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1 Nomenclature

\( \alpha_s \)  Rotational structural acceleration, 3x1 vector
\( \Delta t_{RD} \)  Time step for the radiation memory effect calculations
\( \zeta \)  Wave elevation time history
\( \pi \)  Mathematical constant, pi
\( \omega \)  frequency (rad/s)
\( \omega_s \)  Rotational structural velocities, 3x1 vector, currently not used
\( \rho_f \)  Density of the flooding/ballast fluid
\( \rho_{MG} \)  Density of marine growth
\( \rho_W \)  Water density
\( \ddot{a}_f \)  Linear acceleration of the fluid, 3x1 vector
\( \ddot{a}_s \)  Linear acceleration of the structure, 3x1 vector
\( A \)  Area of super member
\( AM \)  Added-mass, 6x6 matrix
\( AM_p \)  Added-mass due to flooding, 6x6 matrix
\( AM_M \)  Added-mass due to Morison’s equations, 6x6 matrix
\( AM_{MG} \)  Added-mass due to marine growth, 6x6 matrix
\( AM_{RP} \)  Added-mass due to radiation problem applied to the WAMIT reference point, 6x6 matrix
\( [B] \)  Additional damping matrix, 6x6
\( [B_{quad}] \)  Additional quadratic drag matrix, 6x6
\( [C] \)  Member direction cosine 3x3 matrix, transforming local coordinates to global coordinates
\( [C] \)  Additional stiffness matrix, 6x6
\( C_A \)  Added-mass coefficient
\( C_{A_{ax}} \)  Axial added-mass coefficient
\( C_D \)  Transverse viscous-drag coefficient
\( C_{D_{ax}} \)  Axial viscous-drag coefficient
\( C_P \)  Transverse dynamic pressure coefficient
\( C_{P_{ax}} \)  Axial dynamic pressure coefficient
\( d \)  Water depth, unsigned magnitude
\( \bar{F}_0 \)  Additional preload, 3x1 vector
\( \bar{F}_{AM} \)  Total added mass forces from all contributing effects
\( \bar{F}_{AM,F} \)  Added mass forces due to filled/ballasted fluid
\( \bar{F}_{AM,M} \)  Added mass forces due to
\( \bar{F}_{AM,MG} \)  Added mass forces due to marine growth
\( \vec{F}_{ij} \)  \( F_{ADD} \)  \( \vec{F}_B \)  \( \vec{F}_D \)  \( \vec{F}_{FB} \)  \( \vec{F}_{HS} \)  \( \vec{F}_I \)  \( \vec{F}_{MG} \)  \( \vec{F}_{RD} \)  \( \vec{F}_W \)  \( \vec{F}_{i}^{\text{glib}} \)

Total forces and moments applied to node j, 6x1 vector
Total loads due to preload, additional stiffness, and additional damping terms, 6x1 vector
Buoyancy forces and moments applied to node, 6x1 vector
Drag forces and moments applied to node, 6x1 vector
Buoyancy forces and moments due to flooding applied to node, 6x1 vector
Hydrostatic forces applied to the platform reference node, 6x1 vector
Inertial forces and moments applied to node, 6x1 vector
Marine growth-related forces and moments applied to node, 6x1 vector
Radiation memory-effect force applied to platform reference point, 6x1 vector
Incident-wave excitation force applied to platform reference point, 6x1 vector
Point buoyancy forces at the end cap of the ith member which connects to the super member
Incident-wave excitation force applied to platform reference point, 6x1 vector
Total loads at the WAMIT reference point from potential flow theory, 6x1 vector

\( g \)  \( h_{\text{ref}} \)  \( i \)  \( \hat{i} \)  \( \hat{I} \)  \( j \)  \( \hat{j} \)  \( \hat{J} \)  \( \hat{k} \)  \( K \)  \( \hat{K} \)  \( kg \)  \( L_m \)  \( L_{i} \)  \( m \)  \( M \)  \( n \)  \( n^\text{th} \)  \( \hat{n}_i \)  \( N \)  \( P_{dyn} \)  \( R \)  \( R_m \)  \( R_{i} \)

