position) expressed in r</td>
</tr>
<tr>
<td>TipRDxr, TipRDyr, TipRDzr</td>
<td>(°), (°), (°)</td>
<td>Tip angular/rotational deflection Wiener-Milenkovic parameter (relative to the undeflected orientation) expressed in r</td>
</tr>
<tr>
<td>TipTVXg, TipTVYg, TipTVZg</td>
<td>(m/s), (m/s), (m/s)</td>
<td>Tip translational velocities (absolute) expressed in g</td>
</tr>
<tr>
<td>TipRVXg, TipRVYg, TipRVZg</td>
<td>(deg/s), (deg/s), (deg/s)</td>
<td>Tip angular/rotational velocities (absolute) expressed in g</td>
</tr>
<tr>
<td>TipTAXg, TipTAYg, TipTAZg</td>
<td>(m/s²), (m/s²), (m/s²)</td>
<td>Tip translational accelerations (absolute) expressed in g</td>
</tr>
<tr>
<td>TipRAXg, TipRAYg, TipRAZg</td>
<td>(deg/s²), (deg/s²), (deg/s²)</td>
<td>Tip angular/rotational accelerations (absolute) expressed in g</td>
</tr>
<tr>
<td>NβFxl, NβFyl, NβFzl</td>
<td>(N), (N), (N)</td>
<td>Applied point forces at Nβ expressed in l</td>
</tr>
<tr>
<td>NβPMxl, NβPMyl, NβPMzl</td>
<td>(N m), (N m), (N m)</td>
<td>Applied point moments at Nβ expressed in l</td>
</tr>
<tr>
<td>NβDFxl, NβDFyl, NβDFzl</td>
<td>(N/m), (N/m), (N/m)</td>
<td>Applied distributed forces at Nβ expressed in l</td>
</tr>
<tr>
<td>NβDMxl, NβDMyl, NβDMzl</td>
<td>(N m/m), (N m/m), (N m/m)</td>
<td>Applied distributed moments at Nβ expressed in l</td>
</tr>
</tbody>
</table>

Fig. 4.30: BeamDyn Output Channel List
SubDyn relies on two main engineering schematizations: (1) a linear frame finite-element beam model (LFEB), and (2) a dynamics system reduction via the Craig-Bampton (C-B) method, together with a static-improvement method (SIM), greatly reducing the number of modes needed to obtain an accurate solution. More details can be found in Section 6, and in [SDRJ13], [DS13], [DSRJ13], [JBH+20].

In SubDyn, the substructure is considered to be either clamped or supported by springs at the seabed, and rigidly connected to the transition piece (TP) at the substructure top nodes (interface nodes). The spring constants are provided by the user to simulate soil-structure-interaction (SSI). Other restraint formulations may be implemented in the future. Only the substructure structural dynamics are intended to be modeled within SubDyn. When integrated with FAST, the structural dynamics of the TP, tower, and rotor-nacelle assembly (RNA) are modeled within FAST’s ElastoDyn module and hydrodynamics are modeled within FAST’s HydroDyn module. For full lattice support structures or other structures with no transition piece, however, the entire support structure up to the yaw bearing may be modeled within SubDyn. Modeling the tower in SubDyn as opposed to ElastoDyn, for example, allows for the possibility of including more than the first two fore-aft and side-to-side bending modes, thus accounting for more general flexibility of the tower and its segments. However, for tubular towers, the structural model in ElastoDyn tends to be more accurate because ElastoDyn considers geometric nonlinearity not treated in SubDyn.

Loads and responses are transferred between SubDyn, HydroDyn, and ElastoDyn via the FAST driver program (glue code) to enable hydro-elastic interaction at each coupling time step. At the interface nodes, the TP six degree-of-freedom (DOF) displacements (three translations and three rotations), velocities, and accelerations are inputs to SubDyn from ElastoDyn; and the six reaction loads at the TP (three forces and three moments) are outputs from SubDyn to ElastoDyn. SubDyn also outputs the local substructure displacements, velocities, and accelerations to HydroDyn in order to calculate the local hydrodynamic loads that become inputs for SubDyn. In addition, SubDyn can calculate member internal reaction loads, as requested by the user (see Figure 1).

The input file defines the substructure geometry, material properties, restraints and SSI data files, finite-element resolution, number of retained modes in the dynamics system reduction, modal damping coefficients, and auxiliary parameters. The geometry is defined by joint coordinates in the global reference system (inertial-frame coordinate system shown in ), with the origin at the intersection of the undeflected tower centerline with mean sea level (MSL) or ground level for land-based structures. A member connects two joints; multiple members may use a common joint.

Fig. 4.31: SubDyn, HydroDyn, and FAST 8 coupled interaction
Nodes are the result of the member refinement into multiple (*NDiv* input parameter) elements (nodes are located at the ends of each element, as shown in ), and they are calculated by the module.

In the current release, the geometry of a member is defined by its outer diameter and wall thickness (assuming a tubular geometry), and the material properties are defined by its Young’s modulus, shear modulus, and mass density. Member properties are specified at the joints; if properties change from one joint to the other, they will be linearly interpolated for the inner elements. Thus, a tapered member will be treated as a cylindrical member with step-wise variation of its properties. In a future release, a tapered finite-element formulation will be implemented, and a more accurate representation of a tapered member will become available.

The hydrodynamic loads (including buoyancy) are computed by HydroDyn and transferred by the glue code at those nodes that are underwater (submerged nodes). Additionally, the self-weight distributed load components (from gravity) are calculated by SubDyn and applied at all the nodes. Note that other load and inertial properties may be input via the HydroDyn module input file, where marine growth and flooding/ballasting of the members can be specified.

This document is organized as follows. Section 4.7.2 Running SubDyn details how to obtain the SubDyn and FAST software archives and run either the stand-alone version of SubDyn or SubDyn coupled to FAST. Section Input Files describes the SubDyn input files. Section 4 discusses the Output Files generated by SubDyn; these include echo files, a summary file, and the results file. Section 5 provides modeling guidance when using SubDyn. The SubDyn theory is covered in Section SubDyn Theory. Section Known Limitations and Future Work outlines future work, and Section 8 contains a list of references. Example input files are shown in Appendices 4.7.8 and B. A summary of available output channels are found in Appendix D. List of Output Channels. Instructions for compiling the stand-alone SubDyn program are detailed in Appendix D. Appendix E tracks the major changes that have been made to SubDyn for each public release.

### 4.7.2 Running SubDyn

This section discusses how to obtain and execute SubDyn from a personal computer. Both the stand-alone version and the FAST-coupled version of the software are considered.

**Downloading the SubDyn Software**

There are two forms of the SubDyn software to choose from: stand alone and coupled to the FAST simulator. Although the user may not necessarily need both forms, he/she would likely need to be familiar with and run the stand-alone model if building a model of the substructure from scratch. The stand-alone version is also helpful for model troubleshooting and may benefit users who are interested in conducting aero-hydro-servo-elastic simulations of an offshore wind turbine.

Users can refer to the OpenFAST installation to download and compile SubDyn.

**Running SubDyn**

**Running the Stand-Alone SubDyn Program**

The stand-alone SubDyn program, `SubDyn_win32.exe`, simulates substructure dynamic responses of the user’s input model, without coupling to FAST. Unlike the coupled version, the stand-alone software requires the use of a driver file in addition to the primary SubDyn input file. This driver file specifies inputs normally provided to SubDyn by FAST, including motions of the TP reference point. Both the SubDyn summary file and the results output file are available when using the stand-alone SubDyn (see Section 4 for more information regarding the SubDyn output files).

Run the standalone SubDyn software from a DOS command prompt by typing, for example:

```bash
>SubDyn_win32.exe MyDriverFile.dvr
```
where, *MyDriverFile.dvr* is the name of the SubDyn driver file, as described in Section 4.7.3. The SubDyn primary input file is described in Section Section 4.7.3.

**Running SubDyn Coupled to FAST**

Run the coupled FAST software from a DOS command prompt by typing, for example:

```
>FAST_Win32.exe Test21.fst
```

where, *Test21.fst* is the name of the primary FAST input file. This input file has a feature switch to enable or disable the SubDyn capabilities within FAST, and a corresponding reference to the SubDyn input file. See the documentation supplied with FAST for further information.

**4.7.3 Input Files**

The user specifies the substructure model parameters, including its geometry and properties, via a primary SubDyn input file. When used in stand-alone mode, an additional driver input file is required. This driver file specifies inputs normally provided to SubDyn by FAST, including motions of the TP reference point.

No lines should be added or removed from the input files, except in tables where the number of rows is specified.

Additional input files containing soil-structure information (*SSIfile*) can be provided by the user specifying their paths in the main SubDyn input file under the section titled *BASE REACTION JOINTS*.

**Units**

SubDyn uses the SI system (kg, m, s, N). Angles are assumed to be in radians unless otherwise specified.

**SubDyn Driver Input File**

The driver input file is only needed for the stand-alone version of SubDyn and contains inputs that are normally set by FAST, and that are necessary to control the simulation for uncoupled models. It is possible to provide per-time-step inputs to SubDyn, even in stand-alone mode, by tying the driver file to an additional input file containing time-histories of the TP motion (displacements, velocities, and accelerations). A sample SubDyn driver input file is given in Section 4.7.9.

Users can set the *Echo* flag in this file to TRUE so that *SubDyn_win32.exe* echoes the contents of the driver input file (useful for debugging errors in the driver file). The echo file has the naming convention of *OutRootName.dvr.ech*. *OutRootName* is specified in the SUBDYN section of the driver input file (see below).

Set the gravity constant using the *Gravity* parameter. SubDyn expects a magnitude, so in SI units this would be set to 9.80665 \( \frac{m}{s^2} \) for standard gravity. *WtrDpth* specifies the water depth (depth of the seabed), based on the reference MSL, and must be a value greater than zero.

*SDInputFile* is the file name of the primary SubDyn input file. This name should be in quotations and can contain an absolute path or a relative path. All SubDyn-generated output files will be prefixed with *OutRootName*. If this parameter includes a file path, the output will be generated in that folder. *NSteps* specifies the number of simulation time steps, and *TimeStep* specifies the time between steps. Next, the user must specify the location of the TP reference point *TP_RefPoint* (in the global reference system). This is normally set by FAST through the ElastoDyn input file, and it is the so-called platform reference point location. When coupled to FAST, the platform reference point location is identified by only one \( Z \) coordinate. The interface joints, defined in SubDyn’s main input file, are rigidly connected to this reference point. To utilize the same geometry definition within SubDyn’s main input file, while still allowing for different substructure orientations about the vertical, the user can set *SubRotateZ* to a prescribed angle in degrees.
with respect to the global Z-axis. The entire substructure will be rotated by that angle. (This feature is only available in stand-alone mode.)

Setting InputsMod = 0 sets all TP reference-point input motions to zero for all time steps. Setting InputsMod = 1 allows the user to provide steady (fixed) inputs for the TP motion in the STEADY INPUTS section of the file—\texttt{uTPInSteady}, \texttt{uDotTPInSteady}, and \texttt{uDotDotTPInSteady} following the same convention as Table 1 (without time). Setting InputsMod = 2 allows the user to input a time-series file whose name is specified via the InputsFile parameter. The time-series input file is a text-formatted file. This file has no header lines, NSteps rows, and each \(i\)th row has the first column showing time as \(t = (i - 1) \times \text{TimeStep}\) (the data will not be interpolated to other times). The remainder of each row is made of white-space-separated columns of floating point values representing the necessary motion inputs as shown in Table 1. All motions are specified in the global, inertial-frame coordinate system. SubDyn does not check for physical consistency between the displacement, velocity, and acceleration motions specified for the TP reference point in the driver file.

Table 1. TP Reference Point Inputs Time-Series Data File Contents

<table>
<thead>
<tr>
<th>Column Number</th>
<th>Input</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Time step value</td>
<td>s</td>
</tr>
<tr>
<td>2-4</td>
<td>TP reference point translational displacements along X, Y, and Z</td>
<td>m</td>
</tr>
<tr>
<td>5-7</td>
<td>TP reference point rotational displacements about X, Y, and Z (small angle assumptions apply)</td>
<td>rad/s</td>
</tr>
<tr>
<td>8-10</td>
<td>TP reference point translational velocities along X, Y, and Z</td>
<td>m/s</td>
</tr>
<tr>
<td>11-13</td>
<td>TP reference point rotational velocities about X, Y, and Z</td>
<td>rad/s</td>
</tr>
<tr>
<td>14-16</td>
<td>TP reference point translational accelerations along X, Y, and Z</td>
<td>m/s^2</td>
</tr>
<tr>
<td>17-19</td>
<td>TP reference point rotational accelerations about X, Y, and Z</td>
<td>rad/s^2</td>
</tr>
</tbody>
</table>

**SubDyn Primary Input File**

The SubDyn input file defines the substructure geometry, integration and simulation options, finite-element parameters, and output channels. The geometry of members is defined by joint coordinates of the undisplaced substructure in the global reference system (inertial-frame coordinate system), with the origin at the intersection of the undeflected tower centerline with MSL or ground level for land-based structures. A member connects two joints; multiple members can use a common joint. The hydrodynamic and gravity loads are applied at the nodes, which are the resultant of member refinement into multiple (NDiv input) elements (nodes are located at the ends of each element), as calculated by the module. Member properties include outer diameter, thickness, material density, and Young’s and shear moduli. Member properties are specified at the joints; if properties change from one joint to the other, they will be linearly interpolated for the inner nodes. Unlike the geometric properties, the material properties are not allowed to change within a single member.

Future releases will allow for members of different cross-sections, i.e., noncircular members. For this reason, the input file has (currently unused) sections dedicated to the identification of direction cosines that in the future will allow the module to identify the correct orientation of noncircular members. The current release only accepts tubular (circular) members.

The file is organized into several functional sections. Each section corresponds to an aspect of the SubDyn model and substructure.

If this manual refers to an ID in a table entry, it is an integer identifier for the table entry and must be unique for a given table entry.

A sample SubDyn primary input file is given in Section 4.7.8.

The input file begins with two lines of header information, which is for the user but is not used by the software.
Simulation Control Parameters

Users can set the **Echo** flag to TRUE to have SubDyn echo the contents of the SubDyn input file (useful for debugging errors in the input file). The echo file has the naming convention of **OutRootName.SD.ech**. **OutRootName** is either specified in the SUBDYN section of the driver input file when running SubDyn standalone, or by FAST, when running a coupled simulation, from FAST’s main input file.

**SDdeltaT** specifies the fixed time step of the integration in seconds. The keyword ‘DEFAULT’ may be used to indicate that the module should employ the time step prescribed by the driver code (FAST/standalone driver program).

**IntMethod** specifies the integration algorithm to use. There are four options: 1) Runge-Kutta 4th-order explicit (RK4); 2) Adams-Bashforth 4th-order explicit predictor (AB4); 3) Adams-Bashforth-Moulton 4th-order explicit predictor-corrector (ABM4); 4) Adams-Moulton implicit 2nd-order (AM2). See Section on how to properly select this and the previous parameter values.

**SttcSolve** is a flag that specifies whether the static improvement method (SIM, see Section 4.7.6) shall be employed. Through this method, all (higher frequency) modes that are not considered by the C-B reduction are treated quasistatically. This treatment helps minimize the number of retained modes needed to capture effects such as static gravity and buoyancy loads, and high-frequency loads transferred from the turbine. Recommended to set to True.

**GuyanLoadCorrection** is a flag to specify whether the extra moment due to the lever arm from the Guyan deflection of the structure is to be added to the loads passed to SubDyn, and, whether the FEM representation should be expressed in the rotating frame in the floating case (the rotation is induced by the rigid body Guyan modes). See section Section 4.7.6 for details. Recommended to set to True.

FEA and Craig-Bampton Parameters

**FEMMod** specifies one of the following options for finite-element formulation: 1) Euler-Bernoulli; 3) Timoshenko. Tapered formulations (2 and 4) have yet to be implemented and will be available in a future release.

**NDiv** specifies the number of elements per member. Analysis nodes are located at the ends of elements and the number of analysis nodes per member equals **NDiv** + 1. **NDiv** is applied uniformly to all members regardless of the member’s length, hence it could result in small elements in some members and long elements in other members. Increasing the number of elements per member may increase accuracy, with the trade-off of increased memory usage and computation time. We recommend using **NDiv** > 1 when modeling tapered members.

**CBMod** is a flag that specifies whether or not the C-B reduction should be carried out by the module. If FALSE, then the full finite-element model is retained and **Nmodes** is ignored.

**Nmodes** sets the number of internal C-B modal DOFs to retain in the C-B reduction. **Nmodes** = 0 corresponds to a Guyan (static) reduction. **Nmodes** is ignored if **CBMod** is set to FALSE, meaning the full finite-element model is retained by keeping all modes (i.e. a modal analysis is still done, and all the modes are used as DOFs).

**JDampings** specifies value(s) of damping coefficients as a percentage of critical damping for the retained C-B modes. Distinct damping coefficients for each retained mode should be listed on the same line, separated by white space. If the number of **JDampings** is less than the number of retained modes, the last value will be replicated for all the remaining modes. (see Section 4.7.6)

**GuyanDampMod** Guyan damping [0=none, 1=Rayleigh Damping, 2= user specified 6x6 matrix] (see Section 4.7.6)

**RayleighDamp** Mass and stiffness proportional damping coefficients ((\(\alpha\), \(\beta\)) Rayleigh damping) [only if GuyanDampMod=1] Guyan damping matrix (6x6) [only if GuyanDampMod=2] (see Section 4.7.6)

**Guyan damping matrix**: The 6 lines following this input line consists of the 6x6 coefficients of the damping matrix to be applied at the interface. (see Section 4.7.6)

For more information on these parameters and guidelines on how to set them, see Sections Section 4.7.5 and Section 4.7.6.
**Structure Joints**

The finite-element model is based on a substructure composed of joints interconnected by members. \( NJoints \) is the user-specified number of joints, and determines the number of rows in the subsequent table. Because a member connects two joints, \( NJoints \) must be greater than or equal to two. Each joint listed in the table is identified by a unique integer, \( JointID \); each integer between one and \( NJoints \) must be present in the table, but they need not be sequential. The \( (X,Y,Z) \) coordinate of each joint is specified in the substructure (SS) coordinate system, which coincides with the global inertial-frame coordinate system via \( JointXss \), \( JointYss \), and \( JointZss \), respectively. This version of SubDyn does not consider overlap when multiple members meet at a common joint, therefore, it tends to overestimate the total substructure mass. Member overlap and node offset calculations will be considered in a future release of SubDyn. The fifth column specifies the \( JointType \) (see Section 4.7.6):

- Cantilever joints \( (JointType=1) \)
- Universal joint \( (JointType=2) \)
- Pin joint \( (JointType=3) \)
- Ball joint \( (JointType=4) \)

The three following columns specify the vector coordinates of the direction around which rotation is free for a pin joints. The last column, \( JointStiff \) specify a value of additional stiffness to be added to the “free” rotational DOFs of Ball, Pin and Universal joints.

Note for HydroDyn coupling: modeling a fixed-bottom substructure embedded into the seabed (e.g., through piles or suction buckets) requires that the lowest member joint(s) in HydroDyn lie(s) below the water depth. Placing a joint at or above the water depth will result in static and dynamic pressure loads being applied at the joint. When SubDyn is coupled to FAST, the joints and members need not match between HydroDyn and SubDyn—FAST’s mesh-mapping utility handles transfer of motion and loads across meshes in a physically relevant manner (Sprague et al. 2014), but consistency between the joints and members in HydroDyn and SubDyn is advised.

An example of joint table is given below

<table>
<thead>
<tr>
<th>(NJoints ) - Number of joints (-)</th>
<th>JointID</th>
<th>JointXss (m)</th>
<th>JointYss (m)</th>
<th>JointZss (m)</th>
<th>JointType (-)</th>
<th>JointDirX (-)</th>
<th>JointDirY (-)</th>
<th>JointDirZ (-)</th>
<th>JointStiff (Nm/rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>0.0</td>
<td>0.0</td>
<td>50.0</td>
<td>1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>111</td>
<td>0.0</td>
<td>0.0</td>
<td>10.0</td>
<td>2</td>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
<td>102</td>
<td>0.0</td>
<td>0.0</td>
<td>-45.0</td>
<td>1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
</tr>
</tbody>
</table>

**Base Reaction Joints**

SubDyn requires the user to specify the boundary joints. \( NReact \) should be set equal to the number of joints (defined earlier) at the bottom of the structure (i.e., seabed) that are fully constrained; \( NReact \) also determines the number of rows in the subsequent table. In SubDyn, \( NReact \) must be greater than or equal to one. Each joint listed in the table is identified by a unique integer, \( RJointID \), which must correspond to the \( JointID \) value found in the STRUCTURE JOINTS table. The flags \( RetDXs, RetDYs, RetDZs, RetDXs, RetDYs, RetDZs \) indicate the fixity value for the three translations (TD) and three rotations (RD) in the SS coordinate system (global inertial-frame coordinate system). One denotes fixed and zero denotes free (instead of TRUE/FALSE). \( SSIfile \) points to the relative path and filename for an SSI information file. This version of SubDyn can, in fact, handle partially restrained joints by setting one or more DOF flags to 0 and providing the appropriate stiffness and mass matrix elements for that DOF via the \( SSIfile \). If a DOF flag is set to 1, then the node DOF is considered restrained and the associated matrix elements potentially provided in the \( SSIfile \) will be ignored.

An example of base reaction and interface table is given below

<table>
<thead>
<tr>
<th>(NReact ) - Number of reaction joints (-)</th>
<th>RJointID</th>
<th>RetDXs (-)</th>
<th>RetDYs (-)</th>
<th>RetDZs (-)</th>
<th>RetDXs (-)</th>
<th>RetDYs (-)</th>
<th>RetDZs (-)</th>
<th>SSIfile</th>
</tr>
</thead>
<tbody>
<tr>
<td>154 Chapter 4. User Documentation</td>
<td>101</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
</tr>
</tbody>
</table>
### BASE REACTION JOINTS

<table>
<thead>
<tr>
<th>RJointID</th>
<th>RctTDXss</th>
<th>RctTDYss</th>
<th>RctTDZss</th>
<th>RctRDXss</th>
<th>RctRDYss</th>
<th>RctRDZss</th>
<th>SSIfile</th>
</tr>
</thead>
<tbody>
<tr>
<td>61</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>&quot;SSI.txt&quot;</td>
</tr>
</tbody>
</table>

### INTERFACE JOINTS

<table>
<thead>
<tr>
<th>IJointID</th>
<th>ItfTDXss</th>
<th>ItfTDYss</th>
<th>ItfTDZss</th>
<th>ItfRDXss</th>
<th>ItfRDYss</th>
<th>ItfRDZss</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

SubDyn requires the user to specify the interface joints. The number of interface joints should be set equal to the number of joints at the top of the structure (i.e., TP). SubDyn also determines the number of interface joints locked to the Transition Piece (TP). Each joint listed in the table is identified by a unique integer, `JointID`, which must correspond to the `JointID` value found in the STRUCTURE JOINTS table. The flags `IJointID`, `IJointID`, `IJointID`, `IJointID`, `IJointID`, `IJointID`, `IJointID` indicate the fixity value for the three translations (TD) and three rotations (RD) in the SS coordinate system (global inertial-frame coordinate system). One denotes fixed and zero denotes free (instead of TRUE/FALSE). This version of SubDyn cannot handle partially restrained joints, so all flags must be set to one; different degrees of fixity will be considered in a future release.

### Members

Members are the user-specified number of members and determines the number of rows in the subsequent table. Each member listed in the table is identified by a unique integer, `MemberID`. Each integer between one and the user-specified number of members must be present in the table, but they need not be sequential. For each member distinguished by `MemberID`, `MJointID1` specifies the starting joint and `MJointID2` specifies the ending joint, corresponding to an identifier (`JointID`) from the STRUCTURE JOINTS table. Likewise, `MPropSetID1` corresponds to the identifier `PropSetID` from the MEMBER X-SECTION PROPERTY table for starting cross-section properties and `MPropSetID2` specifies the identifier for ending cross-section properties, allowing for tapered members. The sixth column specifies the member type `MType`. A member is one of the following types (see Section 4.7.6):

- **Beams** (`MType=1`), Euler-Bernoulli (`FEMMod=1`) or Timoshenko (`FEMMod=3`)
- **Pretension cables** (`MType=2`)
- **Rigid link** (`MType=3`)

**COSMID** refers to the IDs of the members’ cosine matrices for noncircular members; the current release ignores this column.

An example of a member table is given below:

<table>
<thead>
<tr>
<th>MemberID</th>
<th>MJointID1</th>
<th>MJointID2</th>
<th>MPropSetID1</th>
<th>MPropSetID2</th>
<th>MType</th>
<th>COSMID</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>101</td>
<td>102</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>102</td>
<td>103</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
Member Cross-Section Properties

Members in SubDyn are assumed to be straight, circular, possibly tapered, and hollow cylinders. Future releases will allow for generic cross-sections to be employed. These special cross-section members will be defined in the second of two tables in the input file (Member X-Section Property data 2/2), which is currently ignored.

For the circular cross-section members, properties needed by SubDyn are material Young’s modulus, YoungE, shear modulus, ShearG, and density, MatDens, member outer diameter, XsecD, and member thickness, XsecT. Users will need to create an entry in the first table within this section of the input file distinguished by PropSetID, for each unique combination of these five properties. The member property-set table contains NPropSets rows. The member property sets are referred to by their PropSetID in the MEMBERS table, as described in Section . Note, however, that although diameter and thickness will be linearly interpolated within an individual member, SubDyn will not allow material properties to change within an individual member.

The second table in this section of the input file (not to be used in this release) will have NXPropSets rows (assumed to be zero for this release), and have additional entries when compared to the previous table, including: cross-sectional area (XsecA), cross-sectional shear area along the local principal axes x and y (XsecAsx, XsecAsy), cross-sectional area second moment of inertia about x and y (XsecJxx, XsecJyy), and cross-sectional area polar moment of inertia (XsecJ0). The member cosine matrix section (see Section ) will help determine the correct orientation of the members within the assembly.

Cable Properties

Members that are specified as pretension cables (MType=2), have their properties defined in the cable properties table. The table lists for each cable property: the property ID (PropSetID), the cable tension stiffness (EA), the material density (MatDens), the pretension force (T0), and the control channel (CtrlChannel). The control channel is only used if ServoDyn provides dedicated control signal, in which case the cable tension (given in terms of a length change Δl) is dynamically changed (see Section 4.7.6). The FEM representation of pretension cable is given in Section 4.7.6.

An example of cable properties table is given below:

```
-------------------------- CABLE PROPERTIES -------------------------------------
<table>
<thead>
<tr>
<th>PropSetID</th>
<th>EA</th>
<th>MatDens</th>
<th>T0</th>
<th>CtrlChannel</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-)</td>
<td>(N)</td>
<td>(kg/m)</td>
<td>(N)</td>
<td>(-)</td>
</tr>
<tr>
<td>11</td>
<td>210E7</td>
<td>7850.0</td>
<td>2E7</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>210E7</td>
<td>7850.0</td>
<td>1E7</td>
<td>0</td>
</tr>
</tbody>
</table>
```

Rigid link Properties

Members that are specified as rigid links (MType=3), have their properties defined in the rigid link properties table. The table lists the material density (MatDens) for each rigid link property. The FEM representation of rigid links is given in Section 4.7.6.

An example of rigid link properties table is given below:

```
----------------------- RIGID LINK PROPERTIES ------------------------------------
<table>
<thead>
<tr>
<th>PropSetID</th>
<th>MatDens</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-)</td>
<td>(kg/m)</td>
</tr>
<tr>
<td>12</td>
<td>7850.0</td>
</tr>
<tr>
<td>3</td>
<td>7000.0</td>
</tr>
</tbody>
</table>
```
**Member Cosine Matrices COSM (i,j)**

This table is not currently used by SubDyn, but in future releases it will need to be populated if members with cross-sections other than circular will be employed.

**NCOSMs** rows, one for each unique member orientation set, will need to be provided. Each row of the table will list the nine entries of the direction cosine matrices (COSM11, COSM12,...COSM33) for matrix elements (1,1), (1,2),...,(3,3) that establish the orientation of the local member axes (x,y principal axes in the cross-sectional plane, z along the member longitudinal axis) with respect to the SS coordinate system (local-to-global transformation matrices).

**Joint Additional Concentrated Masses**

SubDyn can accept **NCmass** lumped masses/inertias defined at the joints. The subsequent table will have **NCmass** rows, in which for each joint distinguished by **CMJointID** (corresponding to an identifier, **JointID**, from the STRUCTURE JOINTS table), **JMass** specifies the lumped mass value, and **JMXX, JMYY, JMZZ** specify the mass second moments of inertia with respect to the SS coordinate system (not the element system). Latest version of SubDyn accept 6 additional columns (**JMXY, JMXZ, JMYZ, MCGX, MCGY, MCGZ**) to specify off-diagonal terms.

The additional mass matrix added to the node is computed in the SS system as follows:

\[
M_{add} = \begin{bmatrix}
m & 0 & 0 & 0 & 0 & zm & 0 & 0 & ym \\
0 & m & 0 & zm & 0 & 0 & 0 & xm \\
0 & 0 & m & ym & zm & 0 & J_{xx} + m(y^2 + z^2) & J_{xy} - mxy & J_{xz} - mxz \\
zm & 0 & -xm & J_{xy} - mxy & J_{yy} + m(x^2 + z^2) & J_{yz} - myz \\
0 & ym & xm & J_{xz} - mxz & J_{yz} - myz & J_{zz} + m(x^2 + y^2)
\end{bmatrix}
\]

with \(m\) the parameter **JMass**, and \(x, y, z\), the CG offsets.

An example of concentrated mass table is given below:

<table>
<thead>
<tr>
<th>CMJointID</th>
<th>JMass</th>
<th>JMXX</th>
<th>JMYY</th>
<th>JMZZ</th>
<th>JMYX</th>
<th>JMXZ</th>
<th>JMYZ</th>
<th>MCGX</th>
<th>MCGY</th>
<th>MCGZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-)</td>
<td>(kg)</td>
<td>(kgm^2)</td>
<td>(kgm^2)</td>
<td>(kgm^2)</td>
<td>(kgm^2)</td>
<td>(kgm^2)</td>
<td>(kgm^2)</td>
<td>(m)</td>
<td>(m)</td>
<td>(m)</td>
</tr>
<tr>
<td>1</td>
<td>4090</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>4.2e6</td>
<td>0</td>
<td>0</td>
<td>3.3e9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Output: Summary and Outfile**

In this section of the input file, the user sets flags and switches for the desired output behavior.

Specifying **SDSum** = TRUE causes SubDyn to generate a summary file with name OutRootName.SD.sum*. OutRootName is either specified in the SUBDYN section of the driver input file when running SubDyn in stand-alone mode, or in the FAST input file when running a coupled simulation. See Section 4.2 for summary file details.

In this release, OutCOSM is ignored. In future releases, specifying OutCOSM = TRUE will cause SubDyn to include direction cosine matrices (undeflected) in the summary file for only those members requested in the list of output channels.

Specifying **OutAll** = TRUE causes SubDyn to output forces and moments at all of the joints (not internal nodes). That is, the static (elastic) and dynamic (inertia) components of the three forces and three moments at the end node of each member connected to a given joint are output for all joints. These outputs are included within the OutRootName.SD.out* output file in addition to those directly specified through the output channels section below.

If **OutSwitch** is set to one, outputs are sent to a file with the name OutRootName.SD.out*. If **OutSwitch** is set to two, outputs are sent to the calling program (FAST) for writing in its main output file (not available in stand-alone mode).
If `OutSwtch` is set to three, both file outputs occur. In stand-alone mode, setting `OutSwtch` to two results in no output file being produced.

If `TabDelim` is set to TRUE and `OutSwtch` is set to one, the output file `OutRootName`.SD.out* will be tab-delimited.

With `OutDec` set to an integer value greater than one, the output file data rate will be decimated, and only every `OutDec`-th value will be written to the file. This applies only to SubDyn’s output file (`OutRootName`.SD.out*)—not FAST’s.

The `OutFmt` and `OutSFmt` parameters control the formatting of SubDyn’s output file for the output data and the channel headers, respectively. SubDyn currently does not check the validity of these format strings. They need to be valid Fortran format strings. `OutSFmt` is used for the column header and `OutFmt` is used for the channel data. Therefore, in order for the headers and channel data to align properly, the width specification should match. For example:

```
“ES11.4” OutFmt
“A11” OutSFmt.
```

**Member Output List**

SubDyn can output load and kinematic quantities at up to nine locations for up to nine different members, for a total of 81 possible local member output locations. `NMOutputs` specifies the number of members that output is requested for. The user must create a table entry for each requested member. Within a row of this table, `MemberID` is the ID specified in the MEMBERS table, and `NOutCnt` specifies how many nodes along the member will generate output. `NodeCnt` specifies those node numbers (a separate entry on the same line for each node) for output as an integer index from the start-joint (node 1) to the end-joint (node `NDiv` + 1) of the member. The outputs specified in the SDOutList section determines which quantities are actually output at these locations.

**Output Channels- SDOutList Section**

This section specifies which quantities are output by SubDyn. Enter one or more lines containing quoted strings that in turn contain one or more output parameter names. Separate output parameter names by any combination of commas, semicolons, spaces, and/or tabs. If a parameter name is prefixed with a minus sign, “-”, underscore, “_”, or the characters “m” or “M”, SubDyn will multiply the value for that channel by –1 before writing the data. The parameters are written in the order they are listed in the input file. SubDyn allows the use of multiple lines so that users can break their lists into meaningful groups and so the lines can be shorter. Comments may also be entered after the closing quote on any of the lines. Entering a line with the string “END” at the beginning of the line or at the beginning of a quoted string found at the beginning of the line will cause SubDyn to quit scanning for more lines of channel names. Modal kinematics and member-node-, base-, and interface-related kinematic and load quantities can be selected. Member-node-related data follow the organization described in Section . If SubDyn encounters an unknown/invalid channel name, it prints an error message and halts execution. Please refer to Section 4.7.10 for a complete list of possible output parameters and their names.
SSI Input File

Individual SSI files (SSIfiles) can be provided for each restrained node, therefore the maximum number of SSI files is \( N_{\text{React}} \). In an SSI file, up to 21 elements for the SSI mass matrix and up to 21 SSI stiffness matrix elements can be provided. The mass and stiffness elements account for both pile and soil effects. No additional damping can be provided at this point.


If any matrix element is not provided it will be set to infinity (i.e., machine ‘huge’) by default.

For the mass matrix the accepted labels are: ‘Mxx’, ‘Mxy’, ‘Myy’, ‘Mxz’, ‘Myz’, ‘Mzz’, ‘Mtxx’, ‘Mytx’, ‘Mztx’, ‘Mxtx’, ‘Myty’, ‘Mztz’, ‘Mtty’, ‘Mzty’, ‘Mtxy’, ‘Mtyt’, ‘Mzty’, ‘Mtyt’. If any matrix element is not provided it will be set to 0 by default. The labels contain ‘K’ or ‘M’ to specify stiffness or mass matrix elements, and then the directions they apply to, e.g., ‘Kxy’ refers to the force along x due to a unit displacement along y; the ‘t’ refers to the rotation about one of the ‘x’, ‘y’, or ‘z’ axes in the global coordinate system.

Units are in SI system (N/m; N/m/rad; Nm/rad, Kg, kgm, kgm2).

Note that by selecting fixities of 1 in the various DOFs of the restrained nodes, the columns and rows associated with those DOFs will be removed, therefore the associated matrix elements will be ignored.

A sample SubDyn SSI input file is given in Section 4.7.10.

4.7.4 Output Files

SubDyn produces three types of output files: an echo file, a summary file, and a time-series results file. The following sections detail the purpose and contents of these files.

Echo File

If the user sets the \texttt{Echo} flag to TRUE in the SubDyn driver file or the primary SubDyn input file, the contents of those files will be echoed to a file with the naming conventions, \texttt{OutRootName.dvr.ech} for the driver input file and \texttt{OutRootName.SD.ech} for the primary SubDyn input file. \texttt{OutRootName} is either specified in the \texttt{SUBDYN} section of the driver input file, or in the FAST input file. The echo files are helpful for debugging the input files. The contents of an echo file will be truncated if SubDyn encounters an error while parsing an input file. The error usually corresponds to the line after the last successfully echoed line.

Summary File

SubDyn generates a summary file with the naming convention, \texttt{OutRootName.SD.sum} if the \texttt{SDSum} parameter is set to TRUE. This file summarizes key information about the substructure model, including:

- Undisplaced node geometry: a list of all of the (\( N_{\text{Nodes}} \)) nodes and the \( X,Y,Z \) coordinates in the global SS coordinate system. Note that \( N_{\text{Nodes}} \) may be greater or equal to \( N_{\text{Joints}} \), depending on \( N_{\text{Div}} \) (primary input file parameters).

- Element connectivity and properties at end nodes: a list of all (\( N_{\text{Elems}} \)) elements, the start and end nodes (\texttt{Node\_I, Node\_J}) and the ID of the property set (\texttt{Prop\_I, Prop\_J}) at the start and end nodes. \( N_{\text{Elems}} \) may be greater or equal to \( N_{\text{Members}} \), depending on \( N_{\text{Div}} \) (primary input file parameters).