Gravity, unsigned magnitude
Reference depth for the near-surface current model
member or element index
Unit vector along the local x-axis
Unit vector along the global X-axis
node index, imaginary number constant
Unit vector along the local y-axis
Unit vector along the global Y-axis
Unit vector along the local z-axis
Radiation kernel from potential flow theory, 6x6 matrix
Unit vector along the global Z-axis
Kilograms
Length of master cylinder of a super member
Length of the ith slave cylinder of a super member
Meters
Number of members connected to a given joint
the nth time step
Outward facing normal for member the ith member. Parallel to the local \( \hat{k} \) axis
Newtons
Fluid dynamic pressure
Outer radius of structural member
Outer radius of the super member’s master cylinder
Outer radius of the ith slave cylinder which is part of a super member
s  seconds

\( t \)  time

\( t_M \)  Thickness of structural member

\( t_{Me} \)  Thickness of structural member at element end

\( t_{MGa} \)  Marine-growth thickness on the master cylinder

\( t_{MGi} \)  Marine-growth thickness on ith slave cylinder of a super member

\( t_{Ms} \)  Thickness of structural member at element start

\( t_{MG} \)  Marine-growth thickness

\( U_{0NS} \)  Reference current velocity for the near-surface current model

\( U_{0SS} \)  Reference current velocity for the sub-surface current model

\( U_{NS} \)  Current velocity at depth, \( Z \), for the near-surface current model

\( U_{SS} \)  Current velocity at depth, \( Z \), for the sub-surface current model

\( \vec{v}_f \)  Linear velocity of the fluid, 3x1 vector

\( \vec{v}_{ref} \)  Relative velocity, \( \vec{v}_{ref} = \vec{v}_f - \vec{v}_s \) 3x1 vector

\( \vec{v}_S \)  Translational structural velocities, 3x1 vector

\( V \)  Volume of member (super member)

\( V_i^c \)  Volume of ith cylinder which is a part of the super member

\( V_i \)  Interior cavity volume of member (super member)

\( V_{MG} \)  added volume due to marine growth

\[ \begin{bmatrix} x \\ y \\ z \end{bmatrix} \]  Position in the local, member coordinate system

\[ \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \]  Position in the global, inertial coordinate system

\( x_n^d \)  Discrete states of the radiation solution

\( XD_H \)  Radiation damping history
2 Introduction

HydroDyn is a time-domain hydrodynamics module that has been coupled into the FAST wind turbine computer-aided engineering (CAE) tool to enable aero-hydro-servo-elastic simulation of offshore wind turbines. HydroDyn is applicable to both fixed-bottom and floating offshore substructures. This latest release of HydroDyn follows the requirements of the FAST modularization framework and couples to **FAST version 8**. HydroDyn can also be driven as a standalone code to compute hydrodynamic loading uncoupled from FAST.

HydroDyn allows for multiple approaches for calculating the hydrodynamic loads on a structure: a potential-flow theory solution, a strip-theory solution, or a combination of the two. Waves in HydroDyn can be regular (periodic) or irregular (stochastic) and long-crested (unidirectional) or short-crested (with wave energy spread across a range of directions). HydroDyn treats waves using first-order (linear Airy) or first- plus second-order wave theory [Sharma and Dean, 1981] with the option to include directional spreading, but no wave stretching or higher order wave theories are included. The second-order hydrodynamic implementations are new in this release and include time-domain calculations of difference- (mean- and slow-drift-) and sum-frequency terms. To minimize computational expense, Fast Fourier Transforms (FFTs) are applied in the summation of all wave frequency components.

The potential-flow solution is applicable to substructures or members of substructures that are large relative to a typical wavelength. Potential-flow hydrodynamic loads include linear hydrostatic restoring, the added mass and damping contributions from linear wave radiation (including free-surface memory effects), and the incident-wave excitation from first- and second-order diffraction. The hydrodynamic coefficients (first and second order) required for the potential-flow solution are frequency dependent and must be supplied by a separate frequency-domain panel code (e.g., WAMIT) from a pre-computation step. The radiation memory effect can be calculated either through direct time-domain convolution or through a linear state-space approach, with a state-space model derived through the **SS_Fitting** preprocessor. The second-order terms can be derived from the full difference- and sum-frequency quadratic transfer functions (QTFs) or the difference-frequency terms can be estimated via Standing et al.’s extension to Newman’s approximation, based only on first-order coefficients.

The strip-theory solution may be preferable for substructures or members of substructures that are small in diameter relative to a typical wavelength. Strip-theory hydrodynamic loads can be applied across multiple interconnected members, each with possible incline and taper, and are derived directly from the undisturbed wave and current kinematics at the undisplaced position of the substructure. The undisturbed first- and second-order wave kinematics are implemented analytically for finite depth. The strip-theory loads include the relative form of Morison’s equation for the distributed fluid-inertia, added-mass, and viscous-drag components. Additional distributed load components include axial loads from tapered members and static buoyancy loads. Hydrodynamic loads are also applied as lumped loads on member endpoints (called joints). It is also possible to include flooding or ballasting of members, and the effects of marine growth. The hydrodynamic coefficients required for this solution come through user-specified dynamic-pressure, added-mass, and viscous-drag coefficients.
For some substructures and sea conditions, the hydrodynamic loads from a potential-flow theory must be augmented with the loads brought about by flow separation. For this, the viscous-drag component of the strip-theory solution may be included with the potential-flow theory solution. Another option available is to supply a global damping matrix (linear or quadratic) to the system to represent this effect.

When HydroDyn is coupled to FAST, HydroDyn receives the position, orientation, velocities, and accelerations of the (rigid or flexible) substructure at each coupling time step and then computes the hydrodynamic loads and returns them back to FAST. At this time, FAST’s ElastoDyn structural-dynamics module assumes for a floating platform that the substructure (floating platform) is a six degree-of-freedom (DOF) rigid body. For fixed-bottom offshore wind turbines, FAST’s SubDyn module allows for structural flexibility of multi-member substructures and the coupling to HydroDyn includes hydro-elastic effects.

The primary HydroDyn input file defines the substructure geometry, hydrodynamic coefficients, incident wave kinematics and current, potential-flow solution options, flooding/ballasting and marine growth, and auxiliary parameters. The geometry of strip-theory members is defined by joint coordinates of the undisplaced substructure in the global reference system, with the origin at the intersection of the undeflected tower centerline with mean sea level (MSL). A member connects two joints; multiple members can use a common joint. The hydrodynamic loads are computed at nodes, which are the resultant of member refinement into multiple \( MDivSize \) input elements (nodes are located at the ends of each element), and they are calculated by the module. Member properties include outer diameter, thickness, and dynamic-pressure, added-mass and viscous-drag coefficients. 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.

Section 3 details how to obtain the HydroDyn and FAST software archives and how to run both the stand-alone HydroDyn or HydroDyn coupled to FAST. Section 4 describes the HydroDyn input files. Section 5 discusses the output files generated by HydroDyn; these include echo files, wave-elevation outputs, a summary file, and the results file. Section 6 provides modeling guidance when using HydroDyn. The HydroDyn theory is covered in Section 7. Section 8 outlines future work, and Section 9 contains a list of references. Example input files are shown in Appendix A and B. A summary of available output channels are found in Appendix C. Instructions for compiling the stand-alone HydroDyn program are detailed in Appendix D. Appendix E tracks the major changes we have made to HydroDyn for each public release.
3 Running HydroDyn

3.1 Downloading the HydroDyn Software

3.1.1 Stand-alone HydroDyn Archive

You can download the stand-alone HydroDyn archive from our web server at http://wind.nrel.gov/designcodes/simulators/hydrodyn. The file has a name similar to HD_v2.01.00.exe, but may have a different version number. Run the downloaded self-extracting archive (.exe) to expand the archive into a folder you specify.