- Property sets. If tapered members are used, additional property sets may be included beyond those specified in the main input file, based on interpolated diameter and thickness values. Headers and their meanings are identical to those described in Section.
• Reaction DOFs and interface DOFs and their associated fixity; the actual indices of the DOFs (DOF_ID) associated with reaction and interface nodes are listed together with the (1/0) flag to distinguish the fixity level.

• Concentrated mass schedule. This is an echo of the equivalent section in the primary input file. Refer to Section.

• Member schedule including connectivity to joints, nodes, and their masses. A table lists all of the members by identifier (MemberID), with their start and end nodes (Joint1_ID, Joint2_ID), associated mass (Mass), and list of node identifiers along the length of the members.

• Direction cosine matrices for the members. Each row (columns 2-10) corresponds to the direction cosine matrix entries (DC(1,1) through DC(3,3)) for the member whose identifier is listed in the first column. The direction cosine matrices specify the transformation from the global reference to the local coordinate system for each member.

• Sorted eigenfrequencies [in Hertz (Hz)] for the full substructural system (neglecting a possible coupling to ElastoDyn through FAST), assuming the TP reference point is a free end. There are a total of NDOFs eigenfrequencies and eigenvectors.

• Sorted eigenfrequencies (in Hz) for the C-B reduced system, assuming the TP reference point is a fixed end. There are a total of Nmodes C-B reduced eigenfrequencies and eigenvectors.

• Full substructural system eigenvectors. Each column represents an eigenvector associated with the corresponding eigenfrequency identified previously in the file.

• C-B reduced system eigenvectors (PhiM matrix). Each column represents an eigenvector associated with the corresponding eigenfrequency identified previously in the file.

• PhiR matrix or displacements of the internal nodes caused by unit rigid body motions of the interface DOFs (see Section). Each column of the matrix represents the internal DOF displacements for a given unit rigid-body motion along an interface DOF for each base and interface joint.

• Substructure equivalent stiffness and mass matrices referred to the TP reference point (KBBt and MBBt), based on a Guyan reduction. These are useful to calculate effects of substructure flexibility while calculating tower eigenmodes for ElastoDyn.

• Rigid-body-equivalent mass matrix relative to global origin (MRB); a 6x6 mass matrix.

• Substructure total (dry) mass.

• Substructure center of mass coordinates in the global coordinate system.

The various sections of the summary file and variables are self-explanatory and easily identifiable in the file.

Results File

The SubDyn time-series results are written to a text-based file with the naming convention OutRootName.SD.out when OutSwitch is set to either one or three. If SubDyn is coupled to FAST and OutSwitch is set to two or three, then FAST will generate a master results file that includes the SubDyn results. The results in OutRootName.SD.out are in table format, where each column is a data channel (the first column always being the simulation time), and each row corresponds to a simulation time step. The data channels are specified in the SDOutList section of the input file. The column format of the SubDyn-generated file is specified using the OutFmt and OutSFmt parameters of the input file.
4.7.5 Modeling Considerations

SubDyn was designed as a flexible tool for modeling a wide range of substructures for both land-based and offshore applications. This section provides some general guidance to help construct models that are compatible with SubDyn.

Please refer to the theory in Section 6 for detailed information about SubDyn’s coordinate systems, and the theoretical approach we have followed in SubDyn.

Model Discretization

SubDyn allows for the specification of arbitrary multimember structure geometries. The user defines the geometry of a structure in SubDyn using joints and members. Specifically, the user specifies a list of joints that represent the endpoints of beams, and the connectivity between one or more members at each joint. Members and their cross-sectional properties are then defined between two joints. Members can be further subdivided into multiple ($NDiv$) elements to increase the model resolution. Nodes, where the numerical calculations take place, are located at the endpoints of each element. To keep the mesh as uniform as possible when using $NDiv$, the initial member definition should also have a roughly uniform mesh. For tapered members, we recommend setting $NDiv > 1$. Improper discretization of the members may decrease the accuracy of the model.

When SubDyn is coupled to FAST, the joints and members need not match between HydroDyn and SubDyn—FAST’s mesh-mapping utility handles the transfer of motion and loads across meshes in a physically relevant manner [MJJ14], but consistency between the joints and members in HydroDyn and SubDyn is advised.

For offshore applications, because of the exponential decay of hydrodynamic loads with depth, HydroDyn requires higher resolution near the water free surface to properly capture loads as waves oscillate about the still water level (SWL). We recommend that the HydroDyn discretization not exceed element lengths of 0.5 m in the region of the free surface (5 to 10 m above and below SWL), 1.0 m between 25- and 50-m depth, and 2.0 m in deeper waters.

When SubDyn is hydro-elastically coupled to HydroDyn through FAST for the analysis of fixed-bottom offshore systems, we recommend that the length ratio between elements of SubDyn and HydroDyn not exceed 10 to 1. As such, we recommend that the SubDyn discretization not exceed element lengths of 5 m in the region of the free surface, 10 m down to 25- to 50-m depth, and 20 m in deeper waters. These are not absolute rules, but rather a good starting point that will likely require refinement for a given substructure. Additional considerations for SubDyn discretization include aspects that will impact structural accuracy, such as member weight, substructure modes and/or natural frequencies, load transfer, tapered members, and so on.

Members in SubDyn are assumed to be straight circular (and possibly tapered) cylinders. The use of more generic cross-sectional shapes will be considered in a future release.

Foundations

There are two methods that can be used to model foundation flexibility or soil-structure interaction in SubDyn. The first method makes use of the SSI stiffness and mass matrices at the partially restrained bottom joints as described in Sections 3.3.4, 3.4, and 6. The second method mimics the flexibility of the foundation through the apparent (or effective) fixity (AF) length approach, which idealizes a pile as a cantilever beam that has properties that are different above and below the mudline. The beam above the mudline should have the real properties (i.e., diameter, thickness, and material) of the pile. The beam below the mudline is specified with effective properties and a fictive length (i.e., the distance from the mudline to the cantilevered base) that are tuned to ensure that the overall response of the pile above the mudline is the same as the reality. The response can only be identical under a particular set of conditions; however, it is common for the properties of the fictive beam to be tuned so that the mudline displacement and rotation would be realistic when loaded by a mudline shear force and bending moment that are representative of the loading that exists when the offshore wind turbine is operating under normal conditions.

Note that in HydroDyn, all members that are embedded into the seabed (e.g., through piles or suction buckets) must have a joint that is located below the water depth. In SubDyn, the bottom joint(s) will be considered clamped or
partially restrained and therefore need not be located below the seabed when not applying the AF approach. For example, if the water depth is set to 20 m, and the user is modeling a fixed-bottom monopile with a rigid foundation, then the bottom-most joint in SubDyn can be set at $Z = -20$ m; HydroDyn, however, needs to have a $Z$-coordinate such that $Z < -20$ m. This configuration avoids HydroDyn applying static and dynamic pressure loads from the water on the bottom of the structure. When the AF approach is applied, the bottom-most joint in SubDyn should be set at $Z < -20$ m.

**Member Overlap**

As mentioned earlier, the current version of SubDyn is incapable of treating the overlap of members at the joints, resulting in an overestimate of the mass and potentially of the structure stiffness. One strategy to overcome this shortcoming employs virtual members to simulate the portion of each member within the overlap at a joint. The virtual members should be characterized by low self-mass and high stiffness. This can be achieved by introducing virtual joints at the approximate intersection of the finite-sized members, and then specifying additional members from these new joints to the original (centerline) joints. The new virtual members then use reduced material density and increased Young’s and shear moduli. Care is advised in the choice of these parameters as they may render the system matrix singular. Inspection of the eigenvalue results in the summary file should confirm whether acceptable approximations have been achieved.

**Substructure Tower/Turbine Coupling**

When SubDyn is coupled to FAST, the 6 DOFs of the platform in ElastoDyn must be enabled to couple loads and displacements between the turbine and the substructure. The platform reference-point coordinates in ElastoDyn should also be set equal to the TP reference-point’s coordinates (commonly indicating either the tower-base flange location, or TP centroid, or TP center of mass) that the user may have set in the stand-alone mode for checking the SubDyn model. A rigid connection between the SubDyn interface joints and TP reference point ($\equiv$ platform reference point) is assumed.

For full lattice support structures or other structures with no transition piece, the entire support structure up to the yaw bearing may be modeled within SubDyn. Modeling the tower in SubDyn as opposed to ElastoDyn, for example, allows the ability to include more than the first two fore-aft and side-to-side bending modes, thus accounting for more general flexibility of the tower and its segments; however, for tubular towers, the structural model in ElastoDyn tends to be more accurate because ElastoDyn considers geometric nonlinearities not treated in SubDyn. When modeling full-lattice towers using SubDyn, the platform reference point in ElastoDyn can be located at the yaw bearing; in this case, the tower-bending DOFs in ElastoDyn should be disabled.

If FAST is run with SubDyn but not HydroDyn, the water depth will be automatically set to 0 m. This will influence the calculation of the reaction loads. Reactions are always provided at the assumed mudline, therefore, they would not be correctly located for an offshore turbine as a result. Thus, it is recommended that HydroDyn always be enabled when modeling bottom-fixed offshore wind turbines.

ElastoDyn also needs tower mode shapes specified (coefficients of best-fit sixth-order polynomials), derived using appropriate tower-base boundary conditions. They can be derived with an appropriate software (finite-element analysis, energy methods, or analytically) and by making use of the SubDyn-derived equivalent substructure stiffness and mass matrices (the $K_{BBt}$ and $M_{BBt}$ matrices found in the SubDyn summary file) to prescribe the boundary conditions at the base of the tower.

For instance, using NREL’s BModes software, the SubDyn-obtained matrices can be used in place of the hydrodynamic stiffness ($\text{hydro}_K$) and mass matrices ($\text{hydro}_M$) ($\text{mooring}_K$ can be set to zero). By setting the hub_conn boundary condition to two (free-free), BModes will calculate the mode shapes of the tower when tower cross-sectional properties are supplied. To obtain eigenmodes that are compatible with the FAST modal treatment of the tower (i.e., no axial or torsional modes and no distributed rotational-inertia contribution to the eigenmodes), the tower-distributed properties should be modified accordingly in BModes (e.g., by reducing mass moments of inertia towards zero and by increasing torsional and axial stiffness while assuring convergence of the results; see also https://wind.nrel.gov/forum/wind/viewtopic.php?f=4&t=742).
The rotational inertia of the undeflected tower about its centerline is not currently accounted for in ElastoDyn. Thus, when the nacelle-yaw DOF is enabled in ElastoDyn there will not be any rotational inertia of the platform-yaw DOF (which rotates the tower about its centerline) when both the platform-yaw inertia in ElastoDyn is zero and the tower is undeflected. To avoid a potential division-by-zero error in ElastoDyn when coupled to SubDyn, we recommend setting the platform-yaw inertia ($P_{tfmYIner}$) in ElastoDyn equal to the total rotational inertia of the undeflected tower about its centerline. Note that the platform mass and inertia in ElastoDyn can be used to model heavy and rigid transition pieces that one would not want to model as a flexible body in either the ElastoDyn tower or SubDyn substructure models.

*Damping of the Guyan modes:*

There are three ways to specify the damping associated with the motion of the interface node.

1. SubDyn Guyan damping matrix using Rayleigh damping
2. SubDyn Guyan damping matrix using user defined 6x6 matrix
3. HydroDyn additional linear damping matrix ($AddB LIN$)

The specification of the Guyan damping matrix in SubDyn is discussed in Section 4.7.6.

Old:

The C-B method assumes no damping for the interface modes. This is equivalent to having six undamped rigid-body DOFs at the TP reference point in the absence of aerodynamic or hydrodynamic damping. Experience has shown that negligible platform-heave damping can cause numerical problems when SubDyn is coupled to FAST. One way to overcome this problem is to augment overall system damping with an additional linear damping for the platform-heave DOF. This augmentation can be achieved quite easily by calculating the damping from Eq. (4.93) and specifying this as the (3,3) element of HydroDyn’s additional linear damping matrix, $AddB LIN$. Experience has shown that a damping ratio of 1% of critical ($\zeta = 0.01$) is sufficient. In Eq. (4.93), $K^{(SD)}_3$ is the equivalent heave stiffness of the substructure (the (3,3) element of the $KB_{BB}$ (i.e., $K_{BB}$) matrix found in the SubDyn summary file, see also Section 6), $M^{(SD)}_3$ is the equivalent heave mass of the substructure (the (3,3) element of the $MB_{BB}$ matrix found in the SubDyn summary file, see also Section 6), and $M^{(ED)}$ is the total mass of the rotor, nacelle, tower, and TP (found in the ElastoDyn summary file).

$$C^{(HD)}_3 = 2\zeta \sqrt{K^{(SD)}_3 \left( M^{(SD)}_3 + M^{(ED)} \right)} \quad (4.93)$$

To minimize extraneous excitation of the platform-heave DOF, it is useful to set the initial platform-heave displacement to its natural static-equilibrium position, which can be approximated by Eq. (4.94), where $g$ is the magnitude of gravity. $P_{tfmHeave}$ from Eq. (4.94) should be specified in the initial conditions section of the ElastoDyn input file.

$$P_{tfmHeave} = -\left( M^{(SD)}_3 + M^{(ED)} \right) g K^{(SD)}_3 \quad (4.94)$$

Self-Weight Calculations

SubDyn will calculate the self-weight of the members and apply appropriate forces and moments at the element nodes. Lumped masses will also be considered as concentrated gravity loads at prescribed joints. The array of self-weight forces can be seen in the summary file if the code is compiled with DEBUG compiler directives. In general, SubDyn assumes that structural motions of the substructure are small, such that (1) small-angle assumptions apply to structural rotations and (2) the so-called P- Δ effect is negligible, and therefore undeflected node locations are used for self-weight calculations.
Note On Other Load Calculations

When SubDyn is coupled to HydroDyn through FAST, the hydrodynamic loads, which include buoyancy, marine-growth weight, and wave and current loads, will be applied to the effective, deflected location of the nodes by the mesh-mapping routines in the glue code. Those loads, however, are based on wave kinematics at the undeflected position (see Jonkman et al. 2014 for more information).

Craig-Bampton Guidelines

When SubDyn is coupled with FAST, it is important to choose a sufficient number of C-B modes, ensuring that the vibrational modes of the coupled system are properly captured by the coupled model. We recommend that all modes up to at least 2-3 Hz be captured; wind, wave, and turbine excitations are important for frequencies up to 2-3 Hz. Eigenanalysis of the linearized, coupled system will make checking this condition possible and aid in the selection of the number of retained modes; however, the linearization process has yet to be implemented in FAST v8. Until full-system linearization is made available, experience has shown that it is sufficient to enable all C-B modes up to 10 Hz (the natural frequencies of the C-B modes are written to the SubDyn summary file). If SIM (see Section Section 4.7.6) is not enabled, in addition to capturing physical modes up to a given frequency, the highest C-B mode must include the substructure axial modes so that gravity loading from self-weight is properly accounted for within SubDyn. This inclusion likely requires enabling a high number of C-B modes, reducing the benefit of the C-B reduction. Thus, we recommend employing the C-B reduction with SIM enabled. Because of the fixed-fixed treatment of the substructure boundary conditions in the C-B reduction, the C-B modes will always have higher natural frequencies than the physical modes.

Integration Time Step Guidelines

Another consideration when creating SubDyn input files is the time step size. SubDyn offers three explicit time-integrators — the fourth-order Runge-Kutta (RK4), fourth-order Adams-Bashforth (AB4), fourth-order Adams-Bashforth-Moulton (ABM4) methods — and the implicit second-order Adams-Moulton (AM2) method. Users have the option of using the global time step from the glue code or an alternative SubDyn-unique time step that is an integer multiple smaller than the glue-code time step. It is essential that a small enough time step is used to ensure solution accuracy (by providing a sufficient sampling rate to characterize all key frequencies of the system), numerical stability of the selected explicit time-integrator, and that the coupling with FAST is numerically stable.

For the RK4 and ABM4 methods, we recommend that the SubDyn time step follow the relationship shown in Eq. (4.95), where $f_{max}$ is the higher of (1) the highest natural frequency of the retained C-B modes and (2) the highest natural frequency of the physical modes when coupled to FAST. Although the former can be obtained from the SubDyn summary file, the latter is hard to estimate before the full-system linearization of the coupled FAST model is realized. Until then, experience has shown that the highest physical mode when SubDyn is coupled to FAST is often the platform-heave mode of ElastoDyn, with a frequency given by Eq. (4.96), where the variables are defined in Section 5.3.

$$dt_{max} = \frac{1}{10f_{max}} \quad \text{(4.95)}$$

$$f = \frac{1}{2\pi} \sqrt{\frac{K_{33}^{(SD)}}{M_{33}^{(SD)} + M^{(ED)}}} \quad \text{(4.96)}$$

For the AB4 method, the recommended time step is half the value given by Eq. (4.95).

For AM2, being implicit, the required time step is not driven by natural frequencies within SubDyn, but should still be chosen to ensure solution accuracy and that the coupling to FAST is numerically stable.
4.7.6 SubDyn Theory

Overview

This section focuses on the theory behind the SubDyn module.

SubDyn relies on two main engineering approaches: (1) a linear frame finite-element model (LFEM), and (2) a dynamics system reduction via the Craig-Bampton (C-B) method together with a static-improvement method (SIM), greatly reducing the number of modes needed to obtain an accurate solution.

There are many nonlinearities present in offshore wind substructure models, including material nonlinearity, axial shortening caused by bending, large displacements, and so on. The material nonlinearity is not considered here because most offshore multimember support structures are designed to use steel and the maximum stress is intended to be below the yield strength of the material. [DSRJ13] demonstrate that a linear finite-element method is suitable when analyzing wind turbine substructures. In this work, several wind turbine configurations that varied in base geometry, load paths, sizes, supported towers, and turbine masses were analyzed under extreme loads using nonlinear and linear models. The results revealed that the nonlinear behavior was mainly caused by the mono-tower response and had little effect on the multimember support structures. Therefore, an LFEM model for the substructure is considered appropriate for wind turbine substructures. The LFEM can accommodate different element types, including Euler-Bernoulli and Timoshenko beam elements of either constant or longitudinally tapered cross sections (Timoshenko beam elements account for shear deformation and are better suited to represent low aspect ratio beams that may be used within frames and to transfer the loads within the frame).

The large number of DOFs (~ 10^3) associated with a standard finite-element analysis of a typical multimember structure would hamper computational efficiency during wind turbine system dynamic simulations. As a result, the C-B system reduction was implemented to speed up processing time while retaining a high level of fidelity in the overall system response. The C-B reduction is used to recharacterize the substructure finite-element model into a reduced DOF model that maintains the fundamental low-frequency response modes of the structure. In the SubDyn initialization step, the large substructure physical DOFs (displacements) are reduced to a small number of modal DOFs and interface (boundary) DOFs, and during each time step, only the equations of motion of these DOFs need to be solved. SubDyn only solves the equations of motion for the modal DOFs, the motion of the interface (boundary) DOFs are either prescribed when running SubDyn in stand-alone mode or solved through equations of motion in ElastoDyn when SubDyn is coupled to FAST.

Retaining just a few DOFs may, however, lead to the exclusion of axial modes (normally of very high frequencies), which are important to capture static load effects, such as those caused by gravity and buoyancy. The so-called SIM was implemented to mitigate this problem. SIM computes two static solutions at each time step: one based on the full system stiffness matrix and one based on the C-B reduced stiffness matrix. At each time step the time-varying, C-B based, dynamic solution is superimposed on the difference between the two static solutions, which amounts to quasi-statically accounting for the contribution of those modes not directly included within the dynamic solution.

In SubDyn, the substructure is considered to be clamped, or connected via linear spring-like elements, at the bottom nodes (normally at the seabed) and rigidly connected to the TP at the substructure top nodes (interface nodes). The user can provide 6x6, equivalent stiffness and mass matrices for each of the bottom nodes to account for soil-pile interaction. As described in other sections of this document, the input file defines the substructure geometry, material properties, and constraints. Users can define: element types; full finite-element mode or C-B reduction; the number of modes to be retained in the C-B reduction; modal damping coefficients; whether to take advantage of SIM; and the number of elements for each member.

The following sections discuss the integration of SubDyn within the FAST framework, the main coordinate systems used in the module, and the theory pertaining to the LFEM, the C-B reduction, and SIM. The state-space formulations to be used in the time-domain simulation are also presented. The last section discusses the calculation of the base reaction calculation. For further details, see also [SDRJ13].
Integration with the FAST Modularization Framework

Based on a new modularization framework [JJ013], FAST joins an aerodynamics module, a hydrodynamics module, a control and electrical system (servo) module, and structural-dynamics (elastic) modules to enable coupled nonlinear aero-hydro-servo-elastic analysis of land-based and offshore wind turbines in the time domain. Fig. 4.32 shows the basic layout of the SubDyn module within the FAST modularization framework.

![Fig. 4.32: SubDyn layout within the modularization framework](image)

In the existing loosely coupled time-integration scheme, the glue-code transfers data at each time step. Such data includes hydrodynamic loads, substructure response, loads transmitted to the TP, and TP response among SubDyn, HydroDyn, and ElastoDyn. At the interface nodes, the TP displacement, rotation, velocity, and acceleration are inputs to SubDyn from ElastoDyn, and the reaction forces at the TP are outputs of SubDyn for input to ElastoDyn. SubDyn also outputs the substructure displacements, velocities, and accelerations for input to HydroDyn to calculate the hydrodynamic loads that become inputs for SubDyn. In addition, SubDyn can calculate the member forces, as requested by the user. Within this scheme, SubDyn tracks its states and integrates its equations through its own solver.

In a tightly coupled time-integration scheme (yet to be implemented), SubDyn sets up its own equations, but its states and those of other modules are tracked and integrated by a solver within the glue-code that is common to all of the modules.

SubDyn is implemented in a state-space formulation that forms the equation of motion of the substructure system with physical DOFs at the boundaries and modal DOFs representing all interior motions. At each time step, loads and motions are exchanged between modules through the driver code; the modal responses are calculated inside SubDyn’s state-space model; and the next time-step responses are calculated by the SubDyn integrator for loose coupling and the global system integrator for tight coupling.
Coordinate Systems

Fig. 4.33: Global (coincident with the substructure) coordinate system. Also shown are the DOFs associated with the TP reference point.

**Global and Substructure Coordinate System: \( (X, Y, Z) \) or \( (X_{SS}, Y_{SS}, Z_{SS}) \) (Fig. 4.33)**

- The global axes are represented by the unit vectors \( \hat{I}, \hat{J}, \) and \( \hat{K} \).
- The origin is set at the intersection between the undeflected tower centerline and the horizontal plane identified by the mean sea level (MSL) for offshore systems or ground level for land-based systems.
- The positive \( Z \) \( (Z_{SS}) \) axis is vertical and pointing upward, opposite gravity.
- The positive \( X \) \( (X_{SS}) \) axis is along the nominal (zero-degree) wind and wave propagation direction.
- The \( Y \) \( (Y_{SS}) \) axis is transverse and can be found assuming a right-handed Cartesian coordinate system (directed to the left when looking in the nominal downwind direction).
Member or Element Local Coordinate System \((x_e, y_e, z_e)\) (Fig. 4.34)

- Axes are represented by the unit vectors \(\hat{i}_e, \hat{j}_e, \hat{k}_e\).
- The origin is set at the shear center of the cross section at the start node \((S,MJointID1)\).
- The local \(z_e\) axis is along the elastic axis of the member, directed from the start node \((S)\) to the end node \((E,MJointID2)\). Nodes are ordered along the member main axis directed from start joint to end joint (per user’s input definition).
- The local \(x_e\) axis is parallel to the global XY plane, and directed such that a positive, less than or equal to 180° rotation about it, would bring the local \(z_e\) axis parallel to the global \(Z\) axis.
- The local \(y_e\) axis can be found assuming a right-handed Cartesian coordinate system.

![Fig. 4.34: The element coordinate system. The sketched member contains four elements, and the second element is called out with nodes S and E.](image)

Local to Global Transformation

The transformation from local to global coordinate system can be expressed by the following equation:

\[
\begin{bmatrix}
\Delta X \\
\Delta Y \\
\Delta Z
\end{bmatrix} = [D_c] \begin{bmatrix}
\Delta x_e \\
\Delta y_e \\
\Delta z_e
\end{bmatrix} \tag{4.97}
\]

where \(\begin{bmatrix}
\Delta x_e \\
\Delta y_e \\
\Delta z_e
\end{bmatrix}\) is a generic vector in the local coordinate system, and \(\begin{bmatrix}
\Delta X \\
\Delta Y \\
\Delta Z
\end{bmatrix}\) the same vector but in the global coordinate system; and \([D_c]\) is the direction cosine matrix of the member axes and can be obtained as follows:
\[
[D_c] = \begin{bmatrix}
\frac{Y_E-Y_s}{L_{e,y}} & \frac{(X_E-X_s)(Z_E-Z_s)}{L_{e,y}L_e} & \frac{X_E-X_s}{L_e} \\
\frac{-X_E+X_s}{L_{e,y}} & \frac{(Y_E-Y_s)(Z_E-Z_s)}{L_{e,y}L_e} & \frac{Y_E-Y_s}{L_e} \\
0 & \frac{-Z_E+Z_s}{L_{e,y}} & \frac{Z_E-Z_s}{L_e}
\end{bmatrix}
\]

(4.98)

Where \((X_s, Y_s, Z_s)\) and \((X_E, Y_E, Z_E)\) are the start and end joints of the member (or nodes of the element of interest) in global coordinate system; \(L_{e,y} = \sqrt{(X_E - X_s)^2 + (Y_E - Y_s)^2}\) and \(L_e = \sqrt{(X_E - X_s)^2 + (Y_E - Y_s)^2 + (Z_E - Z_s)^2}\).

If \(X_E = X_s\) and \(Z_E = Z_s\), the \([D_c]\) matrix can be found as follows:

if \(Z_E >= Z_s\) then

\[
[D_c] = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

(4.99)

else

\[
[D_c] = \begin{bmatrix}
1 & 0 & 0 \\
0 & -1 & 0 \\
0 & 0 & -1
\end{bmatrix}
\]

(4.100)

In the current SubDyn release, the transpose (global to local) of these direction cosine matrices for each member is returned in the summary file. Given the circular shape of the member cross sections, the direction cosine matrices have little importance on the member load verification. To verify joints following the standards (e.g., [ISO07] [API14]), however, the bending moments need to be decomposed into in-plane and out-of-plane components, where the plane is that defined by either a pair of braces (for an X-joint), or by the pair brace(s) plus leg (for a K-joint). It is therefore important to have the direction cosines of the interested members readily available to properly manipulate and transform the local shear forces and bending moments.

When member cross sections other than circular are allowed in future releases, the user will need to input cosine matrices to indicate the final orientation of the member principal axes with respect to the global reference frame.

**Finite-Element Model - Elements and Constraints**

**Definitions**

Figure Fig. 4.35 is used to illustrate some of the definitions used. The model of the substructure is assumed to consists of different members. A member is delimited by two joints. A joint is defined by the coordinates of a point of the undeflected structure and a type (JointType). The type of a joint defines the boundary condition or constraint of all the members that are attached to this joint. The following joints are supported:

- Cantilever joints (JointType=1)
- Universal joint (JointType=2)
- Pin joint (JointType=3)
- Ball joint (JointType=4)

A member is one of the three following types:
• Beams (MType=1), Euler-Bernoulli (FEMMod=1) or Timoshenko (FEMMod=3)
• Pretension cables (MType=2)
• Rigid link (MType=3)

Beam members may be split into several elements to increase the accuracy of the model (using the input parameter NDiv). Member of other types (rigid links and pretension cables) are not split. In this document, the term element refers to: a sub-division of a beam member or a member of another type than beam (rigid-link or pretension cable). The term joints refers to the points defining the extremities of the members. Some joints are defined in the input file, while others arise from the subdivision of beam members. The end points of an elements are called nodes and each node consists of 6 degrees of freedom (DOF) for the element implemented. In the current implementation, no geometrical offsets are assumed between a joint and the node of an element, or between the nodes of connected elements.

Fig. 4.35: Definitions of members, element, joints, nodes and rigid assemblies.

FEM process - from elements to system matrices

The process to obtain a FE representation of the system (performed at initialization) is as follows:

• Elements: The mass and stiffness matrices of each element are computed and transformed to global coordinates using directional cosine matrices

• Assembly: The element matrices are inserted into the full system matrices. The DOFs of cantilever joints are mapped to each other. The translational DOFs of the nodes linked by a joint different from a cantilever joint are mapped to each other, but the rotational DOFs of each individual nodes are retained in this system. The vector of degrees of freedom of this full system is noted \( \mathbf{x} \)

• Constraints elimination: A direct-elimination technique is used to apply the constraints introduced by the joints and the rigid links. The elimination consists in forming a matrix \( T \) and a reduced set of degrees of freedom \( \tilde{\mathbf{x}} \) such that \( \mathbf{x} = T \tilde{\mathbf{x}} \).

• CB-reduction: The Craig-Bampton reduction technique is used to obtain a reduced set of degrees of freedom (interface DOFs and Craig-Bampton modes)

• Boundary conditions: The displacements boundary conditions are then applied (e.g. for a fixed bottom foundation)

The remaining of the section focuses on the element matrices, and the account of the constraints introduced by the joints and rigid links. The Craig-Bampton reduction is described in Section 4.7.6.
Self-Weight Loads

The loads caused by self-weight are precomputed during initialization based on the undisplaced configuration. It is therefore assumed that the displacements will be small and that P-delta effects are small for the substructure. The “extra” moment may be accounted for using the flag `GuyanLoadCorrection`, see section Section 4.7.6. For a nontapered beam element, the lumped loads caused by gravity to be applied at the end nodes are as follows (in the global coordinate system):

\[ \{ F_G \} = \rho A z g \]

Note also that if lumped masses exist (selected by the user at prescribed joints), their contribution will be included as concentrated forces along global Z at the relevant nodes.

Beam Element Formulation

The uniform and tapered Euler-Bernoulli beam elements are displacement-based and use third-order interpolation functions that guarantee the displacement and rotation continuity between elements. The uniform Timoshenko beam element is derived by introducing the shear deformation into the uniform Euler-Bernoulli element, so the displacements are represented by third-order interpolation functions as well. Following the classic Timoshenko beam theory, the generic two-node element stiffness and consistent mass matrices can be written as follows (see, for instance, \[\text{[PHL09]}\]):
\[
\begin{bmatrix}
\frac{13A_eL_e}{35} + \frac{6J_e}{5L_e} & 0 & 0 & 0 \\
\frac{12EJ_y}{L_e(1+K_{xx})} & \frac{6EJ_y}{L_e(1+K_{xx})} & 0 & 0 \\
\frac{6EJ_y}{L_e(1+K_{xx})} & \frac{6EJ_y}{L_e(1+K_{xx})} & \frac{11A_eL_e^2}{210} + \frac{J_y}{5L_e} & 0 \\
\frac{(4+K_{xy})EJ_y}{L_e(1+K_{xx})} & \frac{(4+K_{xy})EJ_y}{L_e(1+K_{xx})} & \frac{9A_eL_e}{70} - \frac{6J_e}{5L_e} & 0 \\
\frac{6J_y}{L_e(1+K_{xx})} & \frac{6EJ_y}{L_e(1+K_{xx})} & \frac{12EJ_y}{L_e(1+K_{xx})} & 0 \\
0 & \frac{6EJ_y}{L_e(1+K_{xx})} & \frac{12EJ_y}{L_e(1+K_{xx})} & 0 \\
0 & 0 & \frac{12EJ_y}{L_e(1+K_{xx})} & 0 \\
0 & 0 & 0 & \frac{12EJ_y}{L_e(1+K_{xx})}
\end{bmatrix}
\]

(4.103)

where \(A_e\) is the element cross-section area, \(J_x, J_y, J_z\) are the area second moments of inertia with respect to principal axes of the cross section; \(L_e\) is the length of the undisplaced element from start-node to end-node; \(\rho, E, G\) are material density, Young’s, and Shear moduli, respectively; \(K_{xx}, K_{yy}\) are shear correction factors as shown below (they are set to zero if the E-B formulation is chosen):

\[
K_{xx} = \frac{12EJ_y}{GA_{xx}L_e^2}
\]

\[
K_{yy} = \frac{12EJ_x}{GA_{yy}L_e^2}
\]

(4.104)

where the shear areas along the local \(x\) and \(y\) (principal) axes are defined as:

\[
A_{xx} = k_{ax}A_z
\]

\[
A_{yy} = k_{ay}A_z
\]

(4.105)

and

\[
k_{ax} = k_{ay} = \frac{6(1+\mu)^2 \left( 1 + \left( \frac{D_y}{D_x} \right)^2 \right)^2}{\left( 1 + \left( \frac{D_y}{D_x} \right)^2 \right)^2 (7 + 14\mu + 8\mu^2) + 4 \left( \frac{D_y}{D_x} \right)^2 (5 + 10\mu + 4\mu^2)}
\]

(4.106)

Eq. (4.106) is from [SKM13] for hollow circular cross sections, with \(\mu\) denoting Poisson’s ratio.

Before assembling the global system stiffness (\(K\)) and mass (\(M\)) matrices, the individual \([k_e]\) and \([m_e]\) are modified to the global coordinate system via \([D_e]\) as shown in the following equations:

\[
[k_e] = \begin{bmatrix}
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0
\end{bmatrix} [k_e] \begin{bmatrix}
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0
\end{bmatrix}^T
\]

(4.107)

\[
[m_e] = \begin{bmatrix}
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0
\end{bmatrix} [m_e] \begin{bmatrix}
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0 \\
[D_e] & 0 & 0 & 0
\end{bmatrix}^T
\]

(4.108)

where \(m\) and \(k\) are element matrices in the global coordinate system.
Pretension Cable Element Formulation

The master stiffness equations of FEM assumes that the forces vanish if all displacements also vanish, that is, the relation between force and displacement is linear, \( f = K u \). This assumption does not hold if the material is subject to so-called initial strain, initial stress of prestress. Such effects may be produced by temperature changes and pretensions (or lack-of-fit fabrications). These effects are for instance discussed in the notes of Felippa [Fel04].

Pretension cables may be modelled by assuming an initial elongation of a truss element and considering the restoring force this initial elongation may have in both the longitudinal and orthogonal direction.

**Derivation**

A pretension cable oriented along the \( z \)-direction is considered. To simplify the derivation, the left point is assumed fixed and only the right point deflects. The notations are illustrated in Fig. 4.36.