The archive contains the bin, CertTest, Compiling, Documentation, and Source folders. The bin folder includes the HydroDynDriver_win32.exe, which is used to execute the stand-alone HydroDyn program. The CertTest folder contains a collection of sample HydroDyn input files. If you run the CertTest.bat DOS script, you can compare your results to the ones stored in the NREL_Results subfolder. This manual may be found in the Documentation folder. The Compiling folder contains files for compiling the stand-alone HydroDynDriver_win32.exe with either Visual Studio or gFortran. However, at this time, the software is not functional when compiled with gFortran. The Fortran source code is located in the Source folder.

3.1.2 FAST Archive

You can download the FAST archive, which includes a coupling to HydroDyn, from our web server at http://wind.nrel.gov/designcodes/simulators/fast8/. The file has a name similar to FAST_v8.08.00.exe, but may have a different version number. Run the downloaded self-extracting archive (.exe) to expand the archive into a folder you specify. The FAST executable is located in the archive’s bin folder. Example models using the NREL 5-MW reference turbine and various substructures are located in the CertTest folder. These include Test19: OC3-Monopile, Test20: OC3-Tripod, Test21: OC4-jacket, Test22: ITI Energy barge, Test23: MIT/NREL tension-leg platform (TLP), Test24: OC3-Hywind spar buoy, and Test25: OC4-DeepCwind semi-submersible.

3.2 Running the Stand-alone HydroDyn

The stand-alone HydroDyn program, HydroDynDriver_win32.exe, simulates hydrodynamic responses of your 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 HydroDyn input file. This driver file specifies initialization inputs normally provided to HydroDyn by FAST, as
well as the per-time-step inputs to HydroDyn. Both the HydroDyn summary file and the results output file are available when using the stand-alone HydroDyn, see Section 5 for more information regarding the HydroDyn output files.

Run the standalone HydroDyn software from a DOS command prompt by typing, e.g.

```bash
>HydroDynDriver_win32.exe  MyDriverFile.dvr
```

where, *MyDriverFile.dvr* is the name of the HydroDyn driver file, as described in Section 4.2. The HydroDyn primary input file is described in Section 4.3.

### 3.3 Running HydroDyn Coupled to FAST

Run the coupled FAST software from a DOS command prompt by typing, e.g.

```bash
>FAST_win32.exe  Test22.fst
```

where, *Test22.fst* is the name of the primary FAST input file. This input file has a control flag to turn on or off the HydroDyn capabilities within FAST, and a corresponding reference to the HydroDyn input file. See the documentation supplied with FAST for further information.
4 Input Files

The user configures the hydrodynamic model parameters as well as the substructure geometry and properties via a primary HydroDyn input file. When used in stand-alone mode, an additional driver input file is required. This driver file specifies initialization inputs normally provided to HydroDyn by FAST, as well as the per-time-step inputs to HydroDyn.

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

4.1 Units

HydroDyn uses the SI system (kg, m, s, N).

4.2 HydroDyn Driver Input File

The driver input file is only needed for the stand-alone version of HydroDyn and contains inputs normally generated by FAST, and are necessary to control the hydrodynamic simulation for uncoupled models. A sample HydroDyn driver input file is given in Appendix B.

Set the Echo flag in this file to TRUE if you wish to have HydroDynDriver.exe echo 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 HYDRODYN section of the driver input file. Set the gravity constant using the Gravity parameter. HydroDyn expects a magnitude, so in SI units this would be set to 9.80665 m/s². HDInputFile is the filename of the primary HydroDyn input file. This name should be in quotations and can contain an absolute path or a relative path. All HydroDyn-generated output files will be prefixed with OutRootName. If this parameter includes a filepath, the output will be generated in that folder. NSteps specifies the number of simulation time steps, and TimeInterval specifies the time between steps.

Setting WAMITInputsMod = 0 forces all WAMIT reference point (WRP) input motions to zero for all time. If you set WAMITInputsMod = 1, then you must set the steady-state inputs in the WAMIT STEADY STATE INPUTS section of the file. Setting WAMITInputsMod = 2, requires the time-series input file whose name is specified via the WAMITInputsFile parameter. The WAMIT inputs file is a text-formatted file. This file has no header lines. Each data row corresponds to a given time step, and the whitespace separated columns of floating point values represent the necessary motion inputs as shown in Table 1. All motions are specified in the global inertial-frame coordinate system.