The length of the element prior to the pretension is written \( L_0 \), and its axial stiffness is \( k = E A / L_0 \). In this equilibrium position the stress in the cable is zero. The user inputs for this elements are selected as: the un-displaced joint locations (while pre-tensioned) \( x_1 \) and \( x_2 \), the elongation stiffness \( E A \), and the change in length \( \Delta L_0 = L_0 - L_e < 0 \). The pretension force \( T_0 \) is a derived input. The following quantities are defined:

\[
L_e = \| x_2 - x_1 \|, \quad \epsilon_0 = \frac{T_0}{EA}, \quad L_0 = \frac{L_e}{1 + \epsilon_0}
\]

The different variables are defined as function of the inputs as follows:

\[
L_0 = L_e + \Delta L_0 \quad T_0 = -EA \frac{\Delta L_0}{L_0}, \quad \epsilon_0 = \frac{T_0}{EA} = -\frac{\Delta L_0}{L_0} = -\frac{\Delta L_0}{L_e + \Delta L_0}
\]

The degrees of freedom for the deflections of the cable, \((u_x, u_z)\), are measured from a position which is not the equilibrium position, but a position that is offset from the equilibrium position, such that the pretensioned length of the element is \( L_e > L_0 \). The stress in the cable for \( u_z = 0 \) is noted \( \epsilon_0 = (L_e - L_0)/L_0 \), or \( L_e = L_0(1 + \epsilon_0) \). The initial tension in the cable is \( T_0 = -k(L_e - L_0) e_z = -EA \epsilon_0 e_z \). In its deflected position, the length of the cable is:

\[
L_d = \sqrt{(L_e + u_z)^2 + u_x^2} = L_e \sqrt{1 + \frac{2u_z}{L_e} + \frac{u_x^2}{L_e^2}} + \frac{u_x^2}{L_e^2} \approx L_e \left(1 + \frac{u_z}{L_e}ight)
\]

where the deflections are assumed small compared to the element length \( L_e \), \( u_x \ll L_e \) and \( u_z \ll L_e \), and only the first order terms are kept. The tension force in the deflected cable is then \( T_d = -k(L_d - L_0)e_r \) where the radial vector is the vector along the deflected cable such that:

\[
e_r = \cos \theta e_z + \sin \theta e_x, \quad \text{with} \quad \cos \theta = \frac{L_e + u_z}{L_d} \approx 1, \quad \sin \theta = \frac{u_x}{L_d} \approx \frac{u_x}{L_e} (1 - \frac{u_z}{L_e}) \approx \frac{u_x}{L_e}
\]
The components of the tension force are then:

\[ T_{d,x} = -k(L_d - L_0) \cos \theta \approx -\frac{EA}{L_0}(L_e - L_0 + u_z) 1 = -\frac{EA\epsilon_0}{L_0}u_z \]

\[ T_{d,y} = -k(L_d - L_0) \sin \theta \approx -\frac{EA}{L_0}(L_e - L_0 + u_z) \frac{u_x}{L_e} \approx -\frac{EA\epsilon_0}{L_0}u_x = -\frac{EA\epsilon_0}{L_0(1 + \epsilon_0)}u_x \]

Finite element formulation of a pretension cable

The rotational degrees of freedom are omitted for conciseness since these degrees of freedom are not considered in this cable element. The linear formulation from is applied to both nodes of a finite element, interpreting the force at each node as the internal force that the element exerts on the nodes. Using this convention, the pretension cable element can be represented with an element stiffness matrix \( K_e \) and an additional nodal load vector \( f_{e,0} \) such that the static equilibrium equation of the element writes \( f_e = K_e u + f_{e,0} \), with:

\[
\begin{bmatrix}
  f_{x,1} \\
  f_{y,1} \\
  f_{z,1} \\
  f_{x,2} \\
  f_{y,2} \\
  f_{z,2}
\end{bmatrix} = \frac{EA}{L_0} \begin{bmatrix}
  \epsilon_0 & 0 & 0 & -\frac{\epsilon_0}{1+\epsilon_0} & 0 & 0 \\
  0 & \epsilon_0 & \frac{\epsilon_0}{1+\epsilon_0} & 0 & 0 & -\frac{\epsilon_0}{1+\epsilon_0} \\
  0 & 0 & 1 & 0 & 0 & -1 \\
  -\frac{\epsilon_0}{1+\epsilon_0} & 0 & \epsilon_0 & \frac{\epsilon_0}{1+\epsilon_0} & 0 & 0 \\
  0 & -\frac{\epsilon_0}{1+\epsilon_0} & 0 & 0 & \epsilon_0 & 0 \\
  0 & 0 & -1 & 0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
  u_{x,1} \\
  u_{y,1} \\
  u_{z,1} \\
  u_{x,2} \\
  u_{y,2} \\
  u_{z,2}
\end{bmatrix} + \frac{EA\epsilon_0}{L_0} \begin{bmatrix}
  0 \\
  0 \\
  -1 \\
  0 \\
  0 \\
  1
\end{bmatrix}
\]

The relation above is expressed in the element coordinate system. The stiffness matrix and force vector are transferred to the global system during the assembly process. Inserting \( \epsilon_0 = 0 \) in the above equations leads to the formulation of a truss element. The linear model above is only valid for \( L_d - L_0 > 0 \), that is \( (L_e - L_0 + u_{z,2} - u_{z,1}) > 0 \), and the implementation should abort if this condition is not reached at a given time. If the cable has a positive mass density \( \rho \), the mass matrix of the element is given by:

\[
M_e = \rho L_e \begin{bmatrix}
  13/35 & 0 & 0 & 9/70 & 0 & 0 \\
  0 & 13/35 & 0 & 0 & 9/70 & 0 \\
  0 & 0 & 1/3 & 0 & 0 & 1/6 \\
  0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

with \( L_e \) the undisplaced length of the element (not \( L_0 \)).

Controlled pretension cable

The controller updates the value of \( \Delta L \) at each time step, which effectively changes the pretension properties of the cable. The quantity \( \Delta L \) is the change in restlength if the cable had no pretension. Since cable extension beyond the element length (\( L_e \)) is not allowed in SubDyn, \( \Delta L \) is limited to negative values.

At a given time, the restlength of the cable is \( L_r(t) \) (instead of \( L_0 \)), and the pretension force is \( T(t) \) (instead of \( T_0 \)). The pretension force is then given as:

\[
T(t) = EA\frac{-\Delta L_r(t)}{L_r(t)} = EA\frac{-\Delta L_r(t)}{L_e + \Delta L(t)}, \quad T(0) = T_0 = EA\frac{-\Delta L_0}{L_e + \Delta L_0}, \quad \Delta L(0) = \Delta L_0
\]
The “equations of motions” for a cable element are written:

\[ M_e \ddot{u}_e = f_e \]

If the pretension force is constant, equal to \( T_0 \) then the element force is:

\[ f_e = f_e(t, T_0) = -K_e(T_0)u_e + f_e(T_0) + f_g \]

where \( f_e(T_0) \) and \( K_e(T_0) \) are given in . If the pretension force is varying with time \( (T = T(t)) \), then the force is:

\[ f_e(t) = -K_e(T)u_e + f_e(T) + f_g \]

where is evaluated with \( \epsilon = \frac{T(t)}{T_0} \) and \( L = \frac{L_0}{T(t)} \). We seek to express , as a correction term added to the equation of a constant pretension cable (i.e., with \( T(0) = T_0 \)). We add \( \pm f_e(t, T_0) \) to , leading to:

\[
 f_e(t) = [ -K_e(T_0)u_e + f_e(T_0) + f_g ] - [ -K_e(T_0)u_e + f_e(T_0) + f_g ] + [ -K_e(T)u_e + f_e(T) + f_g ] \\
 = \left[ -K_e(T_0)u_e + f_e(T_0) + f_g \right] \text{in } CB + \left[ -K_e(T)u_e + f_e(T) + f_g \right] \text{in } FG + f_{e, control}(T)
\]

where \( f_{e, control} \) is the correction term accounting for the time variation of \( T \):

\[ f_{e, control}(T) = (K_e(T_0) - K_e(T)) u_e + f_e(T) - f_e(T_0) \]

This equation is transformed to the global system using the direction cosine matrices of the element. The part involving \( u \) introduces non-linearities, and is currently neglected. Using , the additional control force for a given element is:

\[
 f_{e, \text{control}}(T) \approx f_e(T) - f_e(T_0) = (T - T_0) \begin{bmatrix} 0 \\ 0 \\ -1 \\ 0 \\ 0 \end{bmatrix}
\]

**Constraints introduced by Rotational Joints**

As mentioned in Section 4.7.6, the account of constraints is done via a direct elimination technique. The technique is implemented by computing a transformation matrix \( T \) which gives the relationship between the reduced set of DOF (accounting for constraints) and the full set of DOFs. When no constraints are present this matrix is the identity matrix. This section describes how the \( T \) matrix is obtained for rotational joints.

**Formulation** Joints between two nodes \( k \) and \( l \) are here considered. Before accounting for the constraint introduced by the joints, 12 degrees of freedom are present: \( (u_k, \theta_k, u_l, \theta_l) \). After application of the constraints, the new set of degrees of freedom is noted \( (\tilde{u}_{kl}, \tilde{\theta}_{kl}) \). The degrees of freedom retained for each joint type is shown in the table below. The meaning of the different \( \theta \)-variable will be made explicit in the subsequent paragraphs.

<table>
<thead>
<tr>
<th>Joint type</th>
<th>( n_c )</th>
<th>( n_{DOF} )</th>
<th>( \tilde{u}_{kl} )</th>
<th>( \tilde{\theta}_{kl} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cantilever</td>
<td>6</td>
<td>12 ( \rightarrow ) 6</td>
<td>( u_x, u_y, u_z )</td>
<td>( \theta_x, \theta_y, \theta_z )</td>
</tr>
<tr>
<td>Pin</td>
<td>5</td>
<td>12 ( \rightarrow ) 7</td>
<td>( u_x, u_y, u_z )</td>
<td>( \theta_1, \theta_2, \theta_3, \theta_4 )</td>
</tr>
<tr>
<td>Universal</td>
<td>4</td>
<td>12 ( \rightarrow ) 8</td>
<td>( u_x, u_y, u_z )</td>
<td>( \theta_1, \theta_2, \theta_3, \theta_4 )</td>
</tr>
<tr>
<td>Ball</td>
<td>3</td>
<td>12 ( \rightarrow ) 9</td>
<td>( u_x, u_y, u_z )</td>
<td>( \theta_{x,k}, \theta_{y,k}, \theta_{z,k}, \theta_{x,l}, \theta_{y,l}, \theta_{z,l} )</td>
</tr>
</tbody>
</table>
For all the joints considered, the translational DOF of the two nodes are made equal, which may be formally expressed as:

$$
\begin{bmatrix}
    u_k \\
    u_l
\end{bmatrix}
= 
\begin{bmatrix}
    I_3 \\
    I_3
\end{bmatrix}
\tilde{u}_{kl}
$$

Since this relation is the same for all the joints, the relation between the degrees of freedom is taken care in the assembly step. The constraints of each joints will hence be expressed in the following form:

$$
\begin{bmatrix}
    \theta_k \\
    \theta_l
\end{bmatrix}
= T_{kl} \tilde{\theta}_{kl}
$$

**Cantilever joint** For a cantilever joint between two elements, the reduction is:

$$
\begin{bmatrix}
    \theta_k \\
    \theta_l
\end{bmatrix}
= T_{kl} \tilde{\theta}_{kl}, \quad \text{with} \quad \tilde{\theta}_{kl} = \begin{bmatrix} \theta_k \\ \theta_l \end{bmatrix}, \quad T_{kl} = \begin{bmatrix}
    I_3 \\
    0
\end{bmatrix}
$$

This relationship is taken care of during the assembly process directly, and readily extended to \( n \) elements.

**Ball/spherical joint** For a spherical joint between two elements, the reduction is as follows:

$$
\begin{bmatrix}
    \theta_k \\
    \theta_l
\end{bmatrix}
= T_{kl} \tilde{\theta}_{kl}, \quad \text{with} \quad \tilde{\theta}_{kl} = \begin{bmatrix} \theta_k \\ \theta_l \end{bmatrix}, \quad T_{kl} = \begin{bmatrix}
    I_3 \\
    0 \\
    0 \\
    I_3
\end{bmatrix}
$$

For \( n \) elements \([e_1, \ldots, e_n]\) connected by a ball joint (constraint \( c \)), the relationship is extended as follows:

$$
\begin{bmatrix}
    \theta_{e_1} \\
    \vdots \\
    \theta_{e_n}
\end{bmatrix}
= T^c \tilde{\theta}^c, \quad \text{with} \quad \tilde{\theta}^c = \begin{bmatrix} \theta_{e_1} \\ \vdots \\ \theta_{e_n} \end{bmatrix}, \quad T^c = \begin{bmatrix}
    I_3 \\
    0 \\
    0 \\
    I_3
\end{bmatrix}
$$

**Pin/revolute joint** A pin joint is characterized by a direction around which no moment is transferred. The unit vector indicating this direction is noted \( \hat{p} \). Two orthogonal vectors \( p_1 \) and \( p_2 \) are then defined, forming an orthonormal base with \( \hat{p} \), oriented arbitrarily (see Fig. 4.37).

![Fig. 4.37: Notations used for the derivation of the pin-joint constraint](image)

The variables \( \tilde{\theta}_1, \tilde{\theta}_4 \) are then defined as:

$$
\begin{align*}
\tilde{\theta}_1 &= p_1^t \cdot \theta_k = p_1^t \cdot \theta_l \\
\tilde{\theta}_2 &= p_2^t \cdot \theta_k = p_2^t \cdot \theta_l \\
\tilde{\theta}_3 &= \hat{p}^t \cdot \theta_k \\
\tilde{\theta}_4 &= \hat{p}^t \cdot \theta_l
\end{align*}
$$

which may be written in matrix form as:

$$
\begin{bmatrix}
    \tilde{\theta}_1 \\
    \tilde{\theta}_2 \\
    \tilde{\theta}_3 \\
    \tilde{\theta}_4
\end{bmatrix}
= A \begin{bmatrix}
    \theta_k \\
    \theta_l
\end{bmatrix}
= \begin{bmatrix}
    p_1^t / 2 & p_1^t / 2 \\
    p_2^t / 2 & p_2^t / 2 \\
    \hat{p}^t & 0 \\
    0 & \hat{p}^t
\end{bmatrix}
\begin{bmatrix}
    \theta_k \\
    \theta_l
\end{bmatrix}
$$
The relations are inverted using a pseudo inverse, defined as $A^{-1} = A^t(AA^t)^{-1}$. Using the pseudo-inverse, this equation is rewritten in the form of as:

$$\begin{bmatrix} \theta_k \\ \theta_l \end{bmatrix} = T_{kl} \tilde{\theta}_{kl}, \quad \text{with} \quad \tilde{\theta}_{kl} = \begin{bmatrix} \tilde{\theta}_1 \\ \tilde{\theta}_2 \\ \tilde{\theta}_3 \\ \tilde{\theta}_4 \end{bmatrix}, \quad T_{kl} = \begin{bmatrix} p_1^t/2 & p_1^t/2 \\ p_2^t/2 & p_2^t/2 \\ 0 & 0 \end{bmatrix}^{-1}$$

If $n$ elements $[e_1, \ldots, e_n]$, are connected at a pin joint (constraint $c$), the relationship is extended as follows:

$$\begin{bmatrix} \theta_{e_1} \\ \vdots \\ \theta_{e_n} \end{bmatrix} = T_c \tilde{\theta}^c, \quad \text{with} \quad \tilde{\theta}^c = \begin{bmatrix} \tilde{\theta}_1 \\ \tilde{\theta}_2 \\ \vdots \\ \tilde{\theta}_{e_1} \\ \tilde{\theta}_{e_n} \end{bmatrix}, \quad T_c = \begin{bmatrix} p_1^t/n & \ldots & p_1^t/n \\ p_2^t/n & \ldots & p_2^t/n \\ 0 & 0 \end{bmatrix}^{-1}$$

**Universal joint** A universal joint transfers the rotational moment around two misaligned axes. Such joints are connecting only two elements, labelled $j$ and $k$, and the axes are taken as the $z$ axis of each element. The axis vectors are expressed in the global coordinates system and written $\hat{z}_j$ and $\hat{z}_k$. Similar notations are used for the $x$ and $y$ axes. The DOF corresponding to the shared rotation between the two axes is written $\tilde{\theta}_1$. Each element has two additional DOFs that are free to rotate, noted $\tilde{\theta}_x$ and $\tilde{\theta}_y$. The constraint relationship between the original DOFs and the reduced DOFs is obtained by projecting the rotational DOFs of each element against the different axes. The relations are inverted using the pseudo-inverse, defined as $A^{-1} = A^t(AA^t)^{-1}$. The constraints are then defined with:

$$\begin{bmatrix} \tilde{\theta}_1 \\ \tilde{\theta}_{x,j} \\ \tilde{\theta}_{y,j} \\ \tilde{\theta}_{x,k} \\ \tilde{\theta}_{y,k} \\ \tilde{\theta}_{x,e_1} \\ \tilde{\theta}_{y,e_1} \\ \vdots \\ \tilde{\theta}_{x,e_n} \\ \tilde{\theta}_{y,e_n} \end{bmatrix}, \quad T_e = \begin{bmatrix} \tilde{z}_j^t/2 & \tilde{z}_k^t/2 \\ \tilde{x}_j & 0 \\ 0 & \tilde{x}_k \\ 0 & 0 \end{bmatrix}^{-1}$$

**Rigid-links**

Rigid links and rigid elements impose a relationship between several degrees of freedom, and as such, can be treated as linear multipoint constraints. Rigid members can be used to join dissimilar elements together or model a link of large stiffness between two elastic bodies (see Cook [Coo01]). Mass properties for rigid link may be provided in the input file, in which case the mass matrix of a beam element is used for this rigid link.

A rigid link between the nodes $j$ and $k$ is considered, referred to as the element $j - k$. The six degrees of freedom of a given node, three displacements and three rotations, are noted $x = [u_x, u_y, u_z, \theta_x, \theta_y, \theta_z]^t$ in the global system. The fact that the nodes $j$ and $k$ are rigidly connected is formally expressed as follows:

$$x_k = A_{jk} x_j, \quad A_{jk} = \begin{bmatrix} 1 & 0 & 0 & 0 & (z_k - z_j) & -(y_k - y_j) \\ 0 & 1 & 0 & -(z_k - z_j) & 0 & (y_k - y_j) \\ 0 & 0 & 1 & (y_k - y_j) & -(x_k - x_j) & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \quad [x_j] = Tx_j = \begin{bmatrix} I_6 \\ A_{jk} \end{bmatrix} x_j$$

(4.109)
where the nodal coordinates \((x, y, z)\) are expressed in the global system. The matrix \(T\) expresses the relation between the condensed coordinates and the original coordinates.

In the general case, several joints may be coupled together with rigid links. An assembly of \(n\) joints is here assumed with the 6-DOFs of each joint written \(x_1, \ldots, x_n\). It is further assumed that the first joint is selected as leader. For each joint \(j \in \{2, \ldots, n\}\) a matrix \(A_j\) is formed according to (4.109). The matrices are built using the global coordinates of each joint pairs. For this given rigid assembly (or constraint \(c\)), the relation between the joint DOFs and the reduced leader DOF is:

\[
x^c = T^c \tilde{x}^c \quad \text{with} \quad x^c = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}, \quad T^c = \begin{bmatrix} I_6 \\ A_{12} \\ \vdots \\ A_{1n} \end{bmatrix}, \quad \tilde{x}^c = x_1
\]

SubDyn detects rigid link assemblies and selects a leader node for the assembly. If one of the node is an interface node, it is selected as a leader node. The following restriction apply: the follower node cannot be a boundary node.

The constraint are applied after the full system has been assembled.

**Craig-Bampton Reduction (theory)**

**Full system**

The FEM equations of motion of SubDyn are written as follows:

\[
[M] \ddot{U} + [C] \dot{U} + [K] U = F
\]

(4.110)

where \([M]\) and \([K]\) are the global mass and stiffness matrices of the substructure beam frame, assembled from the element mass and stiffness matrices. Additionally, \([M]\) and \([K]\) contain the contribution from any specified \([M_{SSI}]\) and \([K_{SSI}]\) that are directly added to the proper partially restrained node DOF rows and column indexed elements.

\(U\) and \(F\) are the displacements and external forces along all of the DOFs of the assembled system. The damping matrix \([C]\) is not assembled from the element contributions, because those are normally unknown, but can be specified in different ways, as discussed in Section 4.7.6. A derivative with respect to time is represented by a dot, so that \(\dot{U}\) and \(\ddot{U}\) are the first- and second-time derivatives of \(U\), respectively.

The number of DOFs associated with Eq. (4.110) can easily grow to the thousands for typical beam frame substructures. That factor, combined with the need for time-domain simulations of turbine dynamics, may seriously slow down the computational efficiency of aeroelastic codes such as FAST (note that a typical wind turbine system model in ElastoDyn has about 20 DOFs). For this reason, a C-B methodology was used to recharacterize the substructure finite-element model into a reduced DOF model that maintains the fundamental low-frequency response modes of the structure. With the C-B method, the DOFs of the substructure can be reduced to about 10 (user defined, see also Section 4.7.5). This system reduction method was first introduced by [Hur64] and later expanded by [CB68].

**CB-reduced system**

In this section we present the generic Craig-Bampton technique. The specific application in SubDyn is presented in following sections. In a C-B reduction, the structure nodes are separated into two groups: 1) the boundary nodes (identified with a subscript “\(R\)” in what follows) that include the nodes fully restrained at the base of the structure and the interface nodes; and 2) the interior nodes (or leftover nodes, identified with a subscript “\(L\)”). Note that the DOFs of partially restrained or “free” nodes at the base of the structure are included in the “\(L\)” subset in this version of SubDyn that contains SSI capabilities.

The derivation of the system reduction is shown below. The system equation of motion of Eq. (4.110) can be partitioned as follows:

\[
\begin{bmatrix}
M_{RR} & M_{RL} \\
M_{LR} & M_{LL}
\end{bmatrix}
\begin{bmatrix}
\dot{U}_R \\
\dot{U}_L
\end{bmatrix}
+ 
\begin{bmatrix}
C_{RR} & C_{RL} \\
C_{LR} & C_{LL}
\end{bmatrix}
\begin{bmatrix}
\ddot{U}_R \\
\ddot{U}_L
\end{bmatrix}
+ 
\begin{bmatrix}
K_{RR} & K_{RL} \\
K_{LR} & K_{LL}
\end{bmatrix}
\begin{bmatrix}
U_R \\
U_L
\end{bmatrix}
= 
\begin{bmatrix}
F_R \\
F_L
\end{bmatrix}
\]

(4.111)
where the subscript $R$ denotes the boundary DOFs (there are $R$ DOFs), and the subscript $L$ the interior DOFs (there are $L$ DOFs). In Eq. (4.111), the applied forces include external forces (e.g., hydrodynamic forces and those transmitted through the TP to the substructure), gravity and pretension forces which are considered static forces lumped at each node.

The fundamental assumption of the C-B method is that the contribution to the displacement of the interior nodes can be simply approximated by a subset $q_m (q_m \leq L)$ of the interior generalized DOFs ($q_L$). The relationship between physical DOFs and generalized DOFs can be written as:

$$
\begin{bmatrix}
U_R \\
U_L
\end{bmatrix} =
\begin{bmatrix}
I & 0 \\
\Phi_R & \Phi_L
\end{bmatrix}
\begin{bmatrix}
U_R \\
q_L
\end{bmatrix}
$$

(4.112)

where $I$ is the identity matrix; $\Phi_R$ is the $L \times R$ matrix of Guyan modes, which represents the physical displacements of the interior nodes for static, rigid body motions at the boundary (interface nodes’ DOFs, because the restrained nodes DOFs are locked by definition). By considering the homogeneous, static version of (4.111), the second row can be manipulated to yield:

$$
[K_{LL}]U_R + [K_{LR}]U_L = 0
$$

(4.113)

Rearranging and considering yields:

$$
\Phi_R = -K_{LL}^{-1}K_{LR}
$$

(4.114)

where the brackets have been removed for simplicity. If the structure is unconstrained, the matrix $\Phi_R$ corresponds to rigid body modes, ensuring that the internal nodes follow the rigid body displacements imposed by the interface DOFs. This has been verified analytically using the stiffness matrix of a single beam element. $\Phi_L$ ($L \times L$ matrix) represents the internal eigenmodes, i.e., the natural modes of the system restrained at the boundary (interface and bottom nodes), and can be obtained by solving the eigenvalue problem:

$$
[K_{LL}]\Phi_L = \omega^2 M_{LL}\Phi_L
$$

(4.115)

The eigenvalue problem in Eq. (4.115) leads to the reduced basis of generalized modal DOFs $q_m$, which are chosen as the first few ($m$) eigenvectors that are arranged by increasing eigenfrequencies. $\Phi_L$ is mass normalized, so that:

$$
\Phi_L^T M_{LL} \Phi_L = I
$$

(4.116)

By then reducing the number of generalized DOFs to $m (\leq L)$, $\Phi_m$ is the matrix ($(L \times m)$) chosen to denote the truncated set of $\Phi_L$ (keeping $m$ of the total internal modes, hence $m$ columns), and $\Omega_m$ is the diagonal ($m \times m$) matrix containing the corresponding eigenfrequencies (i.e., $\Phi_m^T K_{LL} \Phi_m = \Omega_m^2$). In SubDyn, the user decides how many modes to retain, including possibly zero or all modes. Retaining zero modes corresponds to a Guyan (static) reduction; retaining all modes corresponds to keeping the full finite-element model.

The C-B transformation is therefore represented by the coordinate transformation matrix $T_{\Phi_m}$ as:

$$
\begin{bmatrix}
U_R \\
U_L
\end{bmatrix} =
T_{\Phi_m}
\begin{bmatrix}
U_R \\
q_m
\end{bmatrix},
T_{\Phi_m} =
\begin{bmatrix}
I & 0 \\
\Phi_R & \Phi_m
\end{bmatrix}
$$

(4.117)

By using Eq. (4.117), the interior DOFs are hence transformed from physical DOFs to modal DOFs. By pre-multiplying both sides of Eq. (4.111) by $T_{\Phi_m}^T$ on the left and $T_{\Phi_m}$ on the right, and making use of Eq. (4.116), Eq. (4.111) can be rewritten as:

$$
\begin{bmatrix}
M_{BB} & M_{Bm} \\
M_{mB} & I
\end{bmatrix}
\begin{bmatrix}
\ddot{U}_R \\
\ddot{q}_m
\end{bmatrix} +
\begin{bmatrix}
C_{BB} & C_{Bm} \\
C_{mB} & C_{mm}
\end{bmatrix}
\begin{bmatrix}
\dot{U}_R \\
\dot{q}_m
\end{bmatrix} +
\begin{bmatrix}
K_{BB} & 0 \\
0 & K_{mm}
\end{bmatrix}
\begin{bmatrix}
U_R \\
q_m
\end{bmatrix} =
\begin{bmatrix}
F_B \\
F_m
\end{bmatrix}
$$

(4.118)
where

\[
M_{BB} = M_{RR} + M_{RL}\Phi_R + \Phi_R^T M_{LR} \Phi_R + \Phi_R^T M_{LL} \Phi_R \tag{4.119}
\]

\[
C_{BB} = C_{RR} + C_{RL}\Phi_R + \Phi_R^T C_{LR} \Phi_R + \Phi_R^T C_{LL} \Phi_R
\]

\[
K_{BB} = K_{RR} + K_{RL}\Phi_R
\]

\[
M_m = \Phi_m^T M_{LR} \Phi_m + \Phi_m^T M_{LL} \Phi_m
\]

\[
C_m = \Phi_m^T C_{LR} \Phi_m + \Phi_m^T C_{LL} \Phi_m
\]

\[
K_m = \Phi_m^T K_{LL} \Phi_m = \Omega_m^2
\]

\[
M_{mm} = \Phi_m^T M_{LL} \Phi_m
\]

\[
C_{mm} = \Phi_m^T C_{LL} \Phi_m
\]

\[
F_B = F_R + \Phi_R^T F_L
\]

\[
F_m = \Phi_m^T F_L
\]

and \( M_{Bm} = M_{mB} \), \( C_{Bm} = C_{mB} \).

**FEM formulation in SubDyn**

**Boundary nodes: fixed DOFs and rigid connection to TP**

In this section we present the treatment of the boundary nodes: fixed DOFs are eliminated, and interface DOFs are condensed via a rigid connection to the TP reference point.

The boundary nodes are partitioned into those at the interface, \( \bar{U}_R \), and those at the bottom, which are fixed:

\[
U_R = \begin{bmatrix} \bar{U}_R \\ 0 \end{bmatrix} \tag{4.120}
\]

The overhead bar here and below denotes matrices/vectors after the fixed-bottom boundary conditions are applied.

The interface nodes are assumed to be rigidly connected among one another and to the TP reference point, hence it is convenient to use rigid-body TP DOFs (one node with 6 DOFs at the TP reference point) in place of the interface DOFs. The interface DOFs, \( \bar{U}_R \), and the TP DOFs are related to each other as follows:

\[
\bar{U}_R = T_I U_{TP} \tag{4.121}
\]

where \( T_I \) is a \((6NIN) \times 6\) matrix, \( NIN \) is the number of interface nodes, and \( U_{TP} \) is the 6 DOFs of the rigid transition piece. The matrix \( T_I \) can be written as follows:

\[
T_I = \begin{bmatrix}
1 & 0 & 0 & 0 & \Delta Z_1 & -\Delta Y_1 \\
0 & 1 & 0 & -\Delta Z_1 & 0 & -\Delta X_1 \\
0 & 0 & 1 & \Delta Y_1 & -\Delta X_1 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
1 & 0 & 0 & 0 & \Delta Z_i & -\Delta Y_i \\
0 & 1 & 0 & -\Delta Z_i & 0 & -\Delta X_i \\
0 & 0 & 1 & \Delta Y_i & -\Delta X_i & 0 \\
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
\end{bmatrix}, (i = 1, 2, \ldots, NIN) \tag{4.122}
\]
with
\[
\Delta X_i = X_{INi} - X_{TP} \\
\Delta Y_i = Y_{INi} - Y_{TP} \\
\Delta Z_i = Z_{INi} - Z_{TP}
\]

(4.123)

where \((X_{INi}, Y_{INi}, Z_{INi})\) are the coordinates of the \(i\)th interface node and \((X_{TP}, Y_{TP}, Z_{TP})\) are the coordinates of the TP reference point within the global coordinate system.

In terms of TP DOFs, the system equation of motion (4.118) after the boundary constraints are applied (the rows and columns corresponding to the DOFs of the nodes that are restrained at the seabed are removed from the equation of motion) becomes:

\[
\begin{bmatrix}
\tilde{M}_{BB} & \tilde{M}_{Bm} \\
\tilde{M}_{mB} & I
\end{bmatrix}
\begin{bmatrix}
\ddot{U}_{TP} \\
\ddot{q}_m
\end{bmatrix}
+ \begin{bmatrix}
\tilde{C}_{BB} & \tilde{C}_{Bm} \\
\tilde{C}_{mB} & C_{mm}
\end{bmatrix}
\begin{bmatrix}
\dot{U}_{TP} \\
\dot{q}_m
\end{bmatrix}
+ \begin{bmatrix}
\tilde{K}_{BB} & 0 \\
0 & K_{mm}
\end{bmatrix}
\begin{bmatrix}
U_{TP} \\
q_m
\end{bmatrix}
= \begin{bmatrix}
\dot{F}_{TP} \\
F_m
\end{bmatrix}
\]

(4.124)

with

\[
\tilde{M}_{BB} = T_I^T \tilde{M}_{BB} T_I, \quad \tilde{C}_{BB} = T_I^T \tilde{C}_{BB} T_I, \quad \tilde{K}_{BB} = T_I^T \tilde{K}_{BB} T_I
\]

(4.125)

\[
\tilde{M}_{mB} = T_I^T \tilde{M}_{Bm}, \quad \tilde{C}_{Bm} = T_I^T \tilde{C}_{Bm}
\]

\[
\tilde{F}_{TP} = T_I^T F_B
\]

and \(\tilde{M}_{mB} = \tilde{M}_{mB}, \tilde{C}_{mB} = \tilde{C}_{mB}^T\).

Equation (4.124) represents the equations of motion of the substructure after the C-B reduction. The total DOFs of the substructure are reduced from \((6 \times \text{total number of nodes})\) to \((6 + m)\).

During initialization, SubDyn calculates: the parameter matrices \(\tilde{M}_{BB}, \tilde{M}_{mB}, \tilde{M}_{Bm}, \tilde{K}_{BB}, \Phi_m, \Phi_R, T_I\); constant load arrays; and the internal frequency matrix \(\Omega_m\). The substructure response at each time step can then be obtained by using the state-space formulation discussed in the next section.

**Floating or fixed-bottom structure**

Different formulations are used in SubDyn depending if the structure is “fixed-bottom” or “floating”.

The structure is considered to be “floating” if there is no reaction nodes.

The structure is considered to be “fixed-bottom” in any other case.

**Loads**

In this section, we detail the loads acting on the boundary \((R)\) and interior \((L)\) nodes, and the transition piece \((TP)\) node.

External loads that are accounted for by SubDyn, such as the gravity loads or the pretension loads, are noted with the subscript \(g\). External loads acting on the substructure and coming from additional modules, consisting for instance of hydrodynamic, mooring or soil loads, are noted with the subscript \(e\). The coupling loads that ElastoDyn would transmit to SubDyn are noted with the subscript \(cpl\). In the modular implementation, SubDyn does not receive these coupling loads from ElastoDyn, but instead receives displacements of the transition piece, and outputs the corresponding loads. This will be relevant for the state-space formulation, but for the purpose of this section, the coupling loads can be thought to be coming from ElastoDyn.

The external loads at the boundary nodes \((R)\) consist of the SubDyn gravitational and cable loads \((g)\), the ElastoDyn coupling loads \((cpl)\), and the external loads from other modules \((e)\):

\[
F_R = F_{R,e} + F_{R,g} + F_{R,cpl}
\]

(4.126)
The external loads acting on the internal nodes are similarly decomposed:

\[ F_L = F_{L,e} + F_{L,g} \]  

(4.127)

The loads at the transition piece node (TP) are related to the interface boundary nodes (\( \bar{R} \)) via the transformation matrix \( T_I \), which assumes that the \( \bar{R} \) and TP nodes are rigidly connected:

\[ F_{TP} = T_I^T \bar{F}_R \]  

(4.128)

In particular, the coupling force exchanged between ElastoDyn and SubDyn is:

\[ F_{TP,cpl} = T_I^T \bar{F}_{R,cpl} \]  

(4.129)

The Guyan TP force, \( \tilde{F}_{TP} \), and the CB force, \( F_m \), given in Eq. (4.7.6) are then decomposed as follows:

\[
\tilde{F}_{TP} = F_{TP,cpl} + T_I^T \left[ \bar{F}_{R,e} + \bar{F}_{R,g} + \Phi_T^T (F_{L,e} + F_{L,g}) \right] \\
F_m = \Phi_m^t (F_{L,e} + F_{L,g})
\]  

(4.130)

**Corrections to the baseline formulation (“GuyanLoadCorrection”)**

The baseline FEM implementation needs to be corrected to account for the fact that loads are provided to SubDyn at the displaced positions, and to account for the rigid body motions in the floating case. The corrections are activated by setting the parameter **GuyanLoadCorrection** to True.

**Rotation of coordinate system for floating**

In the floating case, the FEM formulation needs to be rotated to the body frame. This is done when **GuyanLoadCorrection** is set to True. The CB and static modes are solved in a rotating frame of reference, that follows the rigid-body rotation of the Guyan modes. More details on this special case is found in section Section 4.7.6.

**Additional lever arm from external loads**

The external loads that are applied on the substructure are computed at the location of the deflected structure. On the other hand, the finite element formulation expect loads to be provided relative to the undeflected position of the structure, or, if rigid body motions are present, relative to a reference undeflected position (see Figure Fig. 4.38). Nodal forces at a displaced node can be directly applied to the reference nodal position, but the mapping introduces a moment at the reference nodal position.

The parameter **GuyanLoadCorrection** in the input file is used to account for this extra nodal moment occurring due to the fact that the finite element loads are expected to be expressed at a reference position and not at the displaced position.

The mapping of nodal forces is done as follows when the parameter **GuyanLoadCorrection** is set to True. First, a reference undeflected position of the structure is defined, with two possible configurations whether the structure is “fixed” at the sea bed, or not. The two configurations are illustrated in Figure Fig. 4.38.

Second, the external loads are assumed to be applied on the “Guyan” deflected structure, instead of the fully deflected structure. The Craig-Bampton displacements are omitted to avoid the non-linear dependency between the input loads and the Craig-Bampton states. With this assumption, the external loads at the Guyan position are mapped to the reference position.

The additional moment is included for all external forces, including the gravitational forces. For a given node \( i \in [R, L] \), and nodal force \( f_i = f_{i,g} + f_{i,e} \), the following additional moment is computed:

\[ \Delta m_i = \Delta u_i \times [f_{i,g} + f_{i,e}] \]
Fig. 4.38: Illustration for the additional moment occurring due to the distance between the deflected position of the structure and the reference position used for the finite element representation. For simplicity, the loads are assumed to act at the Guyan position instead of the true deflected position.

with the vector \( \Delta \mathbf{u}_i = \{\Delta u_{ix}, \Delta u_{iy}, \Delta u_{iz}\} \), defined differently depending on the reference position (fixed or free) and whether the node is an internal (L) or boundary node (R):

\[
\begin{align*}
\text{(fixed bottom:)} & \quad \Delta u_{ij} = [\bar{\Phi}_R T_I]_{ij} U_{TP} \quad \text{for } i \in L, \text{ and,} \\
\text{(free/floating:)} & \quad \Delta u_{ij} = [T_I]_{ij} U_{TP} - U_{TP} \quad \text{for } i \in L, \text{ and,} \\
& \quad \Delta u_{ij} = [T_I]_{ij} U_{TP} - U_{TP} \quad \text{for } i \in R
\end{align*}
\]

(4.131) (4.132)

where \( j \in [x, y, z] \) and the subscript \( ij \) in \([\bar{\Phi}_R T_I]_{ij}\) indicates the row corresponding to node \( i \) and translational degree of freedom \( j \). Boundary DOFs that are fixed have no displacements and thus no extra moment contribution. Boundary DOFs that are free are part of the internal DOF \( L \) in the implementation. The gravitational and cable forces at each node (that were computed at the initialization and stored in the constant vector \( F_G \)) are used to obtain \( f_{i,g} \). It is noted that the \( g \)-contribution to the moment \( \Delta m_i \), is not a constant and needs to be computed at each time step.

To avoid adding more notations, all the load vectors used in this document will have the additional moment implicitly included when GuyanLoadCorrection=True. This applies e.g.: to \( F_{R,e}, F_{L,e}, F_{R,g}, F_{L,g} \), where the following replacement is implied:

\[
F_R,e = \begin{pmatrix}
\vdots \\
f_{ix,e} \\
f_{iy,e} \\
f_{iz,e} \\
m_{ix,e} \\
m_{iy,e} \\
m_{iz,e} \\
\vdots
\end{pmatrix} \quad \rightarrow \quad F_R,e = \begin{pmatrix}
\vdots \\
f_{ix,e} \\
f_{iy,e} \\
f_{iz,e} \\
m_{ix,e} + \Delta m_{ix,e} \\
m_{iy,e} + \Delta m_{iy,e} \\
m_{iz,e} + \Delta m_{iz,e} \\
\vdots
\end{pmatrix} \quad \text{(GuyanLoadCorrection=True)}
\]

The dependency of the load vectors on \( U_{TP} \) introduces some complications for the state space representation, where for instance the \( B \) and \( F_X \) matrices should be modified to account for the dependency in \( U_{TP} \) in Eq. (4.143). The equation remains valid even if \( F_{L,e} \) and \( F_{L,g} \) contains a dependency in \( U_{TP} \), but the matrix \( B \) shouldn’t be used for the linearization (numerical differentiation is then prefered for simplicity). Similar considerations apply for Eq. (4.152).

The coupling load \( F_{TP,cpl} \) given in Eq. (4.147) corresponds to the reaction force at the TP reference position. In the “free boundary condition” case, there is no need to correct this output load since the reference position is at the deflected position. For the “fixed boundary condition” case, the reference position does not correspond to the deflected position, so the reaction moment needs to be transfered to the deflected position as follows:

\[
F_{TP,cpl} = \begin{pmatrix} f_{TP,cpl} \\ m_{TP,cpl} \end{pmatrix} \quad \rightarrow \quad F_{TP,cpl} = \begin{pmatrix} f_{TP,cpl} \\ m_{TP,cpl} - u_{TP} \times f_{TP,cpl} \end{pmatrix} \quad \text{(GuyanLoadCorrection=True and Fixed BC)}
\]

The output equation \( y_1 = -F_{TP,cpl} \) is then modified to include this extra contribution.
Damping specifications

There are three ways to specify the damping associated with the motion of the interface node in SubDyn: no damping, Rayleigh damping or user defined 6x6 matrix.

NOTE: Damping associated with joints is not documented yet and would change the developments below.

When GuyanDampMod=0, SubDyn assumes zero damping for the Guyan modes, and modal damping for the CB modes, with no cross couplings:

\[
\begin{align*}
C_{BB} &= \tilde{C}_{BB} = 0 \\
C_{Bm} &= C_{mB} = \tilde{C}_{Bm} = \tilde{C}_{mB} = 0 \\
C_{mm} &= \tilde{C}_{mm} = 2\zeta\Omega_m
\end{align*}
\] (4.133)

In other words, the only damping matrix term retained is the one associated with internal DOF damping. This assumption has implications on the damping at the interface with the turbine system, as discussed in Section Substructure Tower/Turbine Coupling. The diagonal (m x m) \(\zeta\) matrix contains the modal damping ratios corresponding to each retained internal mode. In SubDyn, the user provides damping ratios (in percent of critical damping coefficients) for the retained modes.

When GuyanDampMod=1, SubDyn assumes Rayleigh Damping for the Guyan modes, and modal damping for the CB modes, with no cross couplings:

\[
\begin{align*}
\tilde{C}_{BB} &= \alpha\tilde{M}_{BB} + \beta\tilde{K}_{BB} \\
\tilde{C}_{Bm} &= \tilde{C}_{mB} = 0 \\
\tilde{C}_{mm} &= 2\zeta\Omega_m
\end{align*}
\] (4.134)

where \(\alpha\) and \(\beta\) are the mass and stiffness proportional Rayleigh damping coefficients. The damping is directly applied to the tilde matrices, that is, the matrices related to the 6 DOF of the TP node.

The case GuyanDampMod=2, is similar to the previous case, except that the user specifies the 6 x 6 terms of \(\tilde{C}_{BB}\).

Static-Improvement Method

To account for the effects of static gravity (member self-weight) and buoyancy forces, one would have to include all of the structural axial modes in the C-B reduction. This inclusion often translates into hundreds of modes to be retained for practical problems. An alternative method is thus promoted to reduce this limitation and speed up SubDyn. This method is denoted as SIM, and computes two static solutions at each time step: one based on the full system stiffness matrix and one based on the reduced stiffness matrix. The dynamic solution then proceeds as described in the previous sections, and at each time step the time-varying dynamic solution is superimposed on the difference between the two static solutions, which amounts to quasi-statically accounting for the contribution of those modes not directly included within the dynamic solution.

The SIM formulation provides a correction for the displacements of the internal nodes. The uncorrected displacements are now noted \(\hat{U}_L\), while the corrected displacements are noted \(U_L\). The SIM correction consists in an additional term \(U_L\) obtained by adding the total static deflection of all the internal DOFs \((U_{L0})\), and subtracting the static deflection associated with C-B modes \((U_{L0m})\), as cast in (4.135):

\[
U_L = \hat{U}_L + U_{L,SIM} = \hat{U}_L + U_{L0} - U_{L0m} = \Phi_R U_R + \Phi_m q_m + \Phi_L q_{L0} - \Phi_m q_{m0}
\] (4.135)

where \(q_{m0}\) and \(q_{L0}\) are the \(m\) and \(L\) modal coefficients that are assumed to be operating in a static fashion. These coefficients are calculated under the C-B hypothesis that the boundary nodes are fixed. The static displacement vectors can be calculated as follows:

\[
K_{LL} U_{L0} = F_{Le} + F_{Lg}
\] (4.136)
By pre-multiplying both sides times $\Phi_L^T$, Eq. (4.136) can be rewritten as: $\Phi_L^T K_{LL} \Phi_L q_{L0} = \Phi_L^T (F_{L,e} + F_{L,g}) = \tilde{F}_L$ or, recalling that $\Phi_L^T K_{LL} \Phi_L = \Omega_L^2$, as: $\Omega_L^2 q_{L0} = \tilde{F}_L$, or equivalently in terms of $U_{L0}$:

$$U_{L0} = \Phi_L [\Omega_L^2]^{-1} \tilde{F}_L \quad (4.137)$$

Similarly:

$$K_{LL} U_{L0m} = F_{L,e} + F_{L,g} \rightarrow U_{L0m} = \Phi_m [\Omega_m^2]^{-1} \tilde{F}_m \quad (4.138)$$

with $\tilde{F}_m = \Phi_m^T (F_{L,e} + F_{L,g})$. Note that: $\dot{U}_{L0} = \dot{q}_{L0} = \dot{U}_{L0m} = \ddot{q}_{m0} = 0$ and $\ddot{U}_{L0} = \ddot{q}_{L0} = \ddot{U}_{L0m} = \ddot{q}_{m0} = 0$.

In the floating case the loads $F_L$ is rotated to the body coordinate system when “GuyanLoadCorrection” is True (see Section 4.7.6 for more details and Section 4.7.6 for the final equations used).

**State-Space Formulation**

A state-space formulation of the substructure structural dynamics problem was devised to integrate SubDyn within the FAST modularization framework. The state-space formulation was developed in terms of inputs, outputs, states, and parameters. The notations highlighted here are consistent with those used in Jonkman (2013). Inputs (identified by $u$) are a set of values supplied to SubDyn that, along with the states, are needed to calculate future states and the system’s output. Outputs ($y$) are a set of values calculated by and returned from SubDyn that depend on the states, inputs, and/or parameters through output equations (with functions $Y$). States are a set of internal values of SubDyn that are influenced by the inputs and used to calculate future state values and the output. In SubDyn, only continuous states are considered. Continuous states ($x$) are states that are differentiable in time and characterized by continuous time differential equations (with functions $X$). Parameters ($p$) are a set of internal system values that are independent of the states and inputs. Furthermore, parameters can be fully defined at initialization and characterize the system’s state equations and output equations.

In SubDyn, the inputs are defined as:

$$u = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \end{bmatrix} = \begin{bmatrix} U_{TP} \\ \dot{U}_{TP} \\ \ddot{U}_{TP} \\ F_{L,e} \\ F_{R,e} \end{bmatrix} \quad (4.139)$$

where $F_L$ are the hydrodynamic forces on every interior node of the substructure from HydroDyn, and $F_{HDR}$ are the analogous forces at the boundary nodes; $U_{TP}, \dot{U}_{TP},$ and $\ddot{U}_{TP}$ are TP deflections (6 DOFs), velocities, and accelerations, respectively. For SubDyn in stand-alone mode (uncoupled from FAST), $F_{L,e}$ and $F_{R,e}$ are assumed to be zero.

In first-order form, the states are defined as:

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} q_m \\ \dot{q}_m \end{bmatrix} \quad (4.140)$$

From the system equation of motion, the state equation corresponding to Eq. (4.124) can be written as a standard linear system state equation:

$$\dot{x} = X = Ax + Bu + F_X \quad (4.141)$$

These state matrices are obtained by isolating the mode accelerations, $\ddot{q}_m$ from the second block row of Eq. (4.124) as:

$$\ddot{q}_m = \Phi_m^T (F_{L,e} + F_{L,g}) - \dddot{M}_m B \dddot{U}_{TP} - \dddot{C}_m B \dddot{U}_{TP} - \dddot{K}_m q_m - \dddot{K}_m q_m \quad (4.142)$$

leading to the following identification:

\[
A = \begin{bmatrix}
0 & I \\
-K_{mm} & -C_{mm}
\end{bmatrix} , \quad B = \begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & -C_{mB} & -M_{mB} & \Phi_m^T
\end{bmatrix} , \quad F_X = \begin{bmatrix}
0 \\
\Phi_m^T F_{L,g}
\end{bmatrix}
\]  \hspace{1cm} (4.143)

In SubDyn, the outputs to the ElastoDyn module are the coupling (reaction) forces at the transition piece \( F_{TP,cpl} \):

\[
y_1 = Y_1 = -F_{TP,cpl}
\]  \hspace{1cm} (4.144)

By examining Eq. (4.124) and Eq. (4.130), the force is extracted from the first block row as:

\[
F_{TP,cpl} = \tilde{M}_{BB} \tilde{U}_{TP} + \tilde{M}_{Bm} \tilde{q}_m + \tilde{C}_{BB} \tilde{U}_{TP} + \tilde{K}_{BB} \tilde{U}_{TP} - T_1^T (\tilde{F}_{R,e} + \tilde{F}_{R,g} + \tilde{\Phi}_R (F_{L,e} + F_{L,g}))
\]  \hspace{1cm} (4.145)

Inserting the expression of \( \tilde{q}_m \) into \( F_{TP,cpl} \) leads to:

\[
F_{TP,cpl} = \begin{bmatrix}
-\tilde{M}_{Bm} \tilde{K}_{mm} \\
\tilde{C}_{Bm} - \tilde{M}_{Bm} \tilde{C}_{mm}
\end{bmatrix} \tilde{q}_m + \begin{bmatrix}
\tilde{C}_{Bm} - \tilde{M}_{Bm} \tilde{C}_{mm}
\end{bmatrix} \tilde{u}_m + \begin{bmatrix}
\tilde{K}_{BB} \\
\tilde{C}_{BB} - \tilde{M}_{Bm} \tilde{C}_{mm}
\end{bmatrix} \tilde{U}_{TP} + \begin{bmatrix}
\tilde{M}_{BB} - \tilde{M}_{Bm} \tilde{M}_{mB} & \tilde{M}_{BM} \tilde{\Phi}_m - T_1^T \tilde{\Phi}_R
\end{bmatrix} \tilde{U}_{TP} + \begin{bmatrix}
\tilde{M}_{Bm} \Phi_m^T - T_1^T \tilde{\Phi}_R
\end{bmatrix} (F_{L,e} + F_{L,g})
\]  \hspace{1cm} (4.146)

The output equation for \( y_1 \) can now be identified as:

\[
-Y_1 = F_{TP,cpl} = C_1 x + D_1 \tilde{u} + F_{Y_1}
\]  \hspace{1cm} (4.147)

where

\[
C_1 = \begin{bmatrix}
-\tilde{M}_{Bm} \tilde{K}_{mm} & \tilde{C}_{Bm} - \tilde{M}_{Bm} \tilde{C}_{mm}
\end{bmatrix} \\
D_1 = \begin{bmatrix}
\tilde{K}_{BB} & \tilde{C}_{BB} - \tilde{M}_{Bm} \tilde{C}_{mm} \\
\tilde{M}_{BB} - \tilde{M}_{Bm} \tilde{M}_{mB} & \tilde{M}_{BM} \tilde{\Phi}_m - T_1^T \tilde{\Phi}_R
\end{bmatrix} \\
F_{Y_1} = \begin{bmatrix}
\tilde{M}_{Bm} \Phi_m^T F_{L,g} - T_1^T (\tilde{F}_{R,g} + \tilde{\Phi}_R^T F_{L,g})
\end{bmatrix}
\]  \hspace{1cm} (4.148)

\[
\tilde{u} = \begin{bmatrix}
\tilde{U}_{TP} \\
\tilde{U}_{TP} \\
\tilde{F}_{L,e} \\
\tilde{F}_{R,e}
\end{bmatrix}
\]

Note that the overbar is used on the input vector to denote that the forces apply to the interface nodes only.

The outputs to HydroDyn and other modules are the deflections, velocities, and accelerations of the substructure:

\[
y_2 = Y_2 = \begin{bmatrix}
\tilde{U}_R \\
\tilde{U}_L \\
\tilde{\Phi}_R \\
\tilde{\Phi}_L
\end{bmatrix}
\]  \hspace{1cm} (4.149)

From the CB coordinate transformation (Eq. (4.117)), and the link between boundary nodes and TP node (Eq. (4.121)) the motions are given as:

\[
\tilde{U}_R = T_1 \tilde{U}_{TP} , \quad \tilde{U}_L = \tilde{\Phi}_R \tilde{U}_R + \Phi_m \tilde{q}_m + U_{L,\text{SIM}} \\
\tilde{U}_R = T_1 \tilde{U}_{TP} , \quad \tilde{U}_L = \tilde{\Phi}_R \tilde{U}_R + \Phi_m \tilde{q}_m
\]  \hspace{1cm} (4.150)
The expression for \( y_2 \) motions contains the optional SIM contribution (see Section 4.7.6). Using the expression of \( \ddot{q}_m \) from Eq. (4.7.6), the internal accelerations are:

\[
\ddot{U}_L = \Phi_R T_I \ddot{U}_T + \Phi_m \left[ \Phi^T_m (F_{L,e} + F_{L,g}) - \dot{M}_{mB} \ddot{U}_T + \dot{C}_{mB} \ddot{U}_T - \ddot{C}_{mm} \ddot{q}_m - \dddot{K}_{mm} q_m \right]
\]  

(4.151)

In the floating case, the Guyan part of the motion are replaced by the analytical rigid body motion (see details in section Section 4.7.6).

The output equation for \( y_2 \) can then be written as:

\[
Y_2 = C_2 x + D_2 u + F_{Y_2}
\]

(4.152)

where

\[
C_2 = \begin{bmatrix}
0 & 0 \\
\Phi_m & 0 \\
0 & 0 \\
0 & \Phi_m \\
-\Phi_m \ddot{K}_{mm} & -\Phi_m \dddot{C}_{mm}
\end{bmatrix}
\]

\[
D_2 = \begin{bmatrix}
T_I & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & T_I & 0 & 0 & 0 \\
0 & 0 & T_I & 0 & 0 \\
0 & -\Phi_m \dddot{C}_{mB} & \Phi_R T_I - \Phi_m \dddot{M}_{mB} & \Phi_m \Phi_m^T & 0
\end{bmatrix}
\]

(4.153)

\[
F_{Y_2} = \begin{bmatrix}
0 \\
U_{L,SIM} \\
0 \\
0 \\
\Phi_m \Phi_m^T F_{L,g}
\end{bmatrix}
\]

Outputs and Time Integration

Nodal Loads Calculation

We start by introducing how element loads are computed, before detailing how nodal loads are obtained.

**Element Loads:**

SubDyn calculates 12-vector element loads in the element coordinate system using the global motion of the element:

Element Inertia load: \( F_{I,12}^e = [D_{c,12}]^T [m] \ddot{U}_{c,12} \)

Element Stiffness load: \( F_{S,12}^e = [D_{c,12}]^T [k] [\ddot{U}_e + U_{L,SIM}]_{12} \)

(4.154)

where \([k]\) and \([m]\) are element stiffness and mass matrices expressed in the global frame, \(D_{c,12}\) is a 12x12 matrix of DCM for a given element, the subscript 12 indicates that the 12 degrees of freedom of the element are considered, and \(U_e\) and \(\ddot{U}_e\) are element nodal deflections and accelerations respectively, which can be obtained from Eq. (4.149) and may contain the static displacement contribution \(U_{L,SIM}\). There is no good way to quantify the damping forces for each element, so the element damping forces are not calculated.

Nodal loads
For a given element node, the loads are the 6-vector with index 1-6 or 7-12 for the first or second node respectively. By convention, the 6-vector is multiplied by -1 for the first node and +1 for the second node of the element:

\[ F^n_6 = -F^n_{12}(1:6), \quad F^n_6 = +F^n_{12}(7:12) \quad (4.155) \]

The above applies for the inertial and stiffness loads.

**Member nodal loads requested by the user**

The user can output nodal loads for a set of members (see Section 4.7.3).

For the user requested member nodal outputs, the loads are either: 1) the appropriate 6-vector at the member end nodes, or, 2) the average of the 6-vectors from the two elements surrounding a node for the nodes in the middle of a member. When averaging is done, the 12-vectors of both surrounding elements are expressed using the DCM of the member where outputs are requested.

**“AllOuts” nodal loads**

For “AllOuts” nodal outputs, the loads are not averaged and the 6-vector (with the appropriate signs) are directly written to file.

**Reaction nodal loads (See Section 4.7.6)**

**Reaction Calculation**

The reactions at the base of the structure are the nodal loads at the base nodes.

Additionally, the user may request an overall reaction \( \vec{R} \) (six forces and moments) lumped at the center of the substructure (tower centerline and mudline, i.e., at the reference point \((0,0,-\text{WtrDpth})\) in the global reference frame, with \(\text{WtrDpth}\) denoting the water depth.

To obtain this overall reaction, the forces and moments at the \( N_{\text{React}} \) restrained nodes are expressed in the global coordinate frame and gathered into the vector \( F_{\text{React}} \), which is a \((6*N_{\text{React}})\) array. For a given reaction node, the 6-vector of loads is obtained by summing the nodal load contributions from all the elements connected to that node expressed in the global frame (no account of the sign is done here), and subtracting the external loads \( F_{\text{HDR}} \) applied on this node. The loads from all nodes, \( F_{\text{React}} \), are then rigidly-transferred to \((0,0,-\text{WtrDpth})\) to obtain the overall six-element array \( \vec{R} \):

\[ \vec{R} = \begin{bmatrix} F_X \\ \vdots \\ M_Z \end{bmatrix} = T_{\text{React}} F_{\text{React}} \quad (4.156) \]

where \( T_{\text{React}} \) is a \((66*N_{\text{React}})\) matrix, as follows:

\[
T_{\text{React}} = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & \cdots & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & \cdots & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & \cdots & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & -\Delta Z_1 & \Delta Y_1 & 1 & 0 & 0 & \cdots & 0 & -\Delta Z_{N_{\text{React}}} & \Delta Y_{N_{\text{React}}} & 1 & 0 & 0 \\
\Delta Z_1 & 0 & -\Delta X_1 & 0 & 1 & 0 & \cdots & \Delta Z_{N_{\text{React}}} & 0 & -\Delta X_{N_{\text{React}}} & 0 & 1 & 0 \\
\Delta Y_1 & \Delta X_1 & 0 & 0 & 0 & 1 & \cdots & \Delta Y_{N_{\text{React}}} & \Delta X_{N_{\text{React}}} & 0 & 0 & 1 & 0 \\
\end{bmatrix} \quad (4.157)
\]

where \( X_i, Y_i, \) and \( Z_i \) \((i = 1..N_{\text{React}})\) are coordinates of the boundary nodes with respect to the reference point.
**Time Integration**

At time $t = 0$, the initial states are specified as initial conditions (all assumed to be zero in SubDyn) and the initial inputs are supplied to SubDyn. During each subsequent time step, the inputs and states are known values, with the inputs $u(t)$ coming from ElastoDyn and HydroDyn, and the states $x(t)$ known from the previous time-step integration. All of the parameter matrices are calculated in the SubDyn initiation module. With known $u(t)$ and $x(t)$, $\dot{x}(t)$ can be calculated using the state equation $\dot{x}(t) = X(u, x, t)$ (see Eq. (4.141)), and the outputs $y_1(t)$ and $y_2(t)$ can be calculated solving Eqs. (4.147) and (4.152). The element forces can also be calculated using Eq. (4.154). The next time-step states $x(t + \Delta t)$ are obtained by integration:

$$ [u(t), \dot{x}(t), x(t)] \xrightarrow{\text{Integrate}} x(t + \Delta t) $$  \hspace{1cm} (4.158)

For loose coupling, SubDyn uses its own integrator, whereas for tight coupling, the states from all the modules will be integrated simultaneously using an integrator in the glue-code. SubDyn’s built-in time integrator options for loose coupling are:

- Fourth-order explicit Runge-Kutta
- Fourth-order explicit Adams-Bashforth predictor
- Fourth-order explicit Adams-Bashforth-Moulton predictor-corrector
- Implicit second-order Adams-Moulton.

For more information, consult any numerical methods reference, e.g., [CC10].

**Summary of the formulation implemented**

This section summarizes the equations currently implemented in SubDyn, with the distinction between floating and fixed bottom cases. We introduce the operators $R_{g2b}$ (rotation global to body) and $R_{b2g}$ (rotation body to global), which act on the array on the right of the operator. The operators rotate the individual 3-vectors present in an array. When applied to load vectors (e.g. $F_L$), the rotations actually is applied to the loads on the full system, before the loads are transferred to the reduced system by use of the $T$ matrix.

**State equation**

**Fixed-bottom case**

$$ \ddot{q}_m = \Phi_m^T F_L - \tilde{M}_m B \tilde{U}_T P - \tilde{C}_{mm} \dot{q}_m - \tilde{K}_{mm} q_m $$  \hspace{1cm} (4.159)

Note: $F_L$ contains the “extra moment” if user-requested with **GuyanLoadCorrection**.

**Floating case without “GuyanLoadCorrection”**

$$ \ddot{q}_m = \Phi_m^T F_L - \tilde{M}_m B \tilde{U}_T P - \tilde{C}_{mm} \dot{q}_m - \tilde{K}_{mm} q_m $$  \hspace{1cm} (4.160)

Notes: $F_L$ does not contain the “extra moment”.

**Floating case with “GuyanLoadCorrection”**

$$ \ddot{q}_m = \Phi_m^T R_{g2b} F_L - \tilde{M}_m B R_{g2b} \tilde{U}_T P - \tilde{C}_{mm} \dot{q}_m - \tilde{K}_{mm} q_m $$  \hspace{1cm} (4.161)

Notes: $F_L$ does not contain the “extra moment”. The (external + gravity) loads and the acceleration of the TP are rotated to the body coordinate system.
Output: interface reaction

Fixed bottom case

\[-Y_1 = F_{TP, cpl} = \begin{cases} f_{TP, cpl} \\ \frac{-M_B m \ddot{R}}{m_T P_{cpl}} \end{cases} = \begin{bmatrix} -\ddot{M}_B m \ddot{K}_{mm} \\ -\ddot{M}_B m \dddot{C}_{mm} \end{bmatrix} q_m + \begin{bmatrix} -\ddot{M}_B m \dddot{C}_{mm} \end{bmatrix} \dot{q}_m + \begin{bmatrix} \ddot{K}_{BB} \end{bmatrix} U_{TP} + \begin{bmatrix} \dddot{C}_{BB} \end{bmatrix} \dot{U}_{TP} + \begin{bmatrix} \dddot{M}_{BB} - \dddot{M}_B m \dddot{M}_{mm} \end{bmatrix} \dddot{U}_{TP} + \begin{bmatrix} \dddot{M}_B m \dddot{\Phi}_m^T \end{bmatrix} F_L + \begin{bmatrix} -T^T_\text{g} \dddot{\Phi}_R^T \end{bmatrix} F_L + \begin{bmatrix} -T^T_\text{g} \dddot{F}_R \end{bmatrix} \tag{4.162} \end{cases} \]

Note: $F_L$ and $\dddot{F}_R$ contains the “extra moment” if user-requested. If this is the case, the following additional term is added to the moment part of $Y_1$, $m_{Y_1, \text{extra}} = u_{TP} \times f_{TP, cpl}$.

Floating case without “GuyanLoadCorrection”

\[-Y_1 = F_{TP, cpl} = \begin{bmatrix} -\ddot{M}_B m \ddot{K}_{mm} \\ -\ddot{M}_B m \dddot{C}_{mm} \end{bmatrix} q_m + \begin{bmatrix} -\ddot{M}_B m \dddot{C}_{mm} \end{bmatrix} \dot{q}_m + \begin{bmatrix} \ddot{K}_{BB} \end{bmatrix} U_{TP} + \begin{bmatrix} \dddot{C}_{BB} \end{bmatrix} \dot{U}_{TP} + \begin{bmatrix} \dddot{M}_{BB} - \dddot{M}_B m \dddot{M}_{mm} \end{bmatrix} \dddot{U}_{TP} + \begin{bmatrix} \dddot{M}_B m \dddot{\Phi}_m^T \end{bmatrix} F_L + \begin{bmatrix} -T^T_\text{g} \dddot{\Phi}_R^T \end{bmatrix} F_L + \begin{bmatrix} -T^T_\text{g} \dddot{F}_R \end{bmatrix} \tag{4.163} \]

Note: $F_L$ and $\dddot{F}_R$ do not contain the “extra moment”.

Floating case with “GuyanLoadCorrection”

\[-Y_1 = F_{TP, cpl} = R_{b2g} \begin{bmatrix} -\ddot{M}_B m \ddot{K}_{mm} \\ -\ddot{M}_B m \dddot{C}_{mm} \end{bmatrix} q_m + R_{b2g} \begin{bmatrix} -\ddot{M}_B m \dddot{C}_{mm} \end{bmatrix} \dot{q}_m + \begin{bmatrix} \ddot{K}_{BB} \end{bmatrix} U_{TP} + \begin{bmatrix} \dddot{C}_{BB} \end{bmatrix} \dot{U}_{TP} + \begin{bmatrix} \dddot{M}_{BB} - \dddot{M}_B m \dddot{M}_{mm} \end{bmatrix} \dddot{U}_{TP} + R_{b2g} \begin{bmatrix} \dddot{M}_B m \dddot{\Phi}_m^T \end{bmatrix} R_{g2b} F_L + \begin{bmatrix} -T^T_\text{g} \dddot{\Phi}_R^T \end{bmatrix} F_L,\text{extra} + \begin{bmatrix} -T^T_\text{g} \dddot{F}_R,\text{extra} \end{bmatrix} \tag{4.164} \]

Notes: 1) $F_L,\text{extra}$ and $F_R,\text{extra}$ contain the “extra moment” in the Guyan contribution; 2) For the Craig-Bampton contribution, the loads are rotated to the body coordinate system using the operator $R_{g2b}$ (global to body); 3) The rotation $R_{b2g} \dddot{M}_B m \dddot{M}_{mm} R_{g2b}$ is not carried out since it introduced stability issues.

Output: nodal motions

Fixed-bottom case

\[
\begin{align*}
\dddot{U}_R &= T_1 U_{TP}, & \dddot{U}_L &= \dddot{\Phi}_R \dddot{U}_R + \Phi_m \dddot{q}_m + U_{L, \text{SIM}} \\
\dddot{\dot{U}}_R &= T_1 \dddot{U}_{TP}, & \dddot{\dot{U}}_L &= \dddot{\Phi}_R \dddot{\dot{U}}_R + \Phi_m \dot{q}_m \\
\dddot{\dddot{U}}_R &= T_1 \dddot{\dot{U}}_{TP}, & \dddot{\dddot{U}}_L &= \dddot{\Phi}_R \dddot{\dddot{U}}_R + \Phi_m \left[ \Phi_m^T F_L - \dddot{M}_m \dddot{B} \dddot{U}_{TP} - \dddot{C}_{mm} \dddot{q}_m - \dddot{K}_{mm} \dddot{q}_m \right] \tag{4.165}
\end{align*}
\]

Note: $F_L$ contains the “extra moment” if user-requested with GuyanLoadCorrection.

Floating case

\[
\begin{align*}
\dddot{\dddot{U}}_R &= U_{R, \text{rigid}}, & \dddot{\dddot{U}}_L &= U_{L, \text{rigid}} + 0 \cdot R_{b2g} \left( \Phi_m \dddot{q}_m + U_{L, \text{SIM}} \right) \\
\dddot{\dot{U}}_R &= \dddot{\dot{U}}_{R, \text{rigid}}, & \dddot{\dot{U}}_L &= \dddot{\dot{U}}_{L, \text{rigid}} + R_{b2g} \Phi_m \dot{q}_m \\
\dddot{\dddot{U}}_R &= \dddot{\dddot{U}}_{R, \text{rigid}}, & \dddot{\dddot{U}}_L &= \dddot{\dddot{U}}_{L, \text{rigid}} + R_{b2g} \Phi_m \left[ \Phi_m^T R_{g2b} F_L - \dddot{M}_{mm} R_{g2b} \dddot{U}_{TP} - \dddot{C}_{mm} \dddot{q}_m - \dddot{K}_{mm} \dddot{q}_m \right] \tag{4.166}
\end{align*}
\]

where: 1) $F_L$ does not contain the extra moment, 2) the operators $R_{g2b}$ and $R_{b2g}$ are when GuyanLoadCorrection is True, 3) the elastic displacements were set to 0 for stability purposes (assuming that these are small) 4) the Guyan
motion is computed using the exact rigid body motions. For a given node \( P \), located at the position \( r_{IP,0} \) from the interface in the undisplaced configuration, the position (from the interface point), displacement, translational velocity and acceleration due to the rigid body motion are:

\[
\begin{align*}
    r_{IP} &= R_{b2g}r_{IP,0}, \\
    u_P &= r_{IP} - r_{IP,0} + u_{TP}, \\
    \dot{u}_P &= \dot{u}_{TP} + \omega_{TP} \times r_{IP}, \\
    \ddot{u}_P &= \ddot{u}_{TP} + \dot{\omega}_{TP} + \omega_{TP} \times (\omega_{TP} \times r_{IP})
\end{align*}
\]

where \( \omega_{TP} \) is the angular velocity at the transition piece. The small angle rotations, angular velocities and accelerations of each nodes, due to the rigid body rotation, are the same as the interface values, \( \theta_{TP} \), \( \omega_{TP} \) and \( \dot{\omega}_{TP} \), so that:

\[
\begin{align*}
    U_{P,\text{rigid}} &= \{u_P ; \theta_{TP}\}^T, \\
    \dot{U}_{P,\text{rigid}} &= \{\dot{u}_P ; \omega_{TP}\}^T, \\
    \ddot{U}_{P,\text{rigid}} &= \{\ddot{u}_P ; \dot{\omega}_{TP}\}^T
\end{align*}
\]

where \( P \) is a point belonging to the R- or L-set of nodes.

**Outputs to file:**

**Motions:** nodal motions written to file are in global coordinates, and for the floating case they contain the elastic motion \( \bar{U}_L = U_{L,\text{rigid}} + \Phi_m q_m + U_{L,\text{SIM}} \) (whereas these elastic motions are not returned to the glue code)

**Loads:**

Nodal loads are written to file in the element coordinate system. The procedure are the same for fixed-bottom and floating cases.

### 4.7.7 Known Limitations and Future Work

The following list contains known current limitations in the code:

- Tight coupling is not yet supported.
- Only nontapered two-node Euler-Bernoulli (E-B) or Timoshenko (T) element formulations are available. (In the future, tapered E-B and tapered Timoshenko element formulations will be implemented.)
- Only straight circular members are permitted. (In the future, a generic cross section will be allowed.)
- The number of elements per member (\( \text{NDiv} \)) is constant throughout the structure.
- Internal matrices are not stored in sparse form, limiting the total number of possible nodes/DOFs to about 300/1800.
- The dynamics system reduction is performed in the absence of external loading (e.g., hydrodynamic added mass).
- Gravitational loading does not impact the global substructure stiffness.
- Loads (gravitational, inertial, hydrodynamic) can only be applied as concentrated loads at element nodes; distributed loads (per unit length) are not yet supported.
- The overlap of multiple members connected to a single joint is not modeled with super-elements.
- Member-level outputs are only available for up to nine nodes of up to nine members (although the OutAll flag can generate further outputs at the member end nodes).
- No graphics/animation capability is yet available to visualize the substructure geometry, modes, motion, and loads.
4.7.8 Appendix A. OC4 Jacket Input File

SubDyn’s primary input file (OC4 Jacket SubDyn’s Input File):

This file includes information on the integration method (e.g., Adams-Bashforth 4\textsuperscript{th} order), numerical-solution parameters (e.g., integration time interval, static solver flag, number of modes to retain within the Craig-Bampton reduction), finite element analysis information (beam element model, number of elements per member), and the geometric definition of the beam members via joints, member connectivity, and member cross-sectional properties. This file also specifies any SSI input files (soil/pile stiffness and mass matrices).

4.7.9 Appendix B. OC4 Jacket Driver File

SubDyn’s Driver Input File (OC4 Jacket Driver File):

This file includes information on the environmental conditions (gravity and water depth), numerical-solution parameters (e.g., integration time interval, number of time-steps), TP reference point coordinates in global reference frame, rotation angle of the structure geometry in degrees about the global Z axis, the input mode for the TP reference point displacements, velocities, and accelerations (steady-state or time-series from file) and any related input file if not steady-state input.

4.7.10 Appendix C. OC4 Jacket SSI Input File

SubDyn’s SSI File (OC4 Jacket SSI File):

This file includes information on the stiffness of embedded-pile/soil combination.

4.7.11 Appendix D. List of Output Channels

This is a list of all possible output parameters for the SubDyn module. The names are grouped by meaning, but can be ordered in the OUTPUT CHANNELS section of the SubDyn input file as the user sees fit. $M_{\alpha N \beta}$, refers to node $\beta$ of member $\alpha$, where $\alpha$ is a number in the range $[1,9]$ and corresponds to row $\alpha$ in the MEMBER OUTPUT LIST table (see Section 7) and $\beta$ is a number in the range $[1,9]$ and corresponds to node $\beta$ in the NodeCnt list of that table entry.

Some outputs are in the SS reference coordinate system (global inertial-frame coordinate system), and end with the suffix $ss$; others refer to the local (member) reference system and they have suffixes “Xe”, “Ye”, or “Ze” (see Section 7).

Table C-1. List of Output Channels.
<table>
<thead>
<tr>
<th>Channel Name(s)</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base and Interface Reaction Loads</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ReactFXss, ReactFYss, ReactFZss, ReactMXss, ReactMYss, ReactMZss</td>
<td>(N), (N), (N), (Nm), (Nm), (Nm)</td>
<td>Total base reaction forces and moments at the (0.,0.,-\text{WtrDpth}) location in SS coordinate system</td>
</tr>
<tr>
<td>IntfFXss, IntfFYss, IntfFZss, IntfMXss, IntfMYss, IntfMZss</td>
<td>(N), (N), (N), (Nm), (Nm), (Nm)</td>
<td>Total interface reaction forces and moments at the TP reference point (platform reference point) location in SS coordinate system</td>
</tr>
<tr>
<td><strong>Interface Kinematics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IntfTDxss, IntfTDYss, IntfTDZss, IntfRDxss, IntfRDYss IntfRDZss</td>
<td>(m), (m), (m), (rad), (rad), (rad)</td>
<td>Displacements and rotations of the TP reference point (platform reference point) location in SS coordinate system</td>
</tr>
<tr>
<td>IntfTAXss, IntfTAYss, IntfTAZss, IntfRAXss, IntfRAYss IntfRAZss</td>
<td>((m/s^2)), ((m/s^2)), ((m/s^2)), ((rad/s^2)), ((rad/s^2)), ((rad/s^2))</td>
<td>Translational and rotational accelerations of the TP reference point (platform reference point) location in SS coordinate system</td>
</tr>
<tr>
<td><strong>Modal Parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SSqm01-SSqm99</td>
<td>(-)</td>
<td>C-B modal variables (up to first 99)</td>
</tr>
<tr>
<td>SSqmd01-SSqmd99</td>
<td>(1/s)</td>
<td>First time-derivatives of C-B modal variables (up to first 99)</td>
</tr>
<tr>
<td>SSqmd01-SSqmd99</td>
<td>((1/s^2))</td>
<td>Second time-derivatives of C-B modal variables (up to first 99)</td>
</tr>
<tr>
<td><strong>Node Kinematics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(M\alpha N\beta) TDxss, (M\alpha N\beta) TDyss, (M\alpha N\beta) TDzss</td>
<td>(m)</td>
<td>Nodal translational displacements of (M\alpha N\beta) (up to 81 designated locations) in SS coordinate system</td>
</tr>
<tr>
<td>(M\alpha N\beta) RDxe, (M\alpha N\beta) RDye, (M\alpha N\beta) RDze</td>
<td>(rad)</td>
<td>Nodal rotational displacements of (M\alpha N\beta) (up to 81 designated locations) in member local coordinate system</td>
</tr>
<tr>
<td>(M\alpha N\beta) TAxe, (M\alpha N\beta) TAye, (M\alpha N\beta) TAze</td>
<td>((m/s^2))</td>
<td>Nodal translational accelerations of (M\alpha N\beta) (up to 81 designated locations) in member local coordinate system</td>
</tr>
<tr>
<td>(M\alpha N\beta) RAxe, (M\alpha N\beta) RAYe, (M\alpha N\beta) RAze</td>
<td>((rad/s^2))</td>
<td>Nodal rotational accelerations of (M\alpha N\beta) (up to 81 designated locations) in member local coordinate system</td>
</tr>
<tr>
<td><strong>Node Forces and Moments</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(M\alpha N\beta) FKxe, (M\alpha N\beta) FKye, (M\alpha N\beta) FKze</td>
<td>(N), (N), (Nm), (Nm), (Nm)</td>
<td>Static (elastic) component of reaction forces and moments at (M\alpha N\beta) along local member coordinate system</td>
</tr>
<tr>
<td>(M\alpha N\beta) MKxe, (M\alpha N\beta) MKye, (M\alpha N\beta) MKze</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(M\alpha N\beta) FMxe, (M\alpha N\beta) FMye, (M\alpha N\beta) FMze</td>
<td>(N), (N), (Nm), (Nm), (Nm)</td>
<td>Dynamic (inertial) component of reaction forces and moments at (M\alpha N\beta) along local member coordinate system</td>
</tr>
</tbody>
</table>
4.7.12 Appendix E. Compiling Stand-Alone SubDyn

See the FAST documentation for instructions on how to compile SubDyn coupled to FAST. Future versions of the manual will include compiling instructions for building the stand-alone SubDyn program.

4.7.13 Appendix F. Major Changes in SubDyn

When first released, SubDyn (v0.4) was included as an undocumented feature of FAST v8 and packaged as a stand-alone archive. Since v0.4, SubDyn has been well integrated into FAST v8 and OpenFast, and the stand-alone form is also available. This appendix outlines significant modifications to SubDyn made since v0.4. Following are the main changes that the user may notice, but for more information, refer to the changelog.txt text file within the official archive and the GitHub log.

V1.04.00 (September 2020)

- Version 1.04.00 integrates with OpenFAST version 2.4
- Member types: beam, rigid link, pretension cable
- Joint types: cantilever, universal, pin, ball
- Input of all terms for concentrated mass
- Guyan damping matrix
- Extra lever arm
- Coupling with SoilDyn
- Inclusion of soil-structure interaction (SSI) via flexible degrees of fixity at the restrained nodes and a new input file that allows for 6x6 stiffness and mass matrices that simulate boundary conditions at those nodes.
- Controllable pretension cable elements

V1.03.00a-rrd (September 2017)

- Version 1.03.00a-rrd integrates with the OpenFast software.

V1.01.01a-rrd (September 2014)

Version 1.01.01a-rrd integrates with the FAST v8 software v8.09.00a-bjj.

- Finite-element eigenvalue bug fixes: the full system eigenvalues were incorrectly reported in the summary file, although with no further consequences on the results. This bug is now fixed.
- Shear area correction factor improvement: the shear area correction factor in the Timoshenko treatment is now aligned with Steinboeck et al. (2013).
- The formulation for the TP reaction has been rearranged to adhere to the theory manual, with no consequences on the output results.
V1.01.00a-rrd (June 2014)

Version 1.00.01a-rrd integrates with the FAST v8 software v8.08.00c-bjj.

The new implementation has well-defined data exchange interfaces (following the FAST modularization framework) that should make integration of SubDyn into other multiphysics software packages much simpler.

Several improvements and bug fixes have been implemented since version v0.4 and the module has undergone an extensive verification effort with good results.

- Eigensolver bug fixes: the LAPACK solver proved to be unstable in single precision, and now it is solely run in double precision, regardless of the precision used in other parts of the code.
- The input file format has changed. Please refer to the sample input file in Appendix A and the following notes:
  - First header line has been removed.
  - Simulation Control Section:
    - SDeltat: The “DEFAULT” keyword (in place of 0.0) is now used to indicate that the glue-code time step will be used for time integration by SubDyn.
    - IntMethod: Allowed values are now 1-4 (in place of 0-3).
    - SttcSolve: New flag introduced. If set to TRUE, the static-improvement method (SIM) will be used.
  - FEA and Craig-Bampton Parameters Section:
    - In v0.4, the damping coefficients had to be specified for all retained Craig-Bampton modes, or just once for all the modes (if CBMod = FALSE). In this version, the user can input any number of damping coefficients. In case the number of retained C-B modes (NModes) is larger than the input number of damping coefficients (JDampings), the last damping value will be replicated for all the remaining modes.
  - Base Reaction Joints, Interface Joints, Member, and Member Cosine Matrices Sections:
    - One line with units, below the headers, is expected in all the tables of the input file.
  - Output: Summary and Outfile Section:
    - This section now also contains the parameters previously assigned under the Section titled “Output: Fast/Subdyn Output-File Variables”
- Some of the quantities in the summary file have been fixed. Some of the output matrices were, in fact, being output with wrong values because of an index mismatch. The new summary file is shorter and does not contain some of the CB method matrices, unless the compiler directive, DEBUG, is set.
- SIM. This new implementation helps minimize the number of needed modes to capture the contribution of certain loads (such as static gravity and buoyancy loads or high-frequency loads transferred from the turbine). In the previous version, a large number of internal modes were needed to engage substructural modes excited by static and high-frequency forces. These modes are no longer needed and fewer modes can be retained while still achieving accurate results (see also Section 4.7.6). With SIM enabled, all modes that are not considered by the Craig-Bampton reduction are treated quasi-statically.
- There is now the possibility of retaining no internal C-B modes, thus relying solely on SIM, in those cases where the substructure’s first eigenfrequencies are much higher than the expected energy-containing modes of the entire system.
- The coupling of SubDyn within FAST now includes full hydro-elastic coupling with the HydroDyn hydrodynamics module.
4.8 ElastoDyn Users Guide and Theory Manual

4.8.1 Input Files

The user configures the structural model parameters via a primary ElastoDyn input file, as well as separate input files for the tower and *other stuff that will be documented here later.*

No lines should be added or removed from the input files.

Units

ElastoDyn uses the SI system (kg, m, s, N). Angles are assumed to be in radians unless otherwise specified.

ElastoDyn Primary Input File

The primary ElastoDyn input file defines modeling options and geometries for the OpenFAST structure including the tower, nacelle, drivetrain, and blades (if BeamDyn is not used). It also sets the initial conditions for the structure.

Simulation Control

Set the **Echo** flag to TRUE if you wish to have ElastoDyn echo the contents of the ElastoDyn primary, airfoil, and blade input files (useful for debugging errors in the input files). The echo file has the naming convention of *OutRootFile.ED.ech*. *OutRootFile* is either specified in the I/O SETTINGS section of the driver input file when running ElastoDyn standalone, or by the OpenFAST program when running a coupled simulation.

Method
dT

Environmental Condition

gavity

Degrees of Freedom

**FlapDOF1** - First flapwise blade mode DOF (flag)
**FlapDOF2** - Second flapwise blade mode DOF (flag)
**EdgeDOF** - First edgewise blade mode DOF (flag)
**TeetDOF** - Rotor-teeter DOF (flag) [unused for 3 blades]
**DrFrDOF** - Drivetrain rotational-flexibility DOF (flag)
**GenDOF** - Generator DOF (flag)
**YawDOF** - Yaw DOF (flag)
**TwFADOF1** - First fore-aft tower bending-mode DOF (flag)
**TwFADOF2** - Second fore-aft tower bending-mode DOF (flag)
**TwSSDOF1** - First side-to-side tower bending-mode DOF (flag)
TwSSDOF2 - Second side-to-side tower bending-mode DOF (flag)
PtfmSgDOF - Platform horizontal surge translation DOF (flag)
PtfmSwDOF - Platform horizontal sway translation DOF (flag)
PtfmHvDOF - Platform vertical heave translation DOF (flag)
PtfmRDOF - Platform roll tilt rotation DOF (flag)
PtfmPDOF - Platform pitch tilt rotation DOF (flag)
PtfmYDOF - Platform yaw rotation DOF (flag)

**Initial Conditions**

OoPDefl - Initial out-of-plane blade-tip displacement (meters)
IPDefl - Initial in-plane blade-tip deflection (meters)
BlPitch(1) - Blade 1 initial pitch (degrees)
BlPitch(2) - Blade 2 initial pitch (degrees)
BlPitch(3) - Blade 3 initial pitch (degrees) [unused for 2 blades]
TeetDefl - Initial or fixed teeter angle (degrees) [unused for 3 blades]
Azimuth - Initial azimuth angle for blade 1 (degrees)
RotSpeed - Initial or fixed rotor speed (rpm)
NacYaw - Initial or fixed nacelle-yaw angle (degrees)
TTDspFA - Initial fore-aft tower-top displacement (meters)
TTDspSS - Initial side-to-side tower-top displacement (meters)
PtfmSurge - Initial or fixed horizontal surge translational displacement of platform (meters)
PtfmSway - Initial or fixed horizontal sway translational displacement of platform (meters)
PtfmHeave - Initial or fixed vertical heave translational displacement of platform (meters)
PtfmRoll - Initial or fixed roll tilt rotational displacement of platform (degrees)
PtfmPitch - Initial or fixed pitch tilt rotational displacement of platform (degrees)
PtfmYaw - Initial or fixed yaw rotational displacement of platform (degrees)

**Turbine Configuration**

NumBl - Number of blades (-)
TipRad - The distance from the rotor apex to the blade tip (meters)
HubRad - The distance from the rotor apex to the blade root (meters)
PreCone(1) - Blade 1 cone angle (degrees)
PreCone(2) - Blade 2 cone angle (degrees)
PreCone(3) - Blade 3 cone angle (degrees) [unused for 2 blades]
HubCM - Distance from rotor apex to hub mass [positive downwind] (meters)
UndSling - Undersling length [distance from teeter pin to the rotor apex] (meters) [unused for 3 blades]

Delta3 - Delta-3 angle for teetering rotors (degrees) [unused for 3 blades]

AzimB1Up - Azimuth value to use for I/O when blade 1 points up (degrees)

OverHang - Distance from yaw axis to rotor apex [3 blades] or teeter pin [2 blades] (meters)

ShftGagL - Distance from rotor apex [3 blades] or teeter pin [2 blades] to shaft strain gages [positive for upwind rotors] (meters)

ShftTilt - Rotor shaft tilt angle (degrees)

NacCMxn - Downwind distance from the tower-top to the nacelle CM (meters)

NacCMyn - Lateral distance from the tower-top to the nacelle CM (meters)

NacCMzn - Vertical distance from the tower-top to the nacelle CM (meters)

NcIMUxn - Downwind distance from the tower-top to the nacelle IMU (meters)

NcIMUyn - Lateral distance from the tower-top to the nacelle IMU (meters)

NcIMUzn - Vertical distance from the tower-top to the nacelle IMU (meters)

Twr2Shft - Vertical distance from the tower-top to the rotor shaft (meters)

TowerHt - Height of tower above ground level [onshore] or MSL [offshore] (meters)

TowerBsHt - Height of tower base above ground level [onshore] or MSL [offshore] (meters)

PtfmCMxt - Downwind distance from the ground level [onshore] or MSL [offshore] to the platform CM (meters)

PtfmCMyt - Lateral distance from the ground level [onshore] or MSL [offshore] to the platform CM (meters)

PtfmCMzt - Vertical distance from the ground level [onshore] or MSL [offshore] to the platform CM (meters)

PtfmRefzt - Vertical distance from the ground level [onshore] or MSL [offshore] to the platform reference point (meters)

Mass and Inertia

TipMass(1) - Tip-brake mass, blade 1 (kg)

TipMass(2) - Tip-brake mass, blade 2 (kg)

TipMass(3) - Tip-brake mass, blade 3 (kg) [unused for 2 blades]

HubMass - Hub mass (kg)

HubIner - Hub inertia about rotor axis [3 blades] or teeter axis [2 blades] (kg m^2)

GenIner - Generator inertia about HSS (kg m^2)

NacMass - Nacelle mass (kg)

NacYIner - Nacelle inertia about yaw axis (kg m^2)

YawBrMass - Yaw bearing mass (kg)

PtfmMass - Platform mass (kg)

PtfmRIner - Platform inertia for roll tilt rotation about the platform CM (kg m^2)

PtfmPIner - Platform inertia for pitch tilt rotation about the platform CM (kg m^2)

PtfmYIner - Platform inertia for yaw rotation about the platform CM (kg m^2)
Blade

BldNodes - Number of blade nodes (per blade) used for analysis (-)
BldFile(1) - Name of file containing properties for blade 1 (quoted string)
BldFile(2) - Name of file containing properties for blade 2 (quoted string)
BldFile(3) - Name of file containing properties for blade 3 (quoted string) [unused for 2 blades]

Rotor-Teeter

TeetMod - Rotor-teeter spring/damper model {0: none, 1: standard, 2: user-defined from routine UserTeet} (switch) [unused for 3 blades]
TeetDmpP - Rotor-teeter damper position (degrees) [used only for 2 blades and when TeetMod=1]
TeetDmp - Rotor-teeter damping constant (N-m/(rad/s)) [used only for 2 blades and when TeetMod=1]
TeetCDmp - Rotor-teeter rate-independent Coulomb-damping moment (N-m) [used only for 2 blades and when TeetMod=1]
TeetSSStP - Rotor-teeter soft-stop position (degrees) [used only for 2 blades and when TeetMod=1]
TeetHStP - Rotor-teeter hard-stop position (degrees) [used only for 2 blades and when TeetMod=1]
TeetSSSp - Rotor-teeter soft-stop linear-spring constant (N-m/rad) [used only for 2 blades and when TeetMod=1]
TeetHSSp - Rotor-teeter hard-stop linear-spring constant (N-m/rad) [used only for 2 blades and when TeetMod=1]

Drivetrain

GBoxEff - Gearbox efficiency (%) 
GBRatio - Gearbox ratio (-)
DTTorSpr - Drivetrain torsional spring (N-m/rad)
DTTorDmp - Drivetrain torsional damper (N-m/(rad/s))

Furling

Furling - Read in additional model properties for furling turbine (flag) [must currently be FALSE]
FurlFile - Name of file containing furling properties (quoted string) [unused when Furling=False]

Tower

TwrNodes - Number of tower nodes used for analysis (-)
TwrFile - Name of file containing tower properties (quoted string)
Outputs

**SumPrint** [flag] Set this value to TRUE if you want ElastoDyn to generate a summary file with the name `OutFile-Root.ED.sum*`. `OutFileRoot` is specified by the OpenFAST program when running a coupled simulation.

**OutFile** [switch] is currently unused. The eventual purpose is to allow output from ElastoDyn to be written to a module output file (option 1), or the main OpenFAST output file (option 2), or both. At present this switch is ignored.

**TabDelim** [flag] is currently unused. Setting this to True will set the delimiter for text files to the tab character for the ElastoDyn module `OutFile`.

**OutFmt** [quoted string] is currently unused. ElastoDyn will use this string as the numerical format specifier for output of floating-point values in its local output specified by `OutFile`. The length of this string must not exceed 20 characters and must be enclosed in apostrophes or double quotes. You may not specify an empty string. To ensure that fixed-width column data align properly with the column titles, you should ensure that the width of the field is 10 characters. Using an E, EN, or ES specifier will guarantee that you will never overflow the field because the number is too big, but such numbers are harder to read. Using an F specifier will give you numbers that are easier to read, but you may overflow the field. Please refer to any Fortran manual for details for format specifiers.

**TStart** [s] sets the start time for `OutFile`. This is currenty unused.

**DecFact** [-] This parameter sets the decimation factor for output. ElastoDyn will output data to `OutFile` only once each DecFact integration time steps. For instance, a value of 5 will cause FAST to generate output only every fifth time step. This value must be an integer greater than zero.

**NTwGages** [-] The number of strain-gage locations along the tower indicates the number of input values on the next line. Valid values are integers from 0 to 5 (inclusive).

**TwrGagNd** [-] The virtual strain-gage locations along the tower are assigned to the tower analysis nodes specified on this line. Possible values are 1 to TwrNodes (inclusive), where 1 corresponds to the node closest to the tower base (but not at the base) and a value of TwrNodes corresponds to the node closest to the tower top. The exact elevations of each analysis node in the undeformed tower, relative to the base of the tower, are determined as follows:

\[
\text{Elev. of node J} = \text{TwrRBHt} + (J - \frac{1}{2}) \times \left( \frac{\text{TowerHt} + \text{TwrDraft} - \text{TwrRBHt}}{\text{TwrNodes}} \right) \quad (\text{for } J = 1, 2, \ldots, \text{TwrNodes})
\]

You must enter at least NTwGages values on this line. If NTwGages is 0, this line will be skipped, but you must have a line taking up space in the input file. You can separate the values with combinations of tabs, spaces, and commas, but you may use only one comma between numbers.

**NBlGages** [-] specifies the number of strain-gague locations along the blade, and indicates the number of input values expected in `BldGagNd`. This is only used when the blade structure is modeled in ElastoDyn.

**BldGagNd** [-] specifies the virtual strain-gage locations along the blade that should be output. Possible values are 1 to BldNodes (inclusive), where 1 corresponds to the node closest to the blade root (but not at the root) and a value of BldNodes corresponds to the node closest to the blade tip. The node locations are specified by the ElastoDyn blade input files. You must enter at least NBlGages values on this line. If NBlGages is 0, this line will be skipped, but you must have a line taking up space in the input file. You can separate the values with combinations of tabs, spaces, and commas, but you may use only one comma between numbers. This is only used when the blade structure is modeled in ElastoDyn.

The **OutList** section controls output quantities generated by ElastoDyn. Enter one or more lines containing quoted strings that in turn contain one or more output parameter names. Separate output parameter names by any combination of commas, semicolons, spaces, and/or tabs. If you prefix a parameter name with a minus sign, “-”, underscore, “_”, or the characters “m” or “M”, ElastoDyn will multiply the value for that channel by –1 before writing the data. The parameters are written in the order they are listed in the input file. ElastoDyn allows you to use multiple lines so that you can break your list into meaningful groups and so the lines can be shorter. You may enter comments after the closing quote on any of the lines. Entering a line with the string “END” at the beginning of the line or at the beginning of a quoted string found at the beginning of the line will cause ElastoDyn to quit scanning for more lines of channel names. Blade and tower node-related quantities are generated for the requested nodes identified through...
the BldGagNd and TwrGagNd lists above. If ElastoDyn encounters an unknown/invalid channel name, it warns the
users but will remove the suspect channel from the output file. Please refer to the ElastoDyn tab in the Excel file
OutListParameters.xlsx for a complete list of possible output parameters.

Nodal Outputs

In addition to the named outputs in Section 4.8.1 above, ElastoDyn allows for outputting the full set blade node
motions and loads (tower nodes unavailable at present). Please refer to the ElastoDyn_Nodes tab in the Excel file
OutListParameters.xlsx for a complete list of possible output parameters.

This section follows the END statement from normal Outputs section described above, and includes a separator de-
scription line followed by the following optinos.

BldNd_BladesOut specifies the number of blades to output. Possible values are 0 through the number of blades
ElastoDyn is modeling. If the value is set to 1, only blade 1 will be output, and if the value is 2, blades 1 and 2 will be
output.

BldNd_BIOutNd specifies which nodes to output. This is currently unused.

The OutList section controls the nodal output quantities generated by ElastoDyn. In this section, the user specifies
the name of the channel family to output. The output name for each channel is then created internally by ElastoDyn
by combining the blade number, node number, and channel family name. For example, if the user specifies TDx as
the channel family name, the output channels will be named with the convention of B\(\beta\)N###TDx where \(\beta\) is the blade
number, and ### is the three digit node number.

Sample Nodal Outputs section

This sample includes the END statement from the regular outputs section.

```plaintext
END of input file (the word "END" must appear in the first 3 columns of this last
-OutList line)

- ---------------------- NODE OUTPUTS -----------------------

- 3 BldNd_BladesOut - Blades to output
- 99 BldNd_BIOutNd - Blade nodes on each blade (currently unused)

- See OutListParameters.xlsx, ElastoDyn_Nodes tab for a listing of available output
- channels, (-)

- "ALx" - local flapwise acceleration (absolute) of node
- "ALy" - local flapwise acceleration (absolute) of node
- "ALz" - local flapwise acceleration (absolute) of node
- "TDx" - local flapwise (translational) deflection (relative to the undeflected
- position) of node
- "TDy" - local edgewise (translational) deflection (relative to the undeflected
- position) of node
- "TDz" - local axial (translational) deflection (relative to the undeflected
- position) of node
- "RDx" - Local rotational displacement about x-axis (relative to undeflected)
- "RDy" - Local rotational displacement about y-axis (relative to undeflected)
- "RDz" - Local rotational displacement about z-axis (relative to undeflected)
- "MLx" - local edgewise moment at node
- "MLy" - local flapwise moment at node
- "MLz" - local pitching moment at node
- "FLx" - local flapwise shear force at node
- "FLy" - local edgewise shear force at node
- "FLz" - local axial force at node
- "MLxNT" - Edgewise moment in local coordinate system (initial structural twist
- removed)
```

(continues on next page)
22 "MlyNT" - Flapwise shear moment in local coordinate system (initial structural twist removed)
23 "FLxNT" - Flapwise shear force in local coordinate system (initial structural twist removed)
24 "FlyNT" - Edgewise shear force in local coordinate system (initial structural twist removed)
25 END of input file (the word "END" must appear in the first 3 columns of this last OutList line)
26

4.9 InflowWind Users Guide and Theory Manual

4.9.1 InflowWind Driver

Example input files are included in Section 4.9.4.

Command-line syntax for InflowWind driver:

```
InflowWind_Driver <filename> [options]
```

where:  
- `<filename>` -- Name of driver input file to use
- `options`:  
  - `/ifw` -- treat `<filename>` as name of InflowWind input file (no driver input file)

The following options will override values in the driver input file:

```
/Dt[#] -- timestep
/TStart[#] -- start time
/TSteps[#] -- number of timesteps
/xrange[#:#] -- range of x (#’s are reals)
/yrange[#:#] -- range of y
/zrange[#:#] -- range in z (ground = 0.0)
/Dx[#] -- spacing in x
/Dy[#] -- spacing in y
/Dz[#] -- spacing in z
/points[FILE] -- calculates at x,y,z coordinates specified in a white space delimited FILE
/v -- verbose output
/vv -- very verbose output
/hawc -- convert wind file specified in InflowWind to HAWC
/bladed -- convert wind file specified in InflowWind to Bladed
/vtk -- convert wind file specified in InflowWind to VTK
/help -- print this help menu and exit
```

Notes:
- Unspecified ranges and resolutions default to what is in the file.
- If no XRange is specified, assumed to be only at X=0
- Options are not case sensitive.

The InflowWind Manual contains a description of file formats that it can read.
Specifying the InflowWind Input File

The InflowWind driver input file requires that an InflowWind input file be specified within it. See an example InflowWind input file in Section 4.9.4.

Within the InflowWind input file, if the wind file being specified is Bladed native format (WindType = 7), please also see Section 4.9.2.

Wind-file output formats

The InflowWind driver is capable of writing the wind data read from the input wind file into wind files of various formats.

HAWC2

This format generates the following files:

- three binary files, one for each component: <RootName>-HAWC.u, <RootName>-HAWC.v, and <RootName>-HAWC.w
- a text summary file in the style of HAWC2 input files: <RootName>-HAWC.sum

In the conversion script, the u component will have the (approximate) mean removed at each height. The mean value that was removed is displayed as comments in the text summary file. The turbulence is not scaled, so it will have the same scaling as the original file.

Bladed

This format generates a packed binary file and a text summary file.

This output format is in the Bladed-style format that TurbSim generates. That means that the shear is included in the file.

VTK

This format creates files in a subdirectory called vtk. There is one vtk file for each time in the full-field data structure, and the entire Y-Z grid is printed in each file. This format can be used to visualize the wind field using a viewer such as ParaView.

Converting uniform wind to full-field wind format

When converting from a uniform wind file to a full-field wind format, the following assumptions are used:
- The advection speed is the time-averaged horizontal wind speed in the uniform wind file (it does not include the gust speed).
- The constant time-step used in the output file is the smallest difference between any two entries in the hub-height file.
- The maximum time in the uniform wind file will be used as the maximum time in the FF binary file.
- The grid is generated with 5-m resolution in the lateral (Y) and horizontal (Z) directions.
- The size of the grid is based on the RefLength parameter in the InflowWind input file. The converter adds approximately 10% to the grid width, with the exact size determined by achieving the desired grid resolution. The grid is centered in the lateral direction; it extends vertically above RefHt by the same distance as the grid width, and extends below RefHt to the ground (or within one grid point of the ground).
Note that there is a potential time shift between the uniform and full-field wind files, equal to the time it takes to travel the distance of half the grid width. When using the resulting full-field files, care must be taken that the aeroelastic code does not treat it as periodic.

### 4.9.2 InflowWind Input Files

#### Native Bladed wind file support in InflowWind

The ability to read native Bladed wind files (without scaling) has been added to InflowWind. To use this feature, the `WindType` must be set to 7 on line 5 of the primary InflowWind input file. An example of this file is given in Section 4.9.4.

```
# WindType - switch for wind file type (1=steady; 2=uniform; ...
# 3=binary TurbSim FF; 4=binary Bladed-style FF; 5=HAWC format; 6=User defined; ...
# 7=Bladed native)
```

In the section for `WindType = 4`, the name of an intermediate Bladed wind file should be given (including the file extension). The tower file flag is ignored.

```
# ============== Parameters for Binary Bladed-style Full-Field files [used only ...
# for WindType = 4] ============
#
# "tw06_80hh_s200.BladedWind.ipt" FilenameRoot - Name of the Full field wind file to ...
# use (.wnd, .sum)
#
# F TowerFile - Have tower file (.twr) (flag)
```

The intermediate Bladed wind scaling file must contain the following information, which can be retrieved directly from the Bladed project simulation file from the `MSTART WINDSEL` and `MSTART WINDV` sections. Additionally, the file may include an `XOFFSET` line, which allows the wind to be shifted by a given distance. If not included, `XOFFSET` is assumed to be 0. An example of this Native Bladed scaling file is included in Section 4.9.4.

```
UBAR 12
REFHT 90
TI 0.033333
TI_v 0.026667
TI_W 0.016667
WDIR 0
FLINC .139626222222222
WINDF "./tw06_80hh_s200.wnd"
WSHEAR .2
XOFFSET 0
```

In the above file, the names correspond to the following:
<table>
<thead>
<tr>
<th>Line</th>
<th>Variable Name</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>UBAR</td>
<td>(m/s)</td>
<td>Mean wind speed</td>
</tr>
<tr>
<td>2</td>
<td>REFHT</td>
<td>(m)</td>
<td>Reference height (turbine hub height)</td>
</tr>
<tr>
<td>3</td>
<td>TI</td>
<td>(-)</td>
<td>Turbulence intensity in longitudinal (mean wind flow) direction</td>
</tr>
<tr>
<td>4</td>
<td>TI_V</td>
<td>(-)</td>
<td>Turbulence intensity in horizontal direction (orthogonal to mean flow direction)</td>
</tr>
<tr>
<td>5</td>
<td>TI_W</td>
<td>(-)</td>
<td>Turbulence intensity in vertical direction (orthogonal to mean flow direction)</td>
</tr>
<tr>
<td>6</td>
<td>WDIR</td>
<td>(rad)</td>
<td>Wind direction (meteorological rotation direction)</td>
</tr>
<tr>
<td>7</td>
<td>FLINC</td>
<td>(rad)</td>
<td>Upflow angle (positive is up)</td>
</tr>
<tr>
<td>8</td>
<td>WINDF</td>
<td>(-)</td>
<td>Name of native Bladed wind file (absolute or relative path, 200 character limit)</td>
</tr>
<tr>
<td>9</td>
<td>WSHEAR</td>
<td>(-)</td>
<td>Power law wind shear exponent</td>
</tr>
<tr>
<td>10</td>
<td>XOFFSET</td>
<td>(m)</td>
<td>Turbulence box offset in the X direction (how far ahead of the turbine the turbulence box starts). If missing, this value is assumed to be 0.</td>
</tr>
</tbody>
</table>

Limitations: - Wind file is centered on hub height (“Best fit for rotor and tower” not implemented) - Always allow wind file to wrap around (unchecked box not implemented) - Only power-law wind profile is implemented (not logarithmic, none, or user-defined)

### 4.9.3 Angles Specified in InflowWind

Wind direction and upflow angles can be specified in the InflowWind input file. When using Native Bladed wind file support in InflowWind, the angles from the InflowWind input are overwritten with the values specified in the Native Bladed Input Files. InflowWind rotates the wind box about the hub-height tower center line by these wind direction and upflow angles.

The uniform wind files also specify wind direction and upflow angles. The angles specified in uniform wind files DO NOT rotate the wind box, but just convert the local wind speed into global coordinates.

When converting from local \([u \ v \ w]\) to global \([U \ V \ W]\) reference systems, the upflow rotation, \(R(\text{upflow})\) occurs before the wind direction rotation, \(R(\text{wind direction})\):

\[
[U \ V \ W] = R(\text{wind direction}) \times R(\text{upflow}) \times [u \ v \ w]
\]

When using a combination of angles in InflowWind and UniformWind files, the UniformWind angles are applied first.
Note: This means that if you have upflow specified in InflowWind and wind direction specified in UniformWind, the rotation will be performed in a different order than if both angles are specified in the same file.

\[
[U \ V \ W] = R(\text{wind direction: InflowWind}) \times R(\text{upflow: InflowWind}) \times R(\text{wind direction: UniformWind}) \times R(\text{upflow: UniformWind}) \times [u \ v \ w]
\]

4.9.4 Appendix

InflowWind Input Files

In this appendix we describe the InflowWind input-file structure and provide examples.

1) InflowWind Driver Input File (driver input file example):

The driver input file is needed only for the standalone version of InflowWind. It contains inputs regarding the InflowWind file, interpolation parameters, and the desired output files. The InflowWind driver can also be run without this file by using command-line arguments instead.

2) InflowWind Primary Input File (primary input file example):

The primary InflowWind input file defines the inflow that is generated or read from other files. The InflowWind file contains sections for each type of wind-file format.

3) Native Bladed Scaling File (primary input file example):

This file includes lines that determine how to scale the non-dimensional full-field turbulence files from Bladed.

4) Uniform Wind Data File (uniform wind input file example):

This file includes lines that define uniform (deterministic) wind data files.

InflowWind List of Output Channels

This is a list of all possible output parameters for the InflowWind module. See the InflowWind tab of the (OutListParameters.xlsx file):

4.10 ServoDyn Users Guide

4.10.1 Input Files

The user configures the servodynamics model parameters via a primary ServoDyn input file, as well as separate input files for Structural control, and a controller DLL. This information is incomplete and will be documented here at a later date.
Units

ServoDyn uses the SI system (kg, m, s, N). Angles are assumed to be in radians unless otherwise specified.

ServoDyn Primary Input File

The primary ServoDyn input file defines the modeling options for the controller. This includes some DLL options, and Structural control options (typically a tuned mass damper system).

Simulation Control

Echo [flag]

Echo input data to <RootName>.ech

DT [sec]

Communication interval for controllers (or “default”)

Pitch Control

PCMode [switch]

Pitch control mode {0: none, 3: user-defined from routine PitchCntrl, 4: user-defined from Simulink/Labview, 5: user-defined from Bladed-style DLL}

TPCON [sec]

Time to enable active pitch control [unused when PCMode==0 ]

TPitManS(1) [sec]

Time to start override pitch maneuver for blade 1 and end standard pitch control

TPitManS(2) [sec]

Time to start override pitch maneuver for blade 2 and end standard pitch control

TPitManS(3) [sec]

Time to start override pitch maneuver for blade 3 and end standard pitch control [unused for 2 blades]

PitManRat(1) [deg/s]

Pitch rate at which override pitch maneuver heads toward final pitch angle for blade 1

PitManRat(2) [deg/s]

Pitch rate at which override pitch maneuver heads toward final pitch angle for blade 2

PitManRat(3) [deg/s]

Pitch rate at which override pitch maneuver heads toward final pitch angle for blade 3 [unused for 2 blades]

BlPitchF(1) [deg]

Blade 1 final pitch for pitch maneuvers

BlPitchF(2) [deg]

Blade 2 final pitch for pitch maneuvers
BlPitchF(3) [deg]

Blade 3 final pitch for pitch maneuvers [unused for 2 blades]

**Generator and Torque Control**

**VSContrl** [switch]

Variable-speed control mode {0: none, 1: simple VS, 3: user-defined from routine UserVSCont, 4: user-defined from Simulink/Labview, 5: user-defined from Bladed-style DLL}

**GenModel** [switch]

Generator model {1: simple, 2: Thevenin, 3: user-defined from routine UserGen} [used only when VSContrl==0]

**GenEff** [%]

Generator efficiency [ignored by the Thevenin and user-defined generator models]

**GenTiStr** [flag]

Method to start the generator {T: timed using TimGenOn, F: generator speed using SpdGenOn}

**GenTiStp** [Flag]

Method to stop the generator {T: timed using TimGenOf, F: when generator power = 0}

**SpdGenOn** [rpm]

Generator speed to turn on the generator for a startup (HSS speed) [used only when GenTiStr==False]

**TimGenOn** [sec]

Time to turn on the generator for a startup [used only when GenTiStr==True]

**TimGenOf** [sec]

Time to turn off the generator [used only when GenTiStp==True]

**Simple Variable-speed Torque Control**

**VS_RtGnSp** [rpm]

Rated generator speed for simple variable-speed generator control (HSS side) [used only when VSContrl==1]

**VS_RtTq** [N-m]

Rated generator torque/constant generator torque in Region 3 for simple variable-speed generator control (HSS side) [used only when VSContrl==1]

**VS_Rgn2K** [N-m/rpm^2]

Generator torque constant in Region 2 for simple variable-speed generator control (HSS side) [used only when VSContrl==1]

**VS_SlPc** [%]

Rated generator slip percentage in Region 2 1/2 for simple variable-speed generator control [used only when VSContrl==1]
Simple Induction Generator

SIG_SIPc [%]
Rated generator slip percentage \[\text{used only when } \text{VSContrl}==0 \text{ and } \text{GenModel}==1 \]

SIG_SySp [rpm]
Synchronous (zero-torque) generator speed \[\text{used only when } \text{VSContrl}==0 \text{ and } \text{GenModel}==1 \]

SIG_RtTq [N-m]
Rated torque \[\text{used only when } \text{VSContrl}==0 \text{ and } \text{GenModel}==1 \]

SIG_PORt [-]
Pull-out ratio (Tpullout/Trated) \[\text{used only when } \text{VSContrl}==0 \text{ and } \text{GenModel}==1 \]

Thevenin-Equivalent Induction Generator

TEC_Freq [Hz]
Line frequency [50 or 60] \[\text{used only when } \text{VSContrl}==0 \text{ and } \text{GenModel}==2 \]

TEC_NPol [-]
Number of poles [even integer > 0] \[\text{used only when } \text{VSContrl}==0 \text{ and } \text{GenModel}==2 \]

TEC_SRes [ohms]
Stator resistance \[\text{used only when } \text{VSContrl}==0 \text{ and } \text{GenModel}==2 \]

TEC_RRes [ohms]
Rotor resistance \[\text{used only when } \text{VSContrl}==0 \text{ and } \text{GenModel}==2 \]

TEC_VLL [volts]
Line-to-line RMS voltage \[\text{used only when } \text{VSContrl}==0 \text{ and } \text{GenModel}==2 \]

TEC_SLR [ohms]
Stator leakage reactance \[\text{used only when } \text{VSContrl}==0 \text{ and } \text{GenModel}==2 \]

TEC_RLR [ohms]
Rotor leakage reactance \[\text{used only when } \text{VSContrl}==0 \text{ and } \text{GenModel}==2 \]

TEC_MR [ohms]
Magnetizing reactance \[\text{used only when } \text{VSContrl}==0 \text{ and } \text{GenModel}==2 \]

High-speed Shaft Brake

HSSBrMode [switch]
HSS brake model \{0: none, 1: simple, 3: user-defined from routine UserHSSBr, 4: user-defined from Simulink/Labview, 5: user-defined from Bladed-style DLL\}

THSSBrDp [sec]
Time to initiate deployment of the HSS brake

HSSBrDT [sec]
Time for HSS-brake to reach full deployment once initiated \textit{[used only when HSSBrMode==1]}

**HSSBrTqF [N-m]**

Fully deployed HSS-brake torque

### Nacelle-yaw Control

**YCMode [switch]**

Yaw control mode \{0: none, 3: user-defined from routine UserYawCont, 4: user-defined from Simulink/Labview, 5: user-defined from Bladed-style DLL\}

**TYCOn [sec]**

Time to enable active yaw control \textit{[unused when YCMode==0]}\)

**YawNeut [deg]**

Neutral yaw position—yaw spring force is zero at this yaw

**YawSpr [N-m/rad]**

Nacelle-yaw spring constant

**YawDamp [N-m/(rad/s)]**

Nacelle-yaw damping constant

**TYawManS [sec]**

Time to start override yaw maneuver and end standard yaw control

**YawManRat [deg/s]**

Yaw maneuver rate (in absolute value)

**NacYawF [deg]**

Final yaw angle for override yaw maneuvers

### Structural Control

See Section 4.11.1 for descriptions of the mounting locations for each of the following options.

**NumBSStC [integer]**

Number of blade structural controllers

**BSStCfiles [-]**

Name of the files for blade structural controllers (quoted strings on one line) \textit{[unused when NumBSStC==0]}\)

**NumNSStC [integer]**

Number of nacelle structural controllers

**NSStCfiles [-]**

Name of the files for nacelle structural controllers (quoted strings on one line) \textit{[unused when NumNSStC==0]}\)

**NumTSStC [integer]**
Number of tower structural controllers

TStCfiles [-]

Names of the file for tower structural control damping (quoted strings on one line) [unused when NumTStC==0]

NumSStC [integer]

Number of substructure structural controllers

SSStCfiles [-]

Name of the files for substructure structural controllers (quoted strings on one line) [unused when NumSStC==0]

Bladed Controller Interface

DLL.FileName [-]

Name/location of the dynamic library [.dll [Windows] or .so [Linux]] in the Bladed-DLL format [used only with Bladed Interface]

DLL.InFile [-]

Name of input file sent to the DLL [used only with Bladed Interface]

DLL.ProcName [-]

Name of procedure in DLL to be called [case sensitive; used only with DLL Interface]

DLL.DT [sec]

Communication interval for dynamic library (or “default”) [used only with Bladed Interface]

DLL.Ramp [flag]

Whether a linear ramp should be used between DLL.DT time steps [introduces time shift when true] [used only with Bladed Interface]

BPCutoff [Hz]

Cutoff frequency for low-pass filter on blade pitch from DLL [used only with Bladed Interface]

NacYaw.North [deg]

Reference yaw angle of the nacelle when the upwind end points due North [used only with Bladed Interface]

Ptch.Cntrl [switch]

Record 28: Use individual pitch control {0: collective pitch; 1: individual pitch control} [used only with Bladed Interface]

Ptch.SetPnt [deg]

Record 5: Below-rated pitch angle set-point [used only with Bladed Interface]

Ptch.Min [deg]

Record 6: Minimum pitch angle [used only with Bladed Interface]

Ptch.Max [deg]

Record 7: Maximum pitch angle [used only with Bladed Interface]

PtchRate.Min [deg/s]
Record 8: Minimum pitch rate (most negative value allowed) [used only with Bladed Interface]

**PtchRate_Max** [deg/s]

Record 9: Maximum pitch rate [used only with Bladed Interface]

**Gain_OM** [N-m/(rad/s)^2]

Record 16: Optimal mode gain [used only with Bladed Interface]

**GenSpd_MinOM** [rpm]

Record 17: Minimum generator speed [used only with Bladed Interface]

**GenSpd_MaxOM** [rpm]

Record 18: Optimal mode maximum speed [used only with Bladed Interface]

**GenSpd_Dem** [rpm]

Record 19: Demanded generator speed above rated [used only with Bladed Interface]

**GenTrq_Dem** [N-m]

Record 22: Demanded generator torque above rated [used only with Bladed Interface]

**GenPwr_Dem** [W]

Record 13: Demanded power [used only with Bladed Interface]

**Bladed Interface Torque-Speed Look-up table**

**DLL_NumTrq** [-]

Record 26: No. of points in torque-speed look-up table {0 = none and use the optimal mode parameters; nonzero = ignore the optimal mode PARAMETERS by setting Record 16 to 0.0} [used only with Bladed Interface]. The following 2 column table format is expected:

<table>
<thead>
<tr>
<th>GenSpd_TLU (rpm)</th>
<th>GenTrq_TLU (N-m)</th>
</tr>
</thead>
</table>

**Output**

**SumPrint** [flag]

Print summary data to `<RootName>.sum` (currently unused)

**OutFile** [-]

Switch to determine where output will be placed: {1: in module output file only; 2: in glue code output file only; 3: both} (currently unused)

**TabDelim** [flag]

Use tab delimiters in text tabular output file? (currently unused)

**OutFmt** [-]

Format used for text tabular output (except time). Resulting field should be 10 characters. (quoted string) (currently unused)

**TStart** [sec]
Time to begin tabular output (currently unused)

OutList section controls output quantities generated by ServoDyn. Enter one or more lines containing quoted strings that in turn contain one or more output parameter names. Separate output parameter names by any combination of commas, semicolons, spaces, and/or tabs. If you prefix a parameter name with a minus sign, "+", underscore, "+", or the characters “m” or “M”, ServoDyn will multiply the value for that channel by –1 before writing the data. The parameters are written in the order they are listed in the input file. ServoDyn allows you to use multiple lines so that you can break your list into meaningful groups and so the lines can be shorter. You may enter comments after the closing quote on any of the lines. Entering a line with the string “END” at the beginning of the line or at the beginning of a quoted string found at the beginning of the line will cause ServoDyn to quit scanning for more lines of channel names. If ServoDyn encounters an unknown/invalid channel name, it warns the users but will remove the suspect channel from the output file. Please refer to the ServoDyn tab in the Excel file OutListParameters.xlsx for a complete list of possible output parameters.

4.11 Structural Control (SrvD)

4.11.1 Input Files

The user configures each StC instance with a separate input file. This input file defines the location of the StC relative to its mounting location, and defines the properties. It can also be used with an external forces file to apply a timeseries load at the location (primarily used for diagnostic purposes).

Units

Structural Control uses the SI system (kg, m, s, N). Angles are assumed to be in radians unless otherwise specified.

Structural Control Locations

The Structural Control input file defines the location and properties of the StC instance. The location is relative to the type of StC given in the main ServoDyn input file (see Section 4.10.1). The four location types are Nacelle, Tower, Blade, and Platform.

The mapping information for the StC will be given in the main OpenFAST summary file.

Nacelle StC

This StC mounting location is attached relative to the nacelle reference point. It will track with all nacelle motions (including motions due to yaw, tower flex, and platform motions).

Tower StC

This StC mounting location is attached to the tower mesh at the height specified above the tower base. This StC attachment will move with the line mesh at that height. For example, an StC mounted at 85 m on a 90 m tower will move with the mesh line corresponding to the 85 m height position on the tower center line.
Blade StC

This StC mounting location is attached to the blade structural center at the specified distance from the blade root along the z-axis of the blade (IEC blade coordinate system). This location will follow all blade deformations and motions (including blade twist when used with BeamDyn). This option is available with both the BeamDyn and ElastoDyn blade representations.

When this option is used, identical StCs will be attached at each of the blades. The response if each blade mounted StC is tracked separately and is available in the output channels given in the ServoDyn tab of the OutListParameters.xlsx.

Platform StC

This StC mounting location is located relative to the platform reference point. When a rigid body platform is modeled (such as a rigid semi-submersible), it is attached to the platform reference point. When a flexible floating body is modeled, the StC is attached to the SubDyn mesh.

Structural Control Input File

The input file may have an arbitrary number of commented header lines, and commented lines at any location in the input file. (Example Structural Control input file for tuned mass damper on tower for NREL 5 MW TLP):

Simulation Control

Echo [flag]

Echo input data to <RootName>.ech

StC Degrees of Freedom

StC.DOF_MODE [switch]

DOF mode {0: No StC or TLCD DOF; 1: StC_X.DOF, StC.Y.DOF, and/or StC.Z.DOF (three independent StC DOFs); 2: StC.XY.DOF (Omni-Directional StC); 3: TLCD; 4: Prescribed force/moment time series}

StC.X.DOF [flag]

DOF on or off for StC X [Used only when StC.DOF_MODE==1]

StC.Y.DOF [flag]

DOF on or off for StC Y [Used only when StC.DOF_MODE==1]

StC.Z.DOF [flag]

DOF on or off for StC Z [Used only when StC.DOF_MODE==1]
**StC Location**

The location of the StC is relative to the component it is attached to. This is specified in the main ServoDyn input file. See description above.

- **StC_P_X [m]**
  - At rest X position of StC
- **StC_P_Y [m]**
  - At rest Y position of StC
- **StC_P_Z [m]**
  - At rest Z position of StC

**StC Initial Conditions**

*used only when StC_DOF_MODE==1 or 2*

- **StC_X_DSP [m]**
  - StC X initial displacement *relative to at rest position*
- **StC_Y_DSP [m]**
  - StC Y initial displacement *relative to at rest position*
- **StC_Z_DSP [m]**
  - StC Z initial displacement *relative to at rest position; used only when StC_DOF_MODE==1 and StC_Z_DOF==TRUE*

**StC Configuration**

*used only when StC_DOF_MODE==1 or 2*

- **StC_X_PSP [m]**
  - Positive stop position – maximum X mass displacement
- **StC_X_NS [m]**
  - Negative stop position – minimum X mass displacement
- **StC_Y_PSP [m]**
  - Positive stop position – maximum Y mass displacement
- **StC_Y_NS [m]**
  - Negative stop position – minimum Y mass displacement
- **StC_Z_PSP [m]**
  - Positive stop position – maximum Z mass displacement *used only when StC_DOF_MODE==1 and StC_Z_DOF==TRUE*
- **StC_Z_NS [m]**
  - Negative stop position – minimum Z mass displacement *used only when StC_DOF_MODE==1 and StC_Z_DOF==TRUE*
**StC Mass, Stiffness, & Damping**

*used only when StC_DOF_MODE==1 or 2*

**StC X M [kg]**
- StC X mass *used only when StC_DOF_MODE==1 and StC_X_DOF==TRUE*

**StC Y M [kg]**
- StC Y mass *used only when StC_DOF_MODE==1 and StC_Y_DOF==TRUE*

**StC Z M [kg]**
- StC Z mass *used only when StC_DOF_MODE==1 and StC_Z_DOF==TRUE*

**StC XY M [kg]**
- StC XY mass *used only when StC_DOF_MODE==2*

**StC X K [N/m]**
- StC X stiffness

**StC Y K [N/m]**
- StC Y stiffness

**StC Z K [N/m]**
- StC Z stiffness *used only when StC_DOF_MODE==1 and StC_Z_DOF==TRUE*

**StC X C [N/(m/s)]**
- StC X damping

**StC Y C [N/(m/s)]**
- StC Y damping

**StC Z C [N/(m/s)]**
- StC Z damping *used only when StC_DOF_MODE==1 and StC_Z_DOF==TRUE*

**StC X KS [N/m]**
- Stop spring X stiffness

**StC Y KS [N/m]**
- Stop spring Y stiffness

**StC Z KS [N/m]**
- Stop spring Z stiffness *used only when StC_DOF_MODE==1 and StC_Z_DOF==TRUE*

**StC X CS [N/(m/s)]**
- Stop spring X damping

**StC Y CS [N/(m/s)]**
- Stop spring Y damping

**StC Z CS [N/(m/s)]**
- Stop spring Z damping *used only when StC_DOF_MODE==1 and StC_Z_DOF==TRUE*
StC User-Defined Spring Forces

*used only when StC_DOF_MODE==1 or 2*

**Use_F_TBL [flag]**

Use spring force from user-defined table

**NKInpSt [-]**

Number of spring force input stations

The table is expected to contain 6 columns for displacements and equivalent spring forces: X, F_X, Y, F_Y, Z, and F_Z. Displacements are in meters (m) and forces in Newtons (N).

Example spring forces table:

<table>
<thead>
<tr>
<th>X</th>
<th>F_X</th>
<th>Y</th>
<th>F_Y</th>
<th>Z</th>
<th>F_Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>-6.0000000E+00</td>
<td>-4.8000000E+06</td>
<td>-6.0000000E+00</td>
<td>-4.8000000E+06</td>
<td>-6.0000000E+00</td>
<td>-4.0000000E+00</td>
</tr>
<tr>
<td>-5.0000000E+00</td>
<td>-2.4000000E+06</td>
<td>-5.0000000E+00</td>
<td>-2.4000000E+06</td>
<td>-5.0000000E+00</td>
<td>-2.0000000E+00</td>
</tr>
<tr>
<td>-4.5000000E+00</td>
<td>-1.2000000E+06</td>
<td>-4.5000000E+00</td>
<td>-1.2000000E+06</td>
<td>-4.5000000E+00</td>
<td>-1.0000000E+00</td>
</tr>
<tr>
<td>-4.0000000E+00</td>
<td>-6.0000000E+05</td>
<td>-4.0000000E+05</td>
<td>-6.0000000E+05</td>
<td>-4.0000000E+05</td>
<td>-6.0000000E+05</td>
</tr>
<tr>
<td>-3.5000000E+00</td>
<td>-3.0000000E+05</td>
<td>-3.5000000E+00</td>
<td>-3.0000000E+05</td>
<td>-3.5000000E+00</td>
<td>-3.5000000E+00</td>
</tr>
<tr>
<td>-3.0000000E+00</td>
<td>-1.5000000E+05</td>
<td>-3.0000000E+00</td>
<td>-1.5000000E+05</td>
<td>-3.0000000E+00</td>
<td>-3.0000000E+00</td>
</tr>
<tr>
<td>-2.5000000E+00</td>
<td>-1.0000000E+05</td>
<td>-2.5000000E+00</td>
<td>-1.0000000E+05</td>
<td>-2.5000000E+00</td>
<td>-2.5000000E+00</td>
</tr>
<tr>
<td>-2.0000000E+00</td>
<td>-6.5000000E+04</td>
<td>-2.0000000E+04</td>
<td>-6.5000000E+04</td>
<td>-2.0000000E+04</td>
<td>-6.0000000E+04</td>
</tr>
<tr>
<td>-5.0000000E+04</td>
<td>0.0000000E+00</td>
<td>0.0000000E+00</td>
<td>0.0000000E+00</td>
<td>0.0000000E+00</td>
<td>0.0000000E+00</td>
</tr>
<tr>
<td>0.0000000E+00</td>
<td>0.0000000E+00</td>
<td>0.0000000E+00</td>
<td>0.0000000E+00</td>
<td>0.0000000E+00</td>
<td>0.0000000E+00</td>
</tr>
<tr>
<td>2.0000000E+00</td>
<td>6.5000000E+04</td>
<td>2.0000000E+04</td>
<td>6.5000000E+04</td>
<td>2.0000000E+04</td>
<td>6.0000000E+04</td>
</tr>
<tr>
<td>5.0000000E+04</td>
<td>1.0000000E+05</td>
<td>2.5000000E+04</td>
<td>1.0000000E+05</td>
<td>2.5000000E+04</td>
<td>6.0000000E+04</td>
</tr>
<tr>
<td>3.0000000E+05</td>
<td>1.5000000E+05</td>
<td>3.0000000E+05</td>
<td>1.5000000E+05</td>
<td>3.0000000E+05</td>
<td>1.0000000E+05</td>
</tr>
<tr>
<td>5.0000000E+05</td>
<td>3.0000000E+05</td>
<td>3.5000000E+05</td>
<td>3.0000000E+05</td>
<td>3.5000000E+05</td>
<td>3.5000000E+05</td>
</tr>
<tr>
<td>3.5000000E+05</td>
<td>4.0000000E+05</td>
<td>4.0000000E+05</td>
<td>4.0000000E+05</td>
<td>4.0000000E+05</td>
<td>4.0000000E+05</td>
</tr>
<tr>
<td>4.0000000E+05</td>
<td>1.2000000E+06</td>
<td>4.5000000E+05</td>
<td>1.2000000E+06</td>
<td>4.5000000E+05</td>
<td>6.0000000E+05</td>
</tr>
<tr>
<td>4.5000000E+05</td>
<td>2.4000000E+06</td>
<td>5.0000000E+05</td>
<td>2.4000000E+06</td>
<td>5.0000000E+05</td>
<td>8.0000000E+05</td>
</tr>
<tr>
<td>5.0000000E+06</td>
<td>4.8000000E+06</td>
<td>6.0000000E+06</td>
<td>4.8000000E+06</td>
<td>6.0000000E+06</td>
<td>8.0000000E+06</td>
</tr>
</tbody>
</table>
StructCtrl Control

*used only when* \texttt{StC\_DOF\_MODE==1} or \texttt{2}

\textbf{StC\_CMODE} [switch]

Control mode {0:none; 1: Semi-Active Control Mode; 2: Active Control Mode}

\textbf{StC\_SA\_MODE} [-]

Semi-Active control mode {1: velocity-based ground hook control; 2: Inverse velocity-based ground hook control; 3: displacement-based ground hook control 4: Phase difference Algorithm with Friction Force 5: Phase difference Algorithm with Damping Force}

\textbf{StC\_X\_C\_HIGH} [-]

StC X high damping for ground hook control

\textbf{StC\_X\_C\_LOW} [-]

StC X low damping for ground hook control

\textbf{StC\_Y\_C\_HIGH} [-]

StC Y high damping for ground hook control

\textbf{StC\_Y\_C\_LOW} [-]

StC Y low damping for ground hook control

\textbf{StC\_Z\_C\_HIGH} [-]

StC Z high damping for ground hook control \textit{[used only when} \texttt{StC\_DOF\_MODE==1} \textit{and} \texttt{StC\_Z\_DOF==TRUE]}

\textbf{StC\_Z\_C\_LOW} [-]

StC Z low damping for ground hook control \textit{[used only when} \texttt{StC\_DOF\_MODE==1} \textit{and} \texttt{StC\_Z\_DOF==TRUE]}

\textbf{StC\_X\_C\_BRAKE} [-]

StC X high damping for braking the StC \textit{[currently unused. set to zero]}

\textbf{StC\_Y\_C\_BRAKE} [-]

StC Y high damping for braking the StC \textit{[currently unused. set to zero]}

\textbf{StC\_Z\_C\_BRAKE} [-]

StC Z high damping for braking the StC \textit{[used only when} \texttt{StC\_DOF\_MODE==1} \textit{and} \texttt{StC\_Z\_DOF==TRUE] \textit{[currently unused. set to zero]}

\textbf{TLCD – Tuned Liquid Column Damper}

*used only when* \texttt{StC\_DOF\_MODE==3}

\textbf{L\_X} [m]

X TLCD total length

\textbf{B\_X} [m]

X TLCD horizontal length

\textbf{area\_X} [m^2]
X TLCD cross-sectional area of vertical column

area_ratio_X [-]
X TLCD cross-sectional area ratio \[\text{vertical column area divided by horizontal column area}\]

headLossCoeff_X [-]
X TLCD head loss coeff

rho_X [kg/m^3]
X TLCD liquid density

L_Y [m]
Y TLCD total length

B_Y [m]
Y TLCD horizontal length

area_Y [m^2]
Y TLCD cross-sectional area of vertical column

area_ratio_Y [-]
Y TLCD cross-sectional area ratio \[\text{vertical column area divided by horizontal column area}\]

headLossCoeff_Y [-]
Y TLCD head loss coeff

rho_Y [kg/m^3]
Y TLCD liquid density

**Prescribed Time Series**

A prescribed time series of forces and moments may be applied in place of the StC damper. The force and moment may be applied either in a global coordinate frame, or in a local (following) coordinate frame. This feature is *used only when StC_DOF_MODE==4.*

**PrescribedForcesCoord** [switch]

Prescribed forces are in global or local coordinates \{1: global; 2: local\}

**PrescribedForcesFile** [-]

Filename for the prescribed forces. The format expected is 7 columns: \(\text{time, } \text{FX, FY, FZ, MX, MY, MZ} \). Values will be interpolated from the file between the given timestep and value sets. The input file may have an arbitrary number of commented header lines, and commented lines at any location in the input file.

Example prescribed time series file *(example prescribed force timeseries)*:

```plaintext
# This is an input file for the tower top force time-series in the TMD module of ServoDyn

# it has an arbitrary number of header lines denoted with #!% characters
!
Another comment line
#
# Time,  FX,  FY,  FZ,  MX,  MY,  MZ
# (s)   (N)   (N)   (N)   (N-m)  (N-m)  (N-m)
```

(continues on next page)
4.11.2 Theory Manual for the Tuned Mass Damper Module in OpenFAST

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This document was edited by Jason M. Jonkman of NREL to include an independent vertically oriented TMD in OpenFAST. jason.jonkman@nrel.gov

This manual describes updated functionality in OpenFAST that simulates the addition of tuned mass dampers (TMDs) for structural control. The dampers can be added to the blades, nacelle, tower, or substructure. For application studies of these systems, refer to [stc-LR11a][stc-LR11b][stc-NRL13][stc-SL11][stc-SL14][stc-SL13]. The TMDs are three independent, 1 DOF, linear mass spring damping elements that act in the local x, y, and z coordinate systems of each component. The other functionality of the structural control (StC) module, including an omnidirectional TMD and TLCD are not documented herein. We first present the theoretical background and then describe the code changes.

Theoretical Background
## Definitions

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O$</td>
<td>origin point of global inertial reference frame</td>
</tr>
<tr>
<td>$P$</td>
<td>origin point of non-inertial reference frame fixed to component (blade, nacelle, tower, sub-structure) where TMDs are at rest</td>
</tr>
<tr>
<td>$TMD$</td>
<td>location point of a TMD</td>
</tr>
<tr>
<td>$G$</td>
<td>axis orientation of global</td>
</tr>
</tbody>
</table>

### 4.11. Structural Control (SrvD)
Equations of motion

The position vectors of the TMDs in the two reference frames $O$ and $P$ are related by

$$\vec{r}_{TMD/OG} = \vec{r}_{P/OG} + \vec{r}_{TMD/PG}$$

Expressed in orientation $N$,

$$\vec{r}_{TMD/ON} = \vec{r}_{P/ON} + \vec{r}_{TMD/PN}$$

$$\Rightarrow \vec{r}_{TMD/PN} = \vec{r}_{TMD/ON} - \vec{r}_{P/ON}$$

Differentiating,$^1$

$$\dot{\vec{r}}_{TMD/PN} = \dot{\vec{r}}_{TMD/ON} - \dot{\vec{r}}_{P/ON} - \vec{\omega}_{N/ON} \times \vec{r}_{TMD/PN}$$

differentiating again gives the acceleration of the TMD w.r.t. $P$ (the nacelle position), oriented with $N$:

$$\ddot{\vec{r}}_{TMD/PN} = \ddot{\vec{r}}_{TMD/ON} - \ddot{\vec{r}}_{P/ON} - \vec{\omega}_{N/ON} \times (\vec{\omega}_{N/ON} \times \vec{r}_{TMD/PN})$$

$$-\vec{\alpha}_{N/ON} \times \vec{r}_{TMD/PN} - 2\vec{\omega}_{N/ON} \times \dot{\vec{r}}_{TMD/PN}$$

(4.167)

The right-hand side contains the following terms:

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ddot{\vec{r}}_{TMD/ON}$</td>
<td>acceleration of the TMD in the inertial frame $O_N$</td>
</tr>
<tr>
<td>$\ddot{\vec{r}}_{P/ON}$</td>
<td>acceleration of the Nacelle origin $P$ w.r.t. $O_N$</td>
</tr>
<tr>
<td>$\vec{\omega}_{N/ON}$</td>
<td>angular velocity of nacelle w.r.t. $O_N$</td>
</tr>
<tr>
<td>$\vec{\omega}<em>{N/ON} \times (\vec{\omega}</em>{N/ON} \times \vec{r}_{TMD/PN})$</td>
<td>Centripetal acceleration</td>
</tr>
<tr>
<td>$\vec{\alpha}<em>{N/ON} \times \vec{r}</em>{TMD/PN}$</td>
<td>Tangential acceleration</td>
</tr>
<tr>
<td>$2\vec{\omega}<em>{N/ON} \times \dot{\vec{r}}</em>{TMD/PN}$</td>
<td>Coriolis acceleration</td>
</tr>
</tbody>
</table>

The acceleration in the inertial frame $\ddot{\vec{r}}_{TMD/ON}$ can be replaced with a force balance

$$\ddot{\vec{r}}_{TMD/ON} = \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix}_{TMD/ON} = \frac{1}{m} \begin{bmatrix} \sum F_x \\ \sum F_y \\ \sum F_z \end{bmatrix}_{TMD/ON} = \frac{1}{m} \vec{F}_{TMD/ON}$$

Substituting the force balance into Equation (4.167) gives the general equation of motion for a TMD:

$$\ddot{\vec{r}}_{TMD/PN} = \frac{1}{m} \vec{F}_{TMD/O_N} - \ddot{\vec{r}}_{P/ON} - \vec{\omega}_{N/ON} \times (\vec{\omega}_{N/ON} \times \vec{r}_{TMD/PN})$$

$$-\vec{\alpha}_{N/ON} \times \vec{r}_{TMD/PN} - 2\vec{\omega}_{N/ON} \times \dot{\vec{r}}_{TMD/PN}$$

(4.168)

We will now solve the equations of motion for $TMD_X$, $TMD_Y$, and $TMD_Z$.

**TMD_X**

The external forces $\vec{F}_{TMDX/O_N}$ are given by

$$\vec{F}_{TMDX/O_N} = \begin{bmatrix} -c_x \ddot{x}_{TMDX/PN} - k_x \dot{x}_{TMDX/PN} + m_x a_{Gx/ON} + F_{extx} + F_{StopFrCx} \\ F_{Y_{TMDX/O_N}} + m_x a_{Gy/ON} \\ F_{Z_{TMDX/O_N}} + m_x a_{Gz/ON} \end{bmatrix}$$

Note that $(Ra) \times (Rb) = R(a \times b)$. 

---

1 Note that $(Ra) \times (Rb) = R(a \times b)$. 

---

Chapter 4. User Documentation
TMD \(X\) is fixed to frame \(N\) in the \(y\) and \(z\) directions so that

\[
r_{TMDX/PN} = \begin{bmatrix} x_{TMDX/PN} \\ 0 \\ 0 \end{bmatrix}
\]

The other components of Eqn. (4.168) are:

\[
\vec{\omega}_{N/ON} \times (\vec{\omega}_{N/ON} \times \vec{r}_{TMDX/PN}) = x_{TMDX/PN} \begin{bmatrix} -\dot{\phi}^2_{N/ON} + \dot{\psi}^2_{N/ON} \\ -\theta_{N/ON} \dot{\phi}_{N/ON} \\ \theta_{N/ON} \dot{\psi}_{N/ON} \end{bmatrix}
\]

\[
2\vec{\omega}_{N/ON} \times \vec{r}_{TMDX/PN} = \dot{x}_{TMDX/PN} \begin{bmatrix} 0 \\ 2\dot{\psi}_{N/ON} \\ -2\dot{\phi}_{N/ON} \end{bmatrix}
\]

\[
\vec{\alpha}_{N/ON} \times \vec{r}_{TMDX/PN} = x_{TMDX/PN} \begin{bmatrix} 0 \\ -\ddot{\psi}_{N/ON} \\ -\ddot{\phi}_{N/ON} \end{bmatrix}
\]

Therefore \(\ddot{x}_{TMDX/PN}\) is governed by the equations

\[
\ddot{x}_{TMDX/PN} = \left( \dot{\phi}^2_{N/ON} + \dot{\psi}^2_{N/ON} - \frac{k_x}{m_x} x_{TMDX/PN} - \frac{c_x}{m_x} \dot{x}_{TMDX/PN} - \ddot{x}_{P/ON} + a_{Gx/ON} \right) + \frac{1}{m_x} (F_{extX} + F_{StopFrCX})
\]  

(4.169)

The forces \(F_{Y_{TMDX/ON}}\) and \(F_{Z_{TMDX/ON}}\) are solved noting \(\ddot{y}_{TMDX/PN} = \ddot{z}_{TMDX/PN} = 0:\)

\[
F_{Y_{TMDX/ON}} = m_x \left( -a_{GY/ON} + \ddot{y}_{P/ON} + (\ddot{\psi}_{N/ON} + \ddot{\phi}_{N/ON}) x_{TMDX/PN} + 2\ddot{\psi}_{N/ON} \dot{x}_{TMDX/PN} \right)
\]

(4.170)

\[
F_{Z_{TMDX/ON}} = m_x \left( -a_{GZ/ON} + \ddot{z}_{P/ON} - (\ddot{\phi}_{N/ON} - \ddot{\theta}_{N/ON}) \dot{\psi}_{N/ON} x_{TMDX/PN} - 2\ddot{\phi}_{N/ON} \dot{x}_{TMDX/PN} \right)
\]

(4.171)

**TMD\_Y:**

The external forces \(\vec{F}_{TMDY/PN}\) on \(TMDY\) are given by

\[
\vec{F}_{TMDY/PN} = \begin{bmatrix} -c_y \ddot{y}_{TMDY/PN} - k_y y_{TMDY/PN} + m_y a_{Gy/ON} \\ -c_z \ddot{z}_{TMDY/PN} - k_z z_{TMDY/PN} + m_z a_{Gz/ON} + F_{extY} + F_{StopFrCY} \end{bmatrix}
\]

\(TMDY\) is fixed to frame \(N\) in the \(x\) and \(z\) directions so that

\[
r_{TMDY/PN} = \begin{bmatrix} 0 \\ y_{TMDY/PN} \\ 0 \end{bmatrix}
\]

The other components of Eqn. (4.168) are:

\[
\vec{\omega}_{N/ON} \times (\vec{\omega}_{N/ON} \times \vec{r}_{TMDY/PN}) = y_{TMDY/PN} \begin{bmatrix} \dot{\theta}_{N/ON} \dot{\phi}_{N/ON} - \dot{\psi}_{N/ON} \\ -\dot{\theta}_{N/ON} \dot{\phi}_{N/ON} + \dot{\psi}_{N/ON} \end{bmatrix}
\]
\[ 2 \vec{\omega}_{N/O \ N} \times \dot{r}_{TMDY/P \ N} = \dot{y}_{TMDY/P \ N} \begin{bmatrix} -2 \dot{\psi}_{N/O \ N} \\ 0 \\ 2 \dot{\theta}_{N/O \ N} \end{bmatrix} \]

\[ \vec{\alpha}_{N/O \ N} \times \dot{r}_{TMDY/P \ N} = y_{TMDY/P \ N} \begin{bmatrix} -\ddot{\psi}_{N/O \ N} \\ 0 \\ -\ddot{\theta}_{N/O \ N} \end{bmatrix} \]

Therefore \( \ddot{y}_{TMDY/P \ N} \) is governed by the equations

\[ \ddot{y}_{TMDY/P \ N} = \left( \dot{\theta}^2_{N/O \ N} + \dot{\psi}^2_{N/O \ N} - \frac{k_y}{m_y} \right) y_{TMDY/P \ N} - \left( \frac{c_y}{m_y} \right) \dot{y}_{TMDY/P \ N} - \dot{y}_{P/O \ N} + a_{GY/O \ N} \]

\[ + \frac{1}{m_y} (F_{exty} + F_{StopFrcy}) \]  

(4.172)

The forces \( F_{X_{TMDY/O \ N}} \) and \( F_{Z_{TMDY/O \ N}} \) are solved noting \( \ddot{x}_{TMDY/P \ N} = \ddot{z}_{TMDY/P \ N} = 0 \):

\[ F_{X_{TMDY/O \ N}} = m_y \left( -a_{GX/O \ N} + \ddot{x}_{P/O \ N} - (\dot{\psi}_{N/O \ N} - \dot{\theta}_{N/O \ N}) \dot{y}_{TMDY/P \ N} - 2 \dot{\psi}_{N/O \ N} \dot{y}_{TMDY/P \ N} \right) \]  

(4.173)

\[ F_{Z_{TMDY/O \ N}} = m_y \left( -a_{GZ/O \ N} + \ddot{z}_{P/O \ N} + (\dot{\theta}_{N/O \ N} + \dot{\psi}_{N/O \ N}) \dot{y}_{TMDY/P \ N} + 2 \dot{\theta}_{N/O \ N} \dot{y}_{TMDY/P \ N} \right) \]  

(4.174)

**TMDZ:**

The external forces \( \vec{F}_{TMDZ/O \ N} \) are given by

\[ \vec{F}_{TMDZ/O \ N} = \begin{bmatrix} F_{X_{TMDZ/O \ N}} + m_z a_{GX/O \ N} \\ F_{Y_{TMDZ/O \ N}} + m_z a_{GY/O \ N} \\ -c_z \ddot{z}_{TMDZ/P \ N} - k_z \dot{z}_{TMDZ/P \ N} + m_z a_{GZ/O \ N} + F_{extz} + F_{StopFrzc} \end{bmatrix} \]

\( TMDZ \) is fixed to frame \( N \) in the \( x \) and \( y \) directions so that

\[ r_{TMDZ/P \ N} = \begin{bmatrix} 0 \\ 0 \\ z_{TMDZ/P \ N} \end{bmatrix} \]

The other components of Eqn. (4.168) are:

\[ \vec{\omega}_{N/O \ N} \times (\vec{\omega}_{N/O \ N} \times \dot{r}_{TMDZ/P \ N}) = z_{TMDZ/P \ N} \begin{bmatrix} \dot{\theta}_{N/O \ N} \\ \dot{\psi}_{N/O \ N} \\ \dot{\theta}_{N/O \ N} + \dot{\psi}_{N/O \ N} \end{bmatrix} \]

\[ 2 \vec{\alpha}_{N/O \ N} \times \dot{r}_{TMDZ/P \ N} = \ddot{z}_{TMDZ/P \ N} \begin{bmatrix} 2 \dot{\theta}_{N/O \ N} \\ -2 \dot{\theta}_{N/O \ N} \\ 0 \end{bmatrix} \]

\[ \vec{\alpha}_{N/O \ N} \times \dot{r}_{TMDZ/P \ N} = z_{TMDZ/P \ N} \begin{bmatrix} \dot{\phi}_{N/O \ N} \\ \dot{\phi}_{N/O \ N} \\ 0 \end{bmatrix} \]

Therefore \( \ddot{z}_{TMDZ/P \ N} \) is governed by the equations

\[ \ddot{z}_{TMDZ/P \ N} = \left( \dot{\theta}^2_{N/O \ N} + \dot{\phi}^2_{N/O \ N} - \frac{k_z}{m_z} \right) z_{TMDZ/P \ N} - \left( \frac{c_z}{m_z} \right) \ddot{z}_{TMDZ/P \ N} - \ddot{z}_{P/O \ N} + a_{GZ/O \ N} \]

\[ + \frac{1}{m_z} (F_{extz} + F_{StopFrzc}) \]  

(4.175)
The forces $F_{X_{TMDZ/O_N}}$ and $F_{Z_{TMDZ/O_N}}$ are solved noting $\ddot{x}_{TMDZ/P_N} = \ddot{y}_{TMDZ/P_N} = 0$:

$$F_{X_{TMDZ/O_N}} = m_z \left( -a_{Gx/O_N} + \ddot{x}_{P/O_N} + (\ddot{\phi}_{N/O_N} + \dot{\theta}_{N/O_N} \dot{\psi}_{N/O_N}) z_{TMDZ/P_N} + 2 \dot{\phi}_{N/O_N} \dot{z}_{TMDZ/P_N} \right)$$  \hspace{1cm} (4.176)

$$F_{Y_{TMDZ/O_N}} = m_z \left( -a_{Gy/O_N} + \ddot{y}_{P/O_N} - (\ddot{\theta}_{N/O_N} - \phi_{N/O_N} \dot{\psi}_{N/O_N}) z_{TMDZ/P_N} - 2 \dot{\theta}_{N/O_N} \dot{z}_{TMDZ/P_N} \right)$$  \hspace{1cm} (4.177)

**State Equations**

**Inputs:**

The inputs are the component linear acceleration and angular position, velocity and acceleration:

$$\vec{u} = \begin{bmatrix} \dddot{r}_{P/O_G} \\ \dddot{R}_{N/G} \\ \dddot{w}_{N/O_G} \\ \dddot{\alpha}_{N/O_G} \end{bmatrix} \Rightarrow \begin{bmatrix} \dddot{x}_{TMDZ/P_N} \\ \dddot{y}_{TMDZ/P_N} \\ \dddot{z}_{TMDZ/P_N} \end{bmatrix} = \begin{bmatrix} \dddot{r}_{P/O_G} \\ \dddot{R}_{N/G} \\ \dddot{w}_{N/O_G} \\ \dddot{\alpha}_{N/O_G} \end{bmatrix}$$

**States:**

The states are the position and velocity of the TMDs along their respective DOFs in the component reference frame:

$$\vec{R}_{TMD/P_N} = \begin{bmatrix} x \\ \dot{x} \\ y \\ \dot{y} \\ z \\ \dot{z} \end{bmatrix}_{TMD/P_N}$$

The equations of motion can be re-written as a system of non-linear first-order equations of the form

$$\vec{R}_{TMD} = \vec{A}(\vec{u}) \cdot \vec{R}_{TMD} + \vec{B}(\vec{u})$$

where

$$A(\vec{u}) = \begin{bmatrix} \dddot{r}_{P/O_N} + \dddot{R}_{N/O_G} - \frac{k_z}{m_z} & 0 & 0 & 0 \\ 0 & \dddot{w}_{N/O_G} - \frac{k_y}{m_y} & 0 & 0 \\ 0 & 0 & \dddot{\alpha}_{N/O_G} - \frac{k_z}{m_z} & 0 \\ 0 & 0 & 0 & \dddot{\alpha}_{N/O_G} - \frac{k_z}{m_z} \end{bmatrix}$$

and

$$B(\vec{u}) = \begin{bmatrix} -\dddot{x}_{P/O_N} + a_{Gx/O_N} + \frac{1}{m_x} (F_{extx} + F_{St_Frx}) \\ -\dddot{y}_{P/O_N} + a_{Gy/O_N} + \frac{1}{m_y} (F_{exty} + F_{St_Fry}) \\ -\dddot{z}_{P/O_N} + a_{Gz/O_N} + \frac{1}{m_z} (F_{extz} + F_{St_Frz}) \end{bmatrix}$$

The inputs are coupled to the state variables, resulting in A and B as $f(\vec{u})$. 

---

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Outputs

The output vector $\vec{Y}$ is

$$
\vec{Y} = \begin{bmatrix} \vec{F}_{PG} \\ \vec{M}_{PG} \end{bmatrix}
$$

The output includes reaction forces corresponding to $F_{Y_{TMDX/O_N}}$, $F_{Z_{TMDX/O_N}}$, $F_{X_{TMDY/O_N}}$, $F_{Z_{TMDY/O_N}}$, $F_{X_{TMDZ/O_N}}$, and $F_{Y_{TMDZ/O_N}}$ from Eqns. (4.170), (4.171), (4.173), (4.174), (4.176), and (4.177). The resulting forces $\vec{F}_{PG}$ and moments $\vec{M}_{PG}$ acting on the component are

$$
\vec{F}_{PG} = R^T_{N/G} \begin{bmatrix} k_x x_{TMD/P_N} + c_x \dot{x}_{TMD/P_N} - F_{StopFrcX} - F_{extX} - F_{X_{TMDY/O_N}} - F_{X_{TMDZ/O_N}} \\ k_y y_{TMD/P_N} + c_y \dot{y}_{TMD/P_N} - F_{StopFrcY} - F_{extY} - F_{Y_{TMDX/O_N}} - F_{Y_{TMDZ/O_N}} \\ k_z z_{TMD/P_N} + c_z \dot{z}_{TMD/P_N} - F_{StopFrcZ} - F_{extZ} - F_{Z_{TMDX/O_N}} - F_{Z_{TMDY/O_N}} \end{bmatrix}
$$

and

$$
\vec{M}_{PG} = R^T_{N/G} \begin{bmatrix} M_X \\ M_Y \\ M_Z \end{bmatrix}_{N/N} = R^T_{N/G} \begin{bmatrix} -(F_{Z_{TMDY/O_N}}) y_{TMD/P_N} + (F_{Y_{TMDZ/O_N}}) z_{TMD/P_N} \\ (F_{Z_{TMDX/O_N}}) x_{TMD/P_N} - (F_{X_{TMDZ/O_N}}) z_{TMD/P_N} \\ -(F_{Y_{TMDX/O_N}}) x_{TMD/P_N} + (F_{X_{TMDY/O_N}}) y_{TMD/P_N} \end{bmatrix}
$$

Stop Forces

The extra forces $F_{StopFrcX}$, $F_{StopFrcY}$, and $F_{StopFrcZ}$ are added to output forces in the case that the movement of TMD_X, TMD_Y, or TMD_Z exceeds the maximum track length for the mass. Otherwise, they equal zero. The track length has limits on the positive and negative ends in the TMD direction (X_PSP and X_NSP, Y_PSP and Y_NSP, and Z_PSP and Z_NSP). If we define a general maximum and minimum displacements as $x_{max}$ and $x_{min}$, respectively, the stop forces have the form

$$
F_{StopFrc} = \begin{cases} 
- k_S \Delta x & : (x > x_{max} \land \dot{x} <= 0) \lor (x < x_{min} \land \dot{x} >= 0) \\
- k_S \Delta x + c_S \dot{x} & : (x > x_{max} \land \dot{x} > 0) \lor (x < x_{min} \land \dot{x} < 0) \\
0 & : otherwise
\end{cases}
$$

where $\Delta x$ is the distance the mass has traveled beyond the stop position and $k_S$ and $c_S$ are large stiffness and damping constants.

Code Modifications

The Structural Control (StC) function is a submodule linked into ServoDyn. In addition to references in ServoDyn.f90 and ServoDyn.txt, new files that contain the StC module are listed below.

New Files

- StrucCtrl.f90 : the structural control module
- StrucCtrl.txt : registry file include files, inputs, states, parameters, and outputs shown in Tables 1 and 2
- StrucCtrl_Types.f90: automatically generated
Variables

Table 4.10: Summary of field definitions in the StC registry. Note that state vector \( tmd_x \) corresponds to \( \vec{R}_{TMD/P_N} \), and that the outputs \( \vec{F}_{PG} \) and \( \vec{M}_{PG} \) are contained in the MeshType object (y.Mesh). \( X_{DSP}, Y_{DSP}, \) and \( Z_{DSP} \) are initial displacements of the TMDs.

<table>
<thead>
<tr>
<th>Data type</th>
<th>Variable name</th>
</tr>
</thead>
<tbody>
<tr>
<td>InitInput</td>
<td>InputFile</td>
</tr>
<tr>
<td></td>
<td>Gravity</td>
</tr>
<tr>
<td></td>
<td>( \vec{F}_{N/OG} )</td>
</tr>
<tr>
<td>Input u</td>
<td>( \vec{P}/OG )</td>
</tr>
<tr>
<td></td>
<td>( \vec{R}_{N/OG} )</td>
</tr>
<tr>
<td></td>
<td>( \omega_{N/OG} )</td>
</tr>
<tr>
<td></td>
<td>( \sigma_{N/OG} )</td>
</tr>
<tr>
<td>Parameter p</td>
<td>( m_x )</td>
</tr>
<tr>
<td></td>
<td>( c_x )</td>
</tr>
<tr>
<td></td>
<td>( k_x )</td>
</tr>
<tr>
<td></td>
<td>( m_y )</td>
</tr>
<tr>
<td></td>
<td>( c_y )</td>
</tr>
<tr>
<td></td>
<td>( k_y )</td>
</tr>
<tr>
<td></td>
<td>( m_z )</td>
</tr>
<tr>
<td></td>
<td>( c_z )</td>
</tr>
<tr>
<td></td>
<td>( k_z )</td>
</tr>
<tr>
<td></td>
<td>( K_S = [k_{SX} \ k_{SY} \ k_{SZ}] )</td>
</tr>
<tr>
<td></td>
<td>( C_S = [c_{SX} \ c_{SY} \ c_{SZ}] )</td>
</tr>
<tr>
<td></td>
<td>( P_{SP} = [X_{PSP} \ Y_{PSP} \ Z_{PSP}] )</td>
</tr>
<tr>
<td></td>
<td>( P_{NSP} = [X_{NSP} \ Y_{NSP} \ Z_{NSP}] )</td>
</tr>
<tr>
<td></td>
<td>( F_{ext} )</td>
</tr>
<tr>
<td></td>
<td>Gravity</td>
</tr>
<tr>
<td></td>
<td>TMDX_DOF</td>
</tr>
<tr>
<td></td>
<td>TMDY_DOF</td>
</tr>
<tr>
<td></td>
<td>TMDZ_DOF</td>
</tr>
<tr>
<td></td>
<td>( X_{DSP} )</td>
</tr>
<tr>
<td></td>
<td>( Y_{DSP} )</td>
</tr>
<tr>
<td></td>
<td>( Z_{DSP} )</td>
</tr>
<tr>
<td>State x</td>
<td>( tmd_x )</td>
</tr>
<tr>
<td>Output y</td>
<td>Mesh</td>
</tr>
</tbody>
</table>

The input, parameter, state and output definitions are summarized in Table 1. The inputs from file are listed in Table 2.
Table 4.11: Data read in from TMDInputFile.

<table>
<thead>
<tr>
<th>Field Name</th>
<th>Field Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMD_CMODE</td>
<td>int</td>
<td>Control Mode (1:passive, 2:active)</td>
</tr>
<tr>
<td>TMD_X_DOF</td>
<td>logical</td>
<td>DOF on or off</td>
</tr>
<tr>
<td>TMD_Y_DOF</td>
<td>logical</td>
<td>DOF on or off</td>
</tr>
<tr>
<td>TMD_Z_DOF</td>
<td>logical</td>
<td>DOF on or off</td>
</tr>
<tr>
<td>TMD_X_DSP</td>
<td>real</td>
<td>TMD_X initial displacement</td>
</tr>
<tr>
<td>TMD_Y_DSP</td>
<td>real</td>
<td>TMD_Y initial displacement</td>
</tr>
<tr>
<td>TMD_Z_DSP</td>
<td>real</td>
<td>TMD_Z initial displacement</td>
</tr>
<tr>
<td>TMD_X_M</td>
<td>real</td>
<td>TMD mass</td>
</tr>
<tr>
<td>TMD_X_K</td>
<td>real</td>
<td>TMD stiffness</td>
</tr>
<tr>
<td>TMD_X_C</td>
<td>real</td>
<td>TMD damping</td>
</tr>
<tr>
<td>TMD_Y_M</td>
<td>real</td>
<td>TMD mass</td>
</tr>
<tr>
<td>TMD_Y_K</td>
<td>real</td>
<td>TMD stiffness</td>
</tr>
<tr>
<td>TMD_Y_C</td>
<td>real</td>
<td>TMD damping</td>
</tr>
<tr>
<td>TMD_Z_M</td>
<td>real</td>
<td>TMD mass</td>
</tr>
<tr>
<td>TMD_Z_K</td>
<td>real</td>
<td>TMD stiffness</td>
</tr>
<tr>
<td>TMD_Z_C</td>
<td>real</td>
<td>TMD damping</td>
</tr>
<tr>
<td>TMD_X_PSP</td>
<td>real</td>
<td>positive stop position (maximum X mass displacement)</td>
</tr>
<tr>
<td>TMD_X_NSP</td>
<td>real</td>
<td>negative stop position (minimum X mass displacement)</td>
</tr>
<tr>
<td>TMD_X_K_SX</td>
<td>real</td>
<td>stop spring stiffness</td>
</tr>
<tr>
<td>TMD_X_C_SX</td>
<td>real</td>
<td>stop spring damping</td>
</tr>
<tr>
<td>TMD_Y_PSP</td>
<td>real</td>
<td>positive stop position (maximum Y mass displacement)</td>
</tr>
<tr>
<td>TMD_Y_NSP</td>
<td>real</td>
<td>negative stop position (minimum Y mass displacement)</td>
</tr>
<tr>
<td>TMD_Y_K_S</td>
<td>real</td>
<td>stop spring stiffness</td>
</tr>
<tr>
<td>TMD_Y_C_S</td>
<td>real</td>
<td>stop spring damping</td>
</tr>
<tr>
<td>TMD_Z_PSP</td>
<td>real</td>
<td>positive stop position (maximum Z mass displacement)</td>
</tr>
<tr>
<td>TMD_Z_NSP</td>
<td>real</td>
<td>negative stop position (minimum Z mass displacement)</td>
</tr>
<tr>
<td>TMD_Z_K_S</td>
<td>real</td>
<td>stop spring stiffness</td>
</tr>
<tr>
<td>TMD_Z_C_S</td>
<td>real</td>
<td>stop spring damping</td>
</tr>
<tr>
<td>TMD_P_X</td>
<td>real</td>
<td>x origin of P in nacelle coordinate system</td>
</tr>
<tr>
<td>TMD_P_Y</td>
<td>real</td>
<td>y origin of P in nacelle coordinate system</td>
</tr>
<tr>
<td>TMD_P_Z</td>
<td>real</td>
<td>z origin of P in nacelle coordinate system</td>
</tr>
</tbody>
</table>

Acknowledgements

The authors would like to thank Dr. Jason Jonkman for reviewing this manual.

4.11.3 TLCD: Derivations of Equation of Motion
Definitions:

Table 4.12: TLCD Definitions

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O$</td>
<td>origin point of global inertial reference frame, located at center of base of resting turbine</td>
</tr>
<tr>
<td>$P$</td>
<td>origin point of local reference frame (e.g. fixed to nacelle), in the center of the horizontal liquid column</td>
</tr>
<tr>
<td>$W_R$</td>
<td>point attached to the top center of the right liquid column (moving)</td>
</tr>
<tr>
<td>$W_L$</td>
<td>point attached to the top center of the left liquid column (moving)</td>
</tr>
<tr>
<td>$i$</td>
<td>axis orientation of inertial reference frame (global)</td>
</tr>
<tr>
<td>$l$</td>
<td>axis orientation of local reference frame</td>
</tr>
<tr>
<td>$w$</td>
<td>position of the liquid water column as defined in Figure Fig. 4.39</td>
</tr>
<tr>
<td>$g$</td>
<td>gravity vector in the inertial reference frame (global)</td>
</tr>
</tbody>
</table>

Right Vertical Liquid Column

Starting with the right vertical column, we define the following vector expressions:
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\vec{r}_{i}^{O\rightarrow P} = \begin{bmatrix} x \ y \ z \end{bmatrix}$</td>
<td>position vector from point $O$ to point $P$ in inertial coordinate system</td>
</tr>
<tr>
<td>$\vec{r}<em>{i}^{P\rightarrow W</em>{R}} = \begin{bmatrix} x \ y \ z \end{bmatrix}$</td>
<td>position vector from point $P$ to point $W_{R}$ in local coordinate system</td>
</tr>
<tr>
<td>$\vec{\omega}_{i}^{l} = \begin{bmatrix} \theta \ \phi \ \psi \end{bmatrix}$</td>
<td>angular velocity frame $l$ with respect to inertial reference frame $i$</td>
</tr>
<tr>
<td>$\vec{r}<em>{i}^{O\rightarrow W</em>{R}} = \vec{r}<em>{i}^{O\rightarrow P} + \vec{r}</em>{i}^{P\rightarrow W_{R}}$</td>
<td>position vector from point $P$ to point $W_{R}$ in local coordinate system</td>
</tr>
</tbody>
</table>

Taking the derivative of the last expression for $\vec{r}_{i}^{O\rightarrow W_{R}}$ yields the velocity of point $W_{R}$ in the global reference frame:

$$\dot{\vec{r}}_{i}^{W_{R}} = \dot{\vec{r}}_{i}^{P} + \dot{\vec{r}}_{i}^{W_{R}} + \vec{\omega}_{i}^{l} \times \vec{r}_{i}^{P\rightarrow W_{R}}.$$

Repeating this step once more yields its acceleration:

$$\ddot{\vec{r}}_{i}^{W_{R}} = \ddot{\vec{r}}_{i}^{P} + \ddot{\vec{r}}_{i}^{W_{R}} + 2 \vec{\omega}_{i}^{l} \times \dot{\vec{r}}_{i}^{W_{R}} + \vec{\omega}_{i}^{l} \times \left( \vec{\omega}_{i}^{l} \times \vec{r}_{i}^{P\rightarrow W_{R}} \right).$$

Following Newton’s Second Law, the left part of this expression can be replaced with a force balance:

$$\ddot{\vec{r}}_{i}^{W_{R}} = \frac{1}{m_{R}} \left[ \begin{array}{c} \sum F_{x}^{W_{R}} \\ \sum F_{y}^{W_{R}} \\ \sum F_{z}^{W_{R}} \end{array} \right]_{W_{R}}^{P\rightarrow W_{R}} = \frac{1}{m_{R}} \left[ \begin{array}{c} F_{x}^{W_{R}/S} + m_{R}g_{x} \\ F_{y}^{W_{R}/S} + m_{R}g_{y} \\ m_{R}g_{z} \end{array} \right]_{W_{R}}^{P\rightarrow W_{R}}$$

where $g$ is the gravity vector in the inertial frame. The vector describing the position of the right hand column in the local reference frame ($i$) can be written as:

$$\vec{r}_{i}^{P\rightarrow W_{R}} = \begin{bmatrix} B/2 \\ 0 \\ L-B/2 + w \end{bmatrix}_{l}.\$$

Movement of the liquid in the vertical columns is restricted to the $z$-direction in reference frame $N$, thus the expression for the acceleration of the right liquid column becomes:

$$\ddot{\vec{r}}_{i}^{P\rightarrow W_{R}} = \frac{1}{m_{R}} \left[ \begin{array}{c} F_{x}^{W_{R}/S} + m_{R}g_{x} \\ F_{y}^{W_{R}/S} + m_{R}g_{y} \\ m_{R}g_{z} \end{array} \right]_{W_{R}}^{P\rightarrow W_{R}} = \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix}_{l}^{P\rightarrow W_{R}} + 2 \vec{\omega}_{i}^{l} \times \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix}_{i}^{P\rightarrow W_{R}} + \begin{bmatrix} \dot{\theta} \\ \dot{\phi} \\ \dot{\psi} \end{bmatrix}_{i}^{l} \times \begin{bmatrix} B/2 \\ 0 \\ L-B/2 + w \end{bmatrix}_{l}^{P\rightarrow W_{R}}$$
Computing all cross-products yields three distinct expressions in the x, y, and z dimensions:

\[ x : \frac{1}{m_R} \left( F_{x_{WR}} / S + m_R g_x \right) \]
\[ = \ddot{x}_i + 2 \dot{\phi} \dot{w} + \ddot{\phi} \left( L - B \right) \frac{1}{2} + w - \dot{\phi}^2 \frac{B}{2} - \dot{\psi} \ddot{\psi} \left( L - B \right) \frac{1}{2} + w \]

\[ y : \frac{1}{m_R} \left( F_{y_{WR}} / S + m_R g_y \right) \]
\[ = \ddot{y}_i + 2 \dot{\theta} \dot{w} + \ddot{\theta} \left( L - B \right) \frac{1}{2} + w - \dot{\phi} \ddot{\phi} \left( L - B \right) \frac{1}{2} + w + \ddot{\phi} B \]

\[ z : \frac{1}{m_L} g_z \]
\[ = \ddot{z}_i + \ddot{w} - \dot{\phi}^2 \frac{B}{2} + \dot{\theta} \dot{\phi} \left( L - B \right) \frac{1}{2} + w - \ddot{\phi}^2 \left( L - B \right) \frac{1}{2} + w \]

### Left Vertical Liquid Column

Following the same methodology as above the equations describing the movement of the left vertical liquid column can be determined.

Similarly, the acceleration of the left liquid column can be replaced by a force balance:

\[ \ddot{r}_{i_{VL}} = \frac{1}{m_L} \left[ \sum_{j} F_{x_j} \right]_{W_L} = \frac{1}{m_L} \left[ F_{x_{VL}} / S + m_L g_x \right]_{W_L} \]

where \( g \) is the gravity vector in the inertial frame. The vector describing the position of the left hand column in the local reference frame (\( i \)) can be written as:

\[ \ddot{r}_{i_{VL}} = \begin{bmatrix} -B/2 \\ 0 \\ L - B \end{bmatrix}^{P \rightarrow W_L}_{l} \]

The final equation for the acceleration of the left liquid column becomes:

\[ \frac{1}{m_L} \left[ m_L g_z \right]_{W_L} = \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix}^{P \rightarrow W_L}_{l} + \begin{bmatrix} 0 \\ 0 \\ -\ddot{w} \end{bmatrix}^{W_L}_{l} + 2 \begin{bmatrix} \dot{\theta} \\ \dot{\phi} \\ \dot{\psi} \end{bmatrix}^{l} \times \begin{bmatrix} 0 \\ 0 \\ -\ddot{w} \end{bmatrix}^{W_L}_{l} + \begin{bmatrix} \dot{\theta} \\ \dot{\phi} \\ \dot{\psi} \end{bmatrix}^{l} \times \begin{bmatrix} -B/2 \\ 0 \\ L - B \end{bmatrix}^{P \rightarrow W_L}_{l} \]

\[ + \begin{bmatrix} \dot{\theta} \\ \dot{\phi} \\ \dot{\psi} \end{bmatrix}^{l} \times \left( \begin{bmatrix} \dot{\theta} \\ \dot{\phi} \\ \dot{\psi} \end{bmatrix}^{l} \times \begin{bmatrix} -B/2 \\ 0 \\ L - B \end{bmatrix}^{P \rightarrow W_L}_{l} \right) \]
The x, y, and z equations then become:

\[
x : \quad \frac{1}{m_L} \left( F_{xL}^{\text{WS}} + m_L g \right) = \ddot{x} + 2 \dot{\phi} \dot{w} + \dot{\phi} \left( \frac{L - B}{2} - w \right) + \dot{\psi} \frac{B}{2} + \ddot{\psi} \left( \frac{L - B}{2} - w \right)
\]

\[
y : \quad \frac{1}{m_L} \left( F_{yL}^{\text{WS}} + m_L g \right) = \ddot{y} + 2 \dot{\theta} \dot{w} - \dot{\theta} \left( \frac{L - B}{2} - w \right) + \ddot{\phi} \left( \frac{L - B}{2} - w \right) - \dot{\phi} \frac{B}{2}
\]

\[
z : \quad g_z = \ddot{z} - \ddot{\phi} \frac{B}{2} - \dot{\phi} \frac{B}{2} - \ddot{\psi} \left( \frac{L - B}{2} - w \right) - \ddot{\theta} \frac{B}{2}
\]

**Horizontal Liquid Column**

As the movement of the liquid in the horizontal column \((H)\) is restricted to the x-dimension in local reference frame, \(l\), the position vector can be expressed as:

\[
r_{P \rightarrow W_H}^l = \begin{bmatrix} w \\ 0 \\ 0 \end{bmatrix}
\]

Furthermore, the force balance on the horizontal liquid column is...

\[
\ddot{r}_{P \rightarrow W_H}^l = \frac{1}{m_H} \left[ \begin{array}{cccc}
\sum F_x & F_y & F_z \\
\sum F_y & \sum F_z & \sum F_z
\end{array} \right]^{W_H} = \frac{1}{m_H} \left[ m_H g_x - \frac{1}{2} \rho A \left( |\dot{w}| \right) |\dot{w}| \right]^{W_H}
\]

where the \(\rho\) term represents the damping force applied to the liquid as it passes through the restricted orifice, and \(g\) is the gravity vector in the inertial frame.

The final expression for the acceleration of the water through the horizontal column becomes:

\[
\frac{1}{m_H} \left[ m_H g_x - \frac{1}{2} \rho A \left( |\dot{w}| \right) |\dot{w}| \right]^{W_H} = \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix}^l + \begin{bmatrix} \ddot{w} \\ 0 \\ 0 \end{bmatrix}^{W_H}
\]

\[
+ 2 \begin{bmatrix} \dot{\theta} \\ \dot{\phi} \\ \dot{\psi} \end{bmatrix}^l \times \begin{bmatrix} \dot{w} \\ 0 \\ 0 \end{bmatrix}^{W_H}
\]

\[
+ \begin{bmatrix} \dot{\theta} \\ \dot{\phi} \\ \dot{\psi} \end{bmatrix}^l \times \left( \begin{bmatrix} \dot{\theta} \\ \dot{\phi} \\ \dot{\psi} \end{bmatrix}^l \times \begin{bmatrix} w \\ 0 \\ 0 \end{bmatrix}^{P \rightarrow W_H} \right)
\]
The inertial forces are then written as:

\[
\begin{align*}
x & : \quad g_x - \frac{1}{m_H} \left( \frac{1}{2} \rho A \xi |\dot{w}| \dot{w} \right) \\
& = \ddot{x}_i^P + \ddot{w} - \dot{\psi}^2 w - \dot{\psi}^2 w \\
y & : \quad \frac{1}{m_H} \left( F_{yH}^{W/S} + m_H g_y \right) \\
& = \ddot{y}_i^P + 2\dot{\psi} \dot{w} + \dot{\psi} \dot{w} + \dot{\psi} \dot{w} \\
z & : \quad \frac{1}{m_H} \left( F_{zH}^{W/S} + m_H g_z \right) \\
& = \ddot{z}_i^P - \dot{\phi} \dot{w} - \dot{\phi} \dot{w} + \dot{\phi} \dot{w}
\end{align*}
\]

Recalling that the displacement of the liquid in the horizontal column, \( w \) is zero, as the center of mass of the liquid in the horizontal column always remains at point \( l \) even as liquid accelerates through the pipe. Consequently, removing the \( w \) terms from these equations gives the expressions:

\[
\begin{align*}
x & : \quad g_x - \frac{1}{m_H} \left( \frac{1}{2} \rho A \xi |\dot{w}| \dot{w} \right) \\
& = \ddot{x}_i^P + \ddot{w} \\
y & : \quad \frac{1}{m_H} \left( F_{yH}^{W/S} + m_H g_y \right) \\
& = \ddot{y}_i^P + 2\dot{\psi} \dot{w} \\
z & : \quad \frac{1}{m_H} \left( F_{zH}^{W/S} + m_H g_z \right) \\
& = \ddot{z}_i^P - \dot{\phi} \dot{w}
\end{align*}
\]

Now that the accelerations of the three liquid columns have been determined individually, we can extract the inertial forces and derive a singular equation to describe the acceleration of the liquid in the column.

The inertial forces are then written as:

\[
\begin{align*}
F_{xH}^{WR/S} & = m_R \left( \ddot{x}_i^P + 2\dot{\phi} \dot{w} + \ddot{\phi} \left( \frac{L - B}{2} + w \right) - \dot{\psi}^2 B \frac{L - B}{2} + \psi \ddot{\phi} \left( \frac{L - B}{2} + w \right) - g_x \right) \\
F_{yH}^{WR/S} & = m_R \left( \ddot{y}_i^P - 2\dot{\theta} \dot{w} + \ddot{\theta} \left( \frac{L - B}{2} + w \right) + \ddot{\theta} \psi \left( \frac{L - B}{2} + w \right) + \ddot{\theta} \dot{\phi} B \frac{L - B}{2} - g_y \right) \\
F_{xL}^{WL/S} & = m_L \left( \ddot{x}_i^P - 2\dot{\phi} \dot{w} + \ddot{\phi} \left( \frac{L - B}{2} - w \right) + \ddot{\phi}^2 B \frac{L - B}{2} + \ddot{\phi} \psi \left( \frac{L - B}{2} - w \right) - \ddot{\phi} \dot{\phi} B \frac{L - B}{2} - g_x \right) \\
F_{yL}^{WL/S} & = m_L \left( \ddot{y}_i^P + 2\dot{\theta} \dot{w} - \ddot{\theta} \left( \frac{L - B}{2} - w \right) + \ddot{\theta} \psi \left( \frac{L - B}{2} - w \right) - \ddot{\theta} \dot{\phi} B \frac{L - B}{2} - g_y \right) \\
F_{yH}^{WR/S} & = m_H \left( \ddot{y}_i^P + 2\dot{\psi} \dot{w} - g_y \right) \\
F_{zH}^{WR/S} & = m_H \left( \ddot{z}_i^P - \dot{\phi} \dot{w} - g_z \right)
\end{align*}
\]

Equation for \( \ddot{w} \) from right liquid column (z-dimension):

\[
\ddot{w} = -\ddot{z}_i^P + \ddot{\phi} B \frac{L - B}{2} - \ddot{\phi} \dot{\phi} B \frac{L - B}{2} + \dot{\phi} \ddot{\phi} \left( \frac{L - B}{2} + w \right) + \dot{\phi}^2 \left( \frac{L - B}{2} + w \right) + g_z
\]

Equation for \( \ddot{w} \) from left liquid column (z-dimension):

\[
\ddot{w} = -\ddot{z}_i^P + \ddot{\phi} B \frac{L - B}{2} - \ddot{\phi} \dot{\phi} B \frac{L - B}{2} - \dot{\phi} \ddot{\phi} \left( \frac{L - B}{2} - w \right) - \dot{\phi}^2 \left( \frac{L - B}{2} - w \right) - g_z
\]
Equation for $\ddot{w}$ from horizontal liquid column (x-dimension):

$$\ddot{w} = -\ddot{x}_i^P + g_x - \frac{1}{m_H} \left( \frac{1}{2} \rho A \xi |\ddot{w}| \ddot{w} \right)$$

From Newton’s Second Law, we know that the acceleration of the total liquid mass can be described accordingly:

$$m_T \ddot{w} = m_R (\ddot{w}) \ m_L (\ddot{w}) \ m_H (\ddot{w})$$

Where

$$m_T = \rho A L$$
$$m_R = \rho A \left( \frac{L - B}{2} + w \right)$$
$$m_L = \rho A \left( \frac{L - B}{2} - w \right)$$
$$m_H = \rho A B$$

Combining the above equations gives us the expression:

$$\rho A L \ddot{w} = \rho A \left( \frac{L - B}{2} + w \right) \left[ -\ddot{x}_i^P + \ddot{\psi} \
+ \ddot{\psi} \left( \frac{L - B}{2} + w \right) + \ddot{\theta} \left( \frac{L - B}{2} + w \right) + g_z \right]$$

Finally, simplifying this expression gives us the final equation, describing the movement of the liquid through the TLCD:

$$\rho A L \ddot{w} = -2 \rho A w \ddot{x}_i^P + \rho A B \ddot{\psi} \left( \frac{L - B}{2} \right) - \rho A B \ddot{\theta} \left( \frac{L - B}{2} \right)$$
$$+ 2 \rho A w \ddot{\theta} \left( L - B \right) + 2 \rho A w \ddot{\psi} \left( L - B \right)$$
$$+ 2 \rho A w g_z - \rho A B \ddot{x}_i^P + \rho A B g_x$$
$$- \frac{1}{2} \rho A B \xi |\ddot{w}| \ddot{w}$$

**Orthogonal TLCD**

Following the same methodology as above in the side-side orientation (as opposed to fore-aft) yields the following equations for the front, back, and horizontal orthogonal columns:
Back Vertical Orthogonal Liquid Column

\[ x : \frac{1}{m_B} \left( F_{W_B/S} + m_B g_x \right) \]
\[ = \ddot{x}_i + 2\phi \dot{w}_o + \ddot{\phi} \left( \frac{L - B}{2} + w_o \right) + \dddot{\psi} B + \ddot{\phi} \dddot{\phi} + \dddot{\psi} \left( \frac{L - B}{2} + w_o \right) \]
\[ y : \frac{1}{m_B} \left( F_{W_B/S} + m_B g_y \right) \]
\[ = \ddot{y}_i - 2\dot{\theta} \dot{w}_o - \dot{\theta} \left( \frac{L - B}{2} + w_o \right) + \dddot{\psi} \left( \frac{L - B}{2} + w_o \right) + \dddot{\psi} B + \dot{\phi} \left( \frac{L^2 - B^2}{2} + w_o \right) \]
\[ z : \]
\[ = z_i + \dddot{w}_o - \ddot{\theta} \dddot{\theta} - \dot{\phi} \left( \frac{L - B}{2} + w_o \right) - \dddot{\psi} \left( \frac{L - B}{2} + w_o \right) - \dddot{\psi} B \]

Front Vertical Orthogonal Liquid Column

\[ x : \frac{1}{m_F} \left( F_{W_F/S} + m_F g_x \right) \]
\[ = \ddot{x}_i - 2\phi \dot{w}_o + \ddot{\phi} \left( \frac{L - B}{2} - w_o \right) - \dddot{\psi} B + \ddot{\phi} \dddot{\phi} + \dddot{\psi} \left( \frac{L - B}{2} - w_o \right) \]
\[ y : \frac{1}{m_F} \left( F_{W_F/S} + m_F g_y \right) \]
\[ = \ddot{y}_i + 2\dot{\theta} \dot{w}_o - \dot{\theta} \left( \frac{L - B}{2} - w_o \right) + \dddot{\psi} \left( \frac{L - B}{2} - w_o \right) - \dddot{\psi} B - \dot{\phi} \left( \frac{L^2 - B^2}{2} - w_o \right) \]
\[ z : \]
\[ = z_i - \ddot{w}_o + \dddot{\theta} \left( \frac{L - B}{2} - w_o \right) - \dddot{\phi} \left( \frac{L - B}{2} - w_o \right) + \dddot{\psi} B \]

Horizontal Orthogonal Liquid Column

\[ x : \frac{1}{m_H} \left( F_{W_H/S} + m_H g_x \right) \]
\[ = \ddot{x}_i - 2\dot{\psi} \dot{w}_o \]
\[ y : \frac{1}{m_H} \left( m_H g_y - \frac{1}{2} \rho A \xi |\dot{w}_o| \dot{w}_o \right) \]
\[ = \ddot{y}_i + \dot{w}_o \]
\[ z : \frac{1}{m_H} \left( F_{W_H/S} + m_H g_z \right) \]
\[ = \dddot{z}_i + 2\dot{\theta} \dot{w}_o \]
Extracting the inertial forces from these equations leaves us with:

\[
F^{W_b}_x = m_B \left( \ddot{x}_i^P + 2\dot{\theta}\dot{w}_o + \dot{\phi} \left( \frac{L - B}{2} + w_o \right) + \dot{\psi} \frac{B}{2} + \ddot{\psi} \left( \frac{L - B}{2} + w_o \right) - g_x \right)
\]

\[
F^{W_b}_y = m_B \left( \ddot{y}_i^P - 2\dot{\theta}\dot{w}_o + \dot{\theta} \left( \frac{L - B}{2} + w_o \right) + \dot{\phi} \frac{B}{2} + \ddot{\phi} \left( \frac{L - B}{2} + w_o \right) - g_y \right)
\]

\[
F^{W_F}_x = m_F \left( \ddot{x}_i^P - 2\dot{\phi}\dot{w}_o + \dot{\phi} \left( \frac{L - B}{2} - w_o \right) - \dot{\psi} \frac{B}{2} + \ddot{\psi} \left( \frac{L - B}{2} - w_o \right) - g_x \right)
\]

\[
F^{W_F}_y = m_F \left( \ddot{y}_i^P + 2\dot{\phi}\dot{w}_o - \dot{\theta} \left( \frac{L - B}{2} - w_o \right) + \dot{\phi} \left( \frac{L - B}{2} - w_o \right) - \dot{\psi} \frac{B}{2} - \ddot{\psi} \frac{B}{2} - g_y \right)
\]

\[
F^{W_H}_x = m_H \left( \ddot{x}_i + 2\dot{\psi}\dot{w}_o - g_x \right)
\]

\[
F^{W_H}_y = m_H \left( \ddot{y}_i^P + 2\dot{\theta}\dot{w}_o - g_z \right)
\]

The remaining equations, when combined, yield the final equation:

\[
\rho AL\ddot{w} = \rho A \left( \frac{L - B}{2} + w_o \right) \left[-\ddot{z}_i^P + \dot{\theta}\frac{B}{2} + \ddot{\theta} \left( \frac{L - B}{2} + w_o \right) - g_x\right] \\
+ \rho A \left( \frac{L - B}{2} - w_o \right) \left[-\ddot{y}_i^P + \dot{\phi}\frac{B}{2} - \ddot{\phi} \left( \frac{L - B}{2} - w_o \right) + g_y\right] \\
+ \rho AB \left(-\ddot{y}_i^P + g_y\right) - \frac{1}{2} \rho A \xi |\dot{w}_o| \dot{w}_o
\]

Which can be simplified to become:

\[
\rho AL\ddot{w}_o = -2\rho A w_o \ddot{z}_i^P + \rho AB \ddot{\theta} \left( \frac{L - B}{2} \right) - \rho AB \dot{\phi} \ddot{\psi} \left( \frac{L - B}{2} \right) \\
+ 2\rho A w_o \ddot{\theta} \left( L - B \right) + 2\rho A w_o \ddot{\phi} \left( L - B \right) \\
+ 2\rho A w_o g_z - \rho AB \ddot{y}_i^P + \rho AB g_y \\
- \frac{1}{2} \rho A \xi |\dot{w}_o| \dot{w}_o
\]

### 4.12 FAST v8 and the transition to OpenFAST

This page describes the transition from FAST v8, a computer-aided engineering tool for simulating the coupled dynamic response of wind turbines, to OpenFAST. OpenFAST was established by researchers at the National Renewable Energy Laboratory (NREL) in 2017, who were supported by the U.S. Department of Energy Wind Energy Technology Office (DOE-WETO).
4.12.1 FAST v8

FAST v8 is a computer-aided engineering tool for simulating the coupled dynamic response of wind turbines. FAST joins aerodynamics models, hydrodynamics models for offshore structures, control and electrical system (servo) dynamics models, and structural (elastic) dynamics models to enable coupled nonlinear aero-hydro-servo-elastic simulation in the time domain. The FAST tool enables the analysis of a range of wind turbine configurations, including two- or three-blade horizontal-axis rotor, pitch or stall regulation, rigid or teetering hub, upwind or downwind rotor, and lattice or tubular tower. The wind turbine can be modeled on land or offshore on fixed-bottom or floating substructures. FAST is based on advanced engineering models derived from fundamental laws, but with appropriate simplifications and assumptions, and supplemented where applicable with computational solutions and test data.

The aerodynamic models use wind-inflow data and solve for the rotor-wake effects and blade-element aerodynamic loads, including dynamic stall. The hydrodynamics models simulate the regular or irregular incident waves and currents and solve for the hydrostatic, radiation, diffraction, and viscous loads on the offshore substructure. The control and electrical system models simulate the controller logic, sensors, and actuators of the blade-pitch, generator-torque, nacelle-yaw, and other control devices, as well as the generator and power-converter components of the electrical drive. The structural-dynamics models apply the control and electrical system reactions, apply the aerodynamic and hydrodynamic loads, adds gravitational loads, and simulate the elasticity of the rotor, drivetrain, and support structure. Coupling between all models is achieved through a modular interface and coupler.

4.12.2 Transition to OpenFAST

The release of OpenFAST represents a transition to better support an open-source developer community across research laboratories, industry, and academia around FAST-based aero-hydro-servo-elastic engineering models of wind-turbines and wind-plants. OpenFAST aims to provide a solid software-engineering framework for FAST development including well documented source code, extensive automated regression and unit testing, and a robust multi-platform and compiler build system.

OpenFAST includes the following organizational changes relative to FAST v8.16:

- A new GitHub organization has been established at https://github.com/openfast
- The OpenFAST glue codes, modules, module drivers, and compiling tools are contained within a single repository: https://github.com/openfast/openfast
- The FAST program has been renamed OpenFAST (starting from OpenFAST v1.0.0)
- Version numbering has been updated for OpenFAST (starting from OpenFAST v1.0.0), e.g., OpenFAST-v1.0.0-123-gabcd1234-dirty, where:
  - v1.0.0 is the major-minor-bugfix numbering system and corresponds to a tagged commit made by NREL on GitHub
  - 123-g is the number of additional commits after the most recent tag for a build [the ‘-g’ is for ‘git’]
  - abcd1234 is the first 8 characters of the current commit hash
  - dirty denotes that local changes have been made but not committed
- Because all modules are contained in the same repository, the version numbers of each module have been eliminated and now use the OpenFAST version number (starting from OpenFAST v1.0.0) though old documentation may still refer to old version numbers
- The OpenFAST regression test baseline solutions (formerly the Certification Tests or CertTest) reside in a standalone repository: https://github.com/openfast/r-test (starting from OpenFAST v1.0.0)
- Unit testing has been introduced at the subroutine level (starting with BeamDyn from OpenFAST v1.0.0).
An online documentation system has been established to replace existing documentation of FAST v8: http://openfast.readthedocs.io/; during the transition to OpenFAST, most user-related documentation is still provided through the NWTC Information Portal, https://nwtc.nrel.gov

Cross platform compiling is accomplished with CMake on macOS, Linux, and Cygwin (Windows) systems

Visual Studio Projects (VS-Build) are provided for compiling OpenFAST on Windows (starting from OpenFAST v1.0.0), but the development team is working to automate the generation of Visual Studio build files via CMake in a future release

GitHub Issues has been made the primary platform for developers to report and track bugs, request feature enhancements, and to ask questions related to the source code, compiling, and regression/unit testing; general user-related questions on OpenFAST theory and usage should still be handled through the forum at https://wind.nrel.gov/forum/wind

A new API has been added that provides a high level interface to run OpenFAST through a C++ driver code helping to interface OpenFAST with external programs like CFD solvers written in C++ (starting in OpenFAST v1.0.0)

4.12.3 Release Notes for OpenFAST

This section outlines significant modifications to OpenFAST made with each tagged release.

v0.1.0 (April 2017)

Algorithmically, OpenFAST v0.1.0 is the release most closely related to FAST v8.16.

Organizational changes:

- A new GitHub organization has been established at https://github.com/openfast
- The OpenFAST glue codes, modules, module drivers, and compiling tools are contained within a single repository: https://github.com/openfast/openfast
- Cross platform compiling is accomplished with CMake on macOS, Linux, and Cygwin (Windows) systems
- An online documentation system has been established to replace existing documentation of FAST v8: http://openfast.readthedocs.io/
- GitHub Issues has been made the primary platform for developers to report and track bugs, request feature enhancements, and to ask questions related to the source code, compiling, and regression/unit testing; general user-related questions on OpenFAST theory and usage should still be handled through the forum at https://wind.nrel.gov/forum/wind
- The AeroDyn v15 aerodynamics module has been significantly updated. The blade-element/momentum theory (BEMT) solution algorithm has been improved as follows:
  - BEMT now functions for the case where the undisturbed velocity along the x-direction of the local blade coordinate system (Vx) is less than zero
  - BEMT no longer aborts when a valid value of the inflow angle ($\phi$) cannot be found; in this case, the inflow angle is computed geometrically (without induction)
  - The inflow angle ($\phi$) is now initialized on the first call instead of defaulting to using $\phi = 0$, giving better results during simulation start up
  - When hub- and/or tip-loss are enabled (HubLoss = True and/or TipLoss = True), tangential induction ($a'$) is set to 0 instead of -1 at the root and/or tip, respectively (axial induction (a) is still set to 1 at the root and/or tip)
The BEMT solution has been made more efficient

In addition, several bugs in AeroDyn v15 have been fixed, including:

- Fixed a bug whereby when hub- and/or tip-loss are enabled (HubLoss = True and/or TipLoss = True) along with the Pitt/Peters skewed-wake correction (SkewMod = 2), BEMT no longer modifies the induction factors at the hub and/or tip, respectively

- Fixed a bug whereby the time series was affected after the linearization analysis with AeroDyn coupled to OpenFAST when frozen wake is enabled (FrozenWake = True)

- The BeamDyn finite-element blade structural-dynamics model has undergone an extensive cleanup of the source code. A bug in an off-diagonal term in the structural damping-induced stiffness (i.e., representing a change in the damping force with beam displacement) has been corrected.

- A new module for user-specified platform loading (ExtPtfm) has been introduced. ExtPtfm allows the user to specify 6x6 added mass, damping, and stiffness matrices, as well as a 6x1 load vector to define loads to be applied to ElastoDyn’s tower base/platform, e.g., to support the modeling of substructures or foundations through a super-element representation (with super-element derived from external software). ExtPtfm also provides the user with a module to customize with more advanced platform applied loads. Module ExtPtfm can be enabled by setting CompSub to 2 in the FAST primary input file (a new option) and setting SubFile to the name of the file containing the platform matrices and load time history, but setting CompSub to 2 requires one to disable hydrodynamics (by setting CompHydro to 0). Please note that the introduction of option 2 for CompSub represents a minor input file change in OpenFAST v0.1.0, but the MATLAB conversion scripts have not yet been updated.

- In the ServoDyn control and electrical-system module, the units and sign of output parameter YawMom have been corrected

- In the InflowWind wind-inflow module, the ability to use TurbSim-generated tower wind data files in Bladed-style format was corrected

- Minor fixes were made to the error checking in ElastoDyn

v1.0.0 (September 2017)

- Organizational changes:
  - The FAST program has been renamed OpenFAST
  - Version numbering has been updated for OpenFAST (see Section 4.3.2 for details)
  - The OpenFAST regression test baseline solutions (formerly the Certification Tests or CertTest) reside in a standalone repository: https://github.com/openfast/r-test
  - Unit testing has been introduced at the subroutine level (starting with BeamDyn)
  - The online documentation (http://openfast.readthedocs.io/en/latest/index.html) has been extensively updated with additions for installation, testing, user (AeroDyn BeamDyn, transition from FAST v8, release notes), and developer guides, etc
  - The scripts for compiling OpenFAST using CMake on macOS, Linux, and Cygwin (Windows) systems have been updated, including the ability to compile in single precision and building with Spack
  - Visual Studio Projects (VS-Build) are provided for compiling OpenFAST on Windows
  - TurbSim has been included in the OpenFAST repository

- The AeroDyn aerodynamics module has been updated:
  - Added a cavitation check for marine hydrokinetic (MHK) turbines. This includes the additions of new input parameters CavitCheck, Patm, Pvap, and FluidDepth in the AeroDyn primary input file, the addition of the
Cpmin to the airfoil data files (required when CavitCheck = True), and new output channels for the minimum pressure coefficient, critical cavitation, and local cavitation numbers at the blade nodes. Please note that this input file changes represent the only input file change in OpenFAST v1.0.0, but the MATLAB conversion scripts have not yet been updated.

- Fixed a bug in the calculation of wind loads on the tower whereby the tower displacement was used in place of the tower velocity
- Tower strikes detected by the models to calculate the influence of the tower on the wind local to the blade are now treated as fatal errors instead of severe errors
- Fixed minor bugs in the unsteady airfoil aerodynamics model
- The BeamDyn finite-element blade structural-dynamics module has undergone additional changes:
  - The source-code has further undergone clean up, including changing the internal coordinate system to match IEC (with the local z axis along the pitch axis)
  - Trapezoidal points are now correctly defined by blade stations instead of key points
  - The tip rotation outputs were corrected as per GitHub issue #10 (https://github.com/OpenFAST/openfast/issues/10)
  - The BeamDyn driver has been fixed for cases involving spinning blades
- BeamDyn no longer produces numerical “spikes” in single precision, so, it is no longer necessary to compile OpenFAST in double precision when using BeamDyn
- The ElastoDyn structural-dynamics model was slightly updated:
  - The precision on some module-level outputs used as input to the BeamDyn module were increased from single to double to avoid numerical “spikes” when running BeamDyn in single precision
- Minor fixes were made to the error checking
- The ServoDyn control and electrical system module was slightly updated:
  - Fixed the values of the generator torque and electrical power sent from ServoDyn to Bladed-style DLL controllers as per GitHub issue # 40 (https://github.com/OpenFAST/openfast/issues/40)
  - Minor fixes were made to the error checking
- The OpenFAST driver/glue code has been updated:
  - Correction steps have been added to the OpenFAST driver during the first few time steps to address initialization problems with BeamDyn (even with NumCrctn = 0)
  - Fixed a bug in the Line2-to-Point mapping of loads as per GitHub issue #8 (https://github.com/OpenFAST/openfast/issues/8). Previously, the augmented mesh was being formed using an incorrect projection, thus causing strange transfer of loads in certain cases. This could cause issues in the coupling between ElastoDyn and AeroDyn and/or in the coupling between HydroDyn and SubDyn
  - Added an otherwise undocumented feature for writing binary output without compression to support the new regression testing. The new format is available by setting OutFileFmt to 0 in the FAST primary input file.
  - A new API has been added that provides a high level interface to run OpenFAST through a C++ driver code. The primary purpose of the C++ API is to help interface OpenFAST to external programs like CFD solvers that are typically written in C++.
  - The TurbSim wind-inflow turbulence preprocessor was updated:
    - The API spectra was corrected
    - Several minor bugs were fixed.
4.12.4 OpenFAST: Looking forward

Our goal is to continually improve OpenFAST documentation and to increase the coverage of automated unit and regression testing. In order to increase testing coverage and to maintain robust software, we will require that:

- new modules be equipped by the module developer(s) with sufficient module-specific unit and regression testing along with appropriate OpenFAST regression tests;
- bug fixes include appropriate unit tests;
- new features/capabilities include appropriate unit and regression tests. We are in the process of better instrumenting the BeamDyn module with extensive testing as a demonstration of requirements for new modules.

For unit testing, we will employ the pFUnit framework (https://sourceforge.net/projects/pfunit).

For the time being OpenFAST provides project and solution files to support users developing and compiling using Visual Studio. However, the team is continually working to automate the generation of Visual Studio build files via CMake in future releases.

Please contact Michael.A.Sprague@NREL.gov with questions regarding the OpenFAST development plan.

4.13 C++ API Users Guide

The C++ API provides a high level API to run OpenFAST through a C++ gluecode. The primary purpose of the C++ API is to help interface OpenFAST to external programs like CFD solvers that are typically written in C++. The installation of C++ API is enabled via CMake by turning on the BUILD_OPENFAST_CPP_API flag.

A sample glue-code FAST_Prog.cpp is provided as a demonstration of the usage of the C++ API. The glue-code allows for the simulation of multiple turbines using OpenFAST in parallel over multiple processors. The glue-code takes a single input file named cDriver.i (download).

```yaml
# -*- mode: yaml -*-
#
# C++ glue-code for OpenFAST - Example input file
#

#Total number of turbines in the simulation
nTurbinesGlob: 3
#Enable debug outputs if set to true
debug: False
#The simulation will not run if dryRun is set to true
dryRun: False
#Flag indicating whether the simulation starts from scratch or restart
simStart: init # init/trueRestart/restartDriverInitFAST
#Start time of the simulation
tStart: 0.0
#End time of the simulation. tEnd <= tMax
tEnd: 1.0
#Max time of the simulation
tMax: 4.0
#Time step for FAST. All turbines should have the same time step.
dtFAST: 0.00625
#Restart files will be written every so many time steps
nEveryCheckPoint: 160

Turbine0:
    #The position of the turbine base for actuator-line simulations
```

(continues on next page)
4.13.1 Command line invocation

mpiexec -np <N> openfastcpp

4.13.2 Common input file options

nTurbinesGlob
Total number of turbines in the simulation. The input file must contain a number of turbine specific sections
(Turbine0, Turbine1, ..., Turbine(n-1)) that is consistent with nTurbinesGlob.

debug
Enable debug outputs if set to true

dryRun
The simulation will not run if dryRun is set to true. However, the simulation will read the input files, allocate
turbines to processors and prepare to run the individual turbine instances. This flag is useful to test the setup of
the simulation before running it.

simStart
Flag indicating whether the simulation starts from scratch or restart. simStart takes on one of three values:

• init - Use this option when starting a simulation from t=0s.

• trueRestart - While OpenFAST allows for restart of a turbine simulation, external components like
  the Bladed style controller may not. Use this option when all components of the simulation are known to
  restart.
• restartDriverInitFAST - When the restartDriverInitFAST option is selected, the individual turbine models start from \(t=0\)s and run up to the specified restart time using the inflow data stored at the actuator nodes from a hdf5 file. The C++ API stores the inflow data at the actuator nodes in a hdf5 file at every OpenFAST time step and then reads it back when using this restart option. This restart option is especially useful when the glue code is a CFD solver.

\[t_{\text{Start}}\]
Start time of the simulation

\[t_{\text{End}}\]
End time of the simulation. \(t_{\text{End}} \leq t_{\text{Max}}\)

\[t_{\text{Max}}\]
Max time of the simulation

\[dt_{\text{FAST}}\]
Time step for FAST. All turbines should have the same time step.

\[n_{\text{EveryCheckPoint}}\]
Restart files will be written every so many time steps

### 4.13.3 Turbine specific input options

\[turbine\_base\_pos\]
The position of the turbine base for actuator-line simulations

\[num\_force\_pts\_blade\]
The number of actuator points along each blade for actuator-line simulations

\[num\_force\_pts\_tower\]
The number of actuator points along the tower for actuator-line simulations.

\[restart\_filename\]
The checkpoint file for this turbine when restarting a simulation

\[FAST\_input\_filename\]
The FAST input file for this turbine

\[turb\_id\]
A unique turbine id for each turbine
Our goal as developers of OpenFAST is to ensure that it is well tested, well documented, and self-sustaining software. To that end, we continually work to improve the documentation and test coverage along with feature additions and improvements. This section of the documentation outlines the processes and procedures we have established for external developers to work with the NREL OpenFAST team on code development.

If you'd like to help with general OpenFAST development or work on a particular feature, then first install OpenFAST following the installation instructions for your machine. Next, verify that your installation is valid by running the test suite following the testing instructions. While OpenFAST is compiling, we encourage reading through the Development Philosophy section to understand the general workflow for individual and coordinated development. Finally, be sure to review the GitHub workflow to avoid any merge or code conflicts.

With development happening in parallel between NREL, industry partners, and universities, NREL relies on GitHub to coordinate efforts:

- GitHub Issues is the place to ask usage or development questions, report bugs, and suggest code enhancements
- GitHub Pull Requests is the place for engaging with the OpenFAST team to have your new code merged into the main repository.

For other questions regarding OpenFAST, please contact Mike Sprague.

Tip: The following sections provide valuable guidance on workflow and development tips which make the process more efficient and effective:

- Working with OpenFAST on GitHub
- Code Style
- Debugging OpenFAST

5.1 API Reference

Some subroutines and derived types throughout the source code have in-source documentation which is compiled with Doxygen. Though this portion of the documentation is always under development, the existing API reference can be found in the following pages:

- Main Page
- Index of Types
- Source Files
5.2 Development Philosophy

OpenFAST is intended to be a self sustaining community developed software. A couple of tenets of this goal are that the code should be reasonably straightforward to comprehend and manageable to improve. With that in mind, we expect that new capabilities will include adequate testing and documentation.

We have the following guidance for developers:

- When fixing a bug, first introduce a unit test that exposes the bug, fix the bug, and submit a Pull Request. See Testing OpenFAST and Working with OpenFAST on GitHub for more information.

- When adding a new feature, create appropriate automated unit and regression tests as described in Testing OpenFAST. The objective is to create a GitHub pull request that provides adequate verification and validation so that the NREL OpenFAST developer team can merge the pull request with confidence that the new feature is “correct” and supports our goal of self-sustaining software. See Pull Requests for more information on submitting a pull request.

- If a code modification affects regression test results in an expected manner, work with the NREL OpenFAST developer team to upgrade the regression test suite via a GitHub issue or pull request at the openfast/r-test repository.

5.3 Development Guidelines

The following sections provide extended guidance on how to develop source code, interacting with the NREL OpenFAST team and other community contributors, and generally debugging and building out features.

5.3.1 Working with OpenFAST on GitHub

The majority of the collaboration and development for OpenFAST takes place on the GitHub repository. There, issues and pull requests are discussed and new versions are released. It is the best mechanism for engaging with the NREL OpenFAST team and other developers throughout the OpenFAST community.

Issues and work assignment

Issues should be opened with proper documentation and data to fully describe the problem or feature gap. It is here that communication and coordination should happen regarding ongoing work for new development, and developers should make clear any intention to complete a task.

Pull Requests

When a code modification is ready for review, a pull request should be submitted along with all appropriate documentation and tests. An NREL OpenFAST team member will assign a reviewer and work with the developer to have the code merged into the main repository.

New pull requests should contain the following:

- A description of the need for modifications
  - If the pull request fixes a bug, the accompanying GitHub issue should be referenced

- A summary of the work implemented

- Regression test results
- If all tests pass, the summary print out should be provided
- If any tests fail, an explanation of the failing cases and supporting data like plots should be included

- Updated unit tests, if applicable
- Updated documentation in applicable sections ready for compilation and deployment to readthedocs.

**Git workflow and interacting with the main repository**

OpenFAST development should follow “Git Flow” when interacting with the github repository. Git Flow is a well-defined and widely adopted workflow for using git that outlines safe methods of pushing and pulling commits to a shared repository. Maintaining Git Flow is critical to prevent remote changes from blocking your local development. This workflow is detailed nicely [here](http://nvie.com/posts/a-successful-git-branching-model) and the chart below provides a high level perspective.

**OpenFAST Specific Git Flow**

It is important to consider how your current work will be affected by other developer’s commits and how your commits will affect other developers. On public branches, avoid using `git rebase` and never `force push`.

In OpenFAST development, the typical workflow follows this procedure:

1. Fork the OpenFAST repository on GitHub
2. Clone your new fork

```bash
git clone https://github.com/<youruser>/OpenFAST
```

3. Add OpenFAST/OpenFAST as a remote named `upstream`

```bash
# This adds the remote
git remote add upstream https://github.com/OpenFAST/OpenFAST

# This downloads all the info in the remote, but it doesn't change
# the local source code

```bash
git fetch --all
```

4. Create a feature branch for active development starting from the OpenFAST `dev` branch and check it out

```bash

```bash
git branch feature/a_great_feature upstream/dev
```bash
git checkout feature/a_great_feature
```

5. Add new development on `feature/a_great_feature`

```bash

git add a_file.f90
```bash
git commit -m "A message"
```bash
```bash
git push origin feature/a_great_feature
```

6. Update your feature branch with `upstream`

```bash

git pull upstream dev
```bash
git push origin feature/a_great_feature
```

7. Open a new pull request to merge `<youruser>/OpenFAST/feature/a_great_feature` into `OpenFAST/OpenFAST/dev`

---

**5.3.2 Code Style**

OpenFAST and its underlying modules are mostly written in Fortran adhering to the 2003 standard, but modules can be written in C or C++. The *NWTC Programmer’s Handbook* is the definitive reference for all questions related to working with the FAST Framework and adding code to OpenFAST.

Generally, code should be written such that it is straightforward to read. Syntactic sugar or brevity should not detract from readability. The exception to this is in situations where performance requires poorly readable code. Here, comment blocks should be used to describe what is not readily apparent in the code. Indentation is typically three spaces and no tabs.
5.3.3 Developing Documentation

OpenFAST documentation is hosted on readthedocs. It is automatically generated through the readthedocs build system from both the master and dev branches whenever new commits are added. This documentation uses the restructured text markup language.

Building this documentation locally

The documentation is compiled with Sphinx, which is a Python based tool. Install it and the other required Python packages listed in openfast/docs/requirements.txt with pip or another Python package manager.

These additional packages are optional and are not included in the requirements file:

- Doxygen
- Doxylink
- Graphviz
- LaTeX

Doxygen and Graphviz can be installed directly from their website or with a package manager like brew, yum, or apt.

The result of building the documentation locally will be a set of HTML files and their accompanying required files. The main HTML file will exist openfast/build/docs/html/index.html. This file can be opened with any browser to view and navigate the locally-generated documentation as if it were any other web site.

Pure python build

If CMake and Make are not available on your system, the documentation can be generated directly with sphinx.

Note: This method does not generate the API documentation through Doxygen.

First, align your directory structure to the standard OpenFAST build by creating a directory at openfast/build. Then, move into openfast/build and run this command:

```
# sphinx-build -b <builder-name> <source-directory> <output-directory>
sphinx-build -b html ../docs ./docs/html
```

If this completes successfully, an html file will be created at build/docs/html/index.html which can be opened with any web browser.

Building with CMake and Make

In the OpenFAST directory, create a build directory and move into it. Then, run CMake with this flag: -DBUILD_DOCUMENTATION=ON. CMake will configure the build system with the necessary files for building the documentation.

Next, run the command to compile the docs:

```
make docs
```
This will first build the Doxygen API documentation and then the Sphinx documentation. If this completes successfully, a html file will be created at `build/docs/html/index.html` which can be opened with any web browser.

The full procedure for configuring and building the documentation is:

```
mkdir build
cd build
cmake .. -DBUILD_DOCUMENTATION=ON
make docs
```

If any modifications are made to the source files in `openfast/docs/source`, you can simply update the html files by executing the `make` command again.

The table below lists make-targets related to the documentation.

<table>
<thead>
<tr>
<th>Target</th>
<th>Command</th>
<th>Output location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full docs</td>
<td>make docs</td>
<td>openfast/build/docs/html/index.html</td>
</tr>
<tr>
<td>Full docs</td>
<td>make sphinx</td>
<td>openfast/build/docs/html/index.html</td>
</tr>
<tr>
<td>Doxygen API Reference</td>
<td>make doxygen</td>
<td></td>
</tr>
<tr>
<td>HTML only</td>
<td>make sphinx-html</td>
<td>openfast/build/docs/html/index.html</td>
</tr>
<tr>
<td>PDF only</td>
<td>make sphinx-pdf</td>
<td>openfast/build/docs/latex/Openfast.pdf</td>
</tr>
</tbody>
</table>

**Adding documentation**

Coming soon. Feel like contributing? Start here!

### 5.3.4 Types Files and the OpenFAST Registry

Being a modern software project, OpenFAST has a complex system of custom data types. In Fortran, these are known as “derived data types.” Each module contains a unique collection of derived types which may add on to but must comply with the OpenFAST Framework. The module types are generally auto-generated by an included program called OpenFAST Registry. The OpenFAST Registry is written in C and adapted from a similar utility used in WRF. Visit the OpenFAST Registry README for more information.

The OpenFAST Registry requires an input file to describe the necessary types for a given module. Generally, all module use a similar naming convention, `<Module>_Registry.txt`, and resulting Fortran code will be in a file called `<Module>_Types.f90`. For example, the AeroDyn OpenFAST Registry input file is located at `openfast/modules/aerodyn/src/AeroDyn_Registry.txt` and the resulting auto-generated Fortran source code is at `openfast/modules/aerodyn/src/AeroDyn_Types.f90`.

Since the types-modules are autogenerated, any changes to the data types directly should be expressed in the OpenFAST Registry input files so that the changes are not subsequently overwritten.

**Compiling the OpenFAST Registry**

The OpenFAST Registry is included in the OpenFAST build system through CMake. However, the default is to not compile the OpenFAST Registry executable and instead use the types modules that are included in git while compiling OpenFAST. To include the OpenFAST Registry in the build process and compile the Registry program, configure CMake with the `GENERATE_TYPES` flag:

```
cmake .. -DGENERATE_TYPES=ON
```
With `GENERATE_TYPES` enabled, CMake will configure the `openfast-registry` target to compile as a dependency of all other targets. The OpenFAST Registry executable will be found in `openfast/build/modules/openfast-registry/openfast-registry`.

**Regenerating a types module**

With the `GENERATE_TYPES` flag enabled, an additional step will be added to modules that are configured can make use of the OpenFAST Registry. The additional step will execute the OpenFAST Registry and regenerate the types module overwriting the existing modules. Any changes to the types module will be evident in `git`. For modules where the registry input file has not changed, the resulting types module will not change. However, for registry input files that have been modified, the output types module will be recompiled.

**Adding a new types module**

The process for adding a new types module follows *Regenerating a types module* closely. Here, an additional step is required to configure CMake to execute the Registry on the new input file and include the resulting types module in the compile step.

First, a new OpenFAST Registry input file must be created. Then, it must be configured to pass through the Registry in the corresponding module’s `CMakeLists.txt`:

```plaintext
# This is the control statement for allowing the Registry to execute
if (GENERATE_TYPES)
  # Here is the CMake wrapper-function to execute the Registry
  # syntax: generate_f90_types(<Registry input file> <output file location>)
  generate_f90_types(src/AeroDyn_Registry.txt ${CMAKE_CURRENT_LIST_DIR}/src/AeroDyn_ 
  Types.f90)
  generate_f90_types(src/New_Registry.txt ${CMAKE_CURRENT_LIST_DIR}/src/New_Types. 
  f90)
endif()
```

Finally, the resulting types module must be added to the source files for the corresponding module:

```plaintext
# AeroDyn lib
set(AD_LIBS SOURCES
  src/AeroDyn.f90
  src/AeroDyn_IO.f90
  src/AirfoilInfo.f90
  src/BEMT.f90
  src/DBEMT.f90
  src/BEMTUncoupled.f90
  src/UnsteadyAero.f90
  src/fmin_fcn.f90
  src/mod_root1dim.f90
  src/AeroDyn_Types.f90
  src/AirfoilInfo_Types.f90
  src/BEMT_Types.f90
  src/DBEMT_Types.f90
  src/UnsteadyAero_Types.f90

  # Add the new types module here
  src/New_Types.f90
)
```
With CMake properly configured, a message will display during the build process indicating that the OpenFAST Registry is executing:

```
[ 64%] Generating ../../../modules/aerodyn/src/New_Types.f90
----- FAST Registry -------------------
---------------------------------------
input file: /Users/rmudafor/Development/openfast/modules/aerodyn/src/New_Registry.txt
# more build process output will follow
```

And finally there should be an indication that the resulting types module is compiled:

```
Scanning dependencies of target aerodynlib
[ 70%] Building Fortran object modules/aerodyn/CMakeFiles/aerodynlib.dir/src/New_‐Types.f90.o
```

### 5.3.5 Debugging OpenFAST

Being a Fortran project, OpenFAST can be challenging to debug and the process is unique for each system and environment. Keep in mind that some OpenFAST cases can be quite large in their memory footprint and may take a long time to reach the point of interest in the code. Choosing a test case carefully could save a significant amount time.

It may by helpful to write a small fortran program to verify that all debugging tools are set up properly before diving in to OpenFAST. Be sure to simulate a bug by doing something like accessing an array element that is not allocated and verify that you can catch the bug with a given set of tools.

**Note:** A requirement for all systems is to compile OpenFAST in **debug** mode.

#### Debugging on Windows

Windows developers using Intel tools can use Visual Studio solution included in the OpenFAST repository for debugging. This is a straightforward process with lots of support from Intel.

Otherwise, Windows developers compiling in Unix-style environments should proceed to *Debugging on Linux and macOS*.

#### Debugging on Linux and macOS

First, compile OpenFAST in debug mode by setting `CMAKE_BUILD_TYPE` to “Debug”. This can be done on the command line with:

```
cmake .. -D CMAKE_BUILD_TYPE=Debug
```

or by using `ccmake` to open the command line `cmake gui` to change it.

The GNU debugger, `gdb`, works well for debugging compiled code. It has a comprehensive command line interface which enables developers to add breakpoints and inspect variables.

Driving the debugger through an IDE can make inspecting the code much more efficient. One IDE known to work well is Visual Studio Code with the Native Debug extension. You can set up a launch configuration so that you can debug a particular OpenFAST case through the IDE. To do this, open the launch configuration and add a block similar to this:
macOS-specific configuration

GDB on macOS needs some configuration before the system allows it to take over a process. It is recommended that `gdb` be installed with homebrew

```
brew info gdb
brew install gdb
```

After that completes, be sure to follow the caveats to finish the installation. For `gdb 8.2.1`, it looks like this:

```
== Caveats
  gdb requires special privileges to access Mach ports.
  You will need to codesign the binary. For instructions, see:
  https://sourceware.org/gdb/wiki/BuildingOnDarwin

  On 10.12 (Sierra) or later with SIP, you need to run this:
  echo "set startup-with-shell off" >> ~/.gdbinit
```

For Native Debug on macOS, you have to sort of hack the extension to allow breakpoints in fortran files by adding this line to `.vscode/settings.json`:

```
{
  "debug.allowBreakpointsEverywhere": true
}
```

5.3.6 Performance-Profiling and Optimization

The OpenFAST team has been engaged in performance-profiling and optimization work in an effort to improve the time-to-solution performance for the most computationally expensive use cases. This work is supported by Intel® through its designation of NREL as an Intel® Parallel Computing Center (IPCC).

After initial profiling and hotspot analysis, specific subroutines in the physics modules of OpenFAST were targeted for optimization. Among other takeaways, it was learned that the memory alignment of the derived data types could yield a significant increase in performance. Ultimately, tuning the Intel® tools to perform best on NREL’s hardware and adding high level multithreading yielded a maximum 3.8x time-to-solution improvement for one of the benchmark cases.
Approach

The general mechanisms identified for performance improvements in OpenFAST are:

- Intel® compiler suite and Intel® Math Kernel Library (Intel® MKL)
- Algorithmic improvements
- Memory-access optimization enabling more efficient cache usage
- Data type alignment allowing for SIMD vectorization
- Multithreading with OpenMP

To establish a path forward with any of these options, OpenFAST was first profiled with Intel® VTune™ Amplifier which provides a clear breakdown of time spent in the simulation. Then, the optimization report generated from the Intel® Fortran compiler was analyzed to determine area which were not autovectorized. Finally, Intel® Advisor was used to highlight areas of the code which the compiler identified as potentially improved with multithreading.

Test cases

Two OpenFAST test cases have been chosen to provide meaningful and realistic timing benchmarks. In addition to real-world turbine and atmospheric models, these cases are computationally expensive and expose the areas where performance improvements would make a difference.

5MW_Land_BD_DLL_WTurb

Download files here.

The physics modules used in this case are:

- BeamDyn
- InflowWind
- AeroDyn 15
- ServoDyn

This is a land based NREL 5-MW turbine simulation using BeamDyn as the structural module. It simulates 20 seconds with a time step size of 0.001 seconds and executes in 3m 55s on NREL’s Peregrine supercomputer.

5MW_OC4Jckt_DLL_WTurb_WavesIrr_MGrowth

Download files here.

This is an offshore, fixed-bottom NREL 5-MW turbine simulation with the majority of the computational expense occurring in the HydroDyn wave-dynamics calculation.

The physics modules used in this case are:

- ElastoDyn
- InflowWind
- AeroDyn 15
- ServoDyn
- HydroDyn
- SubDyn

It simulates 60 seconds with a time step size of 0.01 seconds and executes in 20m 27s on NREL’s Peregrine supercomputer.

**Profiling**

The OpenFAST test cases were profiled with Intel® VTune™ Amplifier to identify performance hotspots. Being that the two test cases exercise difference portions of the OpenFAST software, different hotspots were identified. In all cases and environment settings, the majority of the CPU time was spent in `fast_solution` loop which is a high-level subroutine that coordinates the solution calculation from each physics module.

**LAPACK**

In the offshore case, the LAPACK usage was identified as a performance load. Within the `fast_solution` loop, the calls to the LAPACK function `dgetrs` consume 3.3% of the total CPU time.

**BeamDyn**

While BeamDyn provides a high-fidelity blade-response calculation, it is a computationally expensive module. Initial profiling highlighted the `bd_elementmatrixga2` subroutine, in particular, as a hotspot. However, initial attempts to improve performance in BeamDyn highlighted needs for algorithmic improvements and refinements to the module’s data structures.

5.3. Development Guidelines
Results

Though work is ongoing, OpenFAST time-to-solution performance has improved and the performance potential is better understood.

Some keys outcomes from the first year of the IPCC project are as follows:

- Use of Intel® compiler and MKL library provides dramatic speedup over GCC and LAPACK
  - Additional significant gains are possible through MKL threading for offshore simulations
- Offshore-wind-turbine simulations are poorly load balanced across modules
  - Land-based-turbine configuration better balanced
  - OpenMP Tasks are employed to achieve better load-balancing
- OpenMP module-level parallelism provides significant, but limited speed up due to imbalance across different module tasks
- Core algorithms need significant modification to enable OpenMP and SIMD benefits

Speedup - Intel® Compiler and MKL

By employing the standard Intel® developer tools tech stack, a performance improvement over GNU tools was demonstrated:

<table>
<thead>
<tr>
<th>Compiler</th>
<th>Math Library</th>
<th>5MW_Land_BD_DLL_WTurb</th>
<th>5MW_OC4Jckt_DLL_WTurb_WavesIrr_MGrowth</th>
</tr>
</thead>
<tbody>
<tr>
<td>GNU</td>
<td>LAPACK</td>
<td>2265 s (1.0x)</td>
<td>673 s (1.0x)</td>
</tr>
<tr>
<td>Intel® 17</td>
<td>LAPACK</td>
<td>1650 s (1.4x)</td>
<td>251 s (2.7x)</td>
</tr>
<tr>
<td>Intel® 17</td>
<td>MKL</td>
<td>1235 s (1.8x)</td>
<td>—</td>
</tr>
<tr>
<td>Intel® 17</td>
<td>MKL Multithreaded</td>
<td>722 s (3.1x)</td>
<td>—</td>
</tr>
</tbody>
</table>

Speedup - OpenMP at FAST_Solver

A performance improvement was demonstrated by adding OpenMP directives to the FAST_Solver module. Although the solution scheme is not well balanced, parallelizing mesh mapping and calculation routines resulted in the following speedup:

<table>
<thead>
<tr>
<th>Compiler</th>
<th>Math Library</th>
<th>5MW_Land_BD_DLL_WTurb</th>
<th>5MW_OC4Jckt_DLL_WTurb_WavesIrr_MGrowth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intel® 17</td>
<td>MKL - 1 thread</td>
<td>1073 s (2.1x)</td>
<td>100 s (6.7x)</td>
</tr>
<tr>
<td>Intel® 17</td>
<td>MKL - 8 threads</td>
<td>597 s (3.8x)</td>
<td>—</td>
</tr>
</tbody>
</table>
Ongoing Work

The next phase of the OpenFAST performance improvements are focused in two key areas:

1. Implementing the outcomes from previous work throughout OpenFAST modules and glue codes
2. Preparing OpenFAST for efficient execution on Intel®’s next generation platforms

5.3.7 Versioning

OpenFAST follows semantic versioning. In summary, this means that with a version number as MAJOR.MINOR.PATCH, the components will be incremented as follows:

- MAJOR version when introducing incompatible API changes,
- MINOR version when adding functionality in a backwards-compatible manner, and
- PATCH version when making backwards-compatible bug fixes.

For example, OpenFAST-v1.0.0-123-gabcd1234-dirty describes OpenFAST as:

<table>
<thead>
<tr>
<th>Version Component</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>v1.0.0</td>
<td>MAJOR.MINOR.PATCH numbering system; corresponds to a tagged commit made by NREL on GitHub</td>
</tr>
<tr>
<td>123-g</td>
<td>Number of additional commits after the most recent tag for a build (the -g is for git)</td>
</tr>
<tr>
<td>abcd1234</td>
<td>First 8 characters of the current commit hash</td>
</tr>
<tr>
<td>dirty</td>
<td>Denotes that local changes have been made but not committed; omitted if there are no local changes</td>
</tr>
</tbody>
</table>

5.4 Other Documentation

Additional documentation exists that may be useful for developers seeking deeper understanding of the solver and mathematics. This documentation is not generally necessary for most development efforts.

5.4.1 Other documentation

Additional documentation exists that may be useful for developers seeking deeper understanding of the solver and mathematics. This documentation is not generally necessary for most development efforts.

- **DCM_Interpolation.pdf** This is a summary of the mathematics used in the interpolation of DCM (direction cosine matrices) using logarithmic mapping and matrix exponentials.
- **OpenFAST_Algorithms.pdf** This is a summary of the solve method used in the glue code.
- **OutListParameters.xls** This Excel file contains the full list of outputs for each module. It is used to generate the Fortran code for the output channel list handling for each module (this code is generally in the _IO.f90 files). The MATLAB script available in the matlab-toolbox repository at Utilities/GetOutListParameters.m.
LICENSING

The OpenFAST software, including its underlying modules, are licensed under Apache License Version 2.0 open-source license.
GETTING HELP

For possible bugs, enhancement requests, or code questions, please submit an issue at the OpenFAST Github repository.

For OpenFAST usage questions, users should consider the FAST Forum, which provides a large 10+ year legacy of FAST-related Q&A; the forum’s search functionality should be used before posting questions to either github issues or the forum.

Users may find the established FAST v8 through the NWTC Information Portal: https://nwtc.nrel.gov/

Please contact Michael.A.Sprague@NREL.gov with questions regarding the OpenFAST development plan or how to contribute.
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      input file parameter, 243
    num_force_pts_tower
      input file parameter, 243

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    input file parameter, 242
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  turbine_base_pos
    input file parameter, 243