<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>Translational displacements along X, Y, and Z</td>
<td>m</td>
</tr>
<tr>
<td>5-7</td>
<td>Rotational displacements about X, Y, and Z (small angle)</td>
<td>radians</td>
</tr>
<tr>
<td>8-10</td>
<td>Translational velocities along X, Y, and Z</td>
<td>( \frac{m}{s} )</td>
</tr>
<tr>
<td>11-13</td>
<td>Rotational velocities about X, Y, and Z</td>
<td>radians ( \frac{\text{rad}}{s} )</td>
</tr>
<tr>
<td>14-16</td>
<td>Translational accelerations along X, Y, and Z</td>
<td>( \frac{m}{s^2} )</td>
</tr>
<tr>
<td>17-19</td>
<td>Rotational accelerations about X, Y, and Z</td>
<td>radians ( \frac{\text{rad}}{s^2} )</td>
</tr>
</tbody>
</table>

In a similar fashion, the input motions for the Morison members (strip-theory model) are set to zero if \( \text{MorisonInputsMod} = 0 \). If you select \( \text{MorisonInputsMod} = 1 \) then the motions at each substructure joint are set to the steady-state values given in the MORISON STEADY STATE INPUTS section. Currently, option 2 is unavailable for the Morison inputs.

The stand-alone HydroDyn does not check for physical consistency between motions specified for the WRP and Morison members in the driver file.

Setting \( \text{WaveElevSeriesFlag} \) to TRUE enables the outputting of a grid of wave elevations to a text-based file with the name \( \text{OutRootName}.\text{WaveElev}.out \). The grid consists of \( \text{WaveElevNX} \) by \( \text{WaveElevNY} \) wave elevations (centered at \( X = 0, Y = 0 \)) with a \( dX \) and \( dY \) spacing in the global inertial-frame coordinate system. These wave elevations are distinct and output separately from the wave elevations determined by \( N\text{WaveElev} \) in the HydroDyn primary input file, such that the total number of wave elevation outputs is \( N\text{WaveElev} + (\text{WaveElevNX} \times \text{WaveElevNY}) \). The wave-elevation output file \( \text{OutRootName}.\text{WaveElev}.out \) contains the total wave elevation, which is the sum of the first- and second-order terms (when the second-order wave kinematics are optionally enabled).

### 4.3 HydroDyn Primary Input File

The HydroDyn input file defines the substructure geometry, hydrodynamic coefficients, incident wave kinematics and current, potential-flow solution options, flooding/ballasting and marine growth, and auxiliary parameters. The geometry of strip-theory members is defined by joint coordinates of the undisplaced substructure in the global reference system, with the origin at the intersection of the undeflected tower centerline with MSL. A member connects two joints; multiple members can use a common joint. The hydrodynamic loads are computed at nodes, which are the resultant of member refinement into multiple (\( M\text{DivSize} \) input) elements (nodes are located at the ends of each element), and they are calculated by the module. Member properties include outer diameter, thickness, and dynamic-pressure, added-mass and viscous-drag coefficients. 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.

The file is organized into several functional sections. Each section corresponds to an aspect of the hydrodynamics model or the submerged substructure.
If this manual refers to an ID in a table entry, this is an integer identifier for the table entry, and these IDs do not need to be consecutive or increasing, but they must be unique for a given table entry.

A sample HydroDyn primary input file is given in Appendix A.

The input file begins with two lines of header information which is for your use, but is not used by the software. On the next line, set the Echo flag to TRUE if you wish to have HydroDyn echo the contents of the HydroDyn input file (useful for debugging errors in the input file). The echo file has the naming convention of OutRootName.HD.ech. OutRootName is either specified in the HYDRODYN section of the driver input file when running HydroDyn standalone, or by FAST when running a coupled simulation.

4.3.1 Environmental Conditions

WtrDens specifies the water density and must be a value greater than or equal to zero; a typical value of seawater is around 1025 kg/m³. WtrDpth specifies the water depth (depth of the seabed), based on the reference MSL, and must be a value greater than zero. MSL2SWL is the offset between the MSL and the still water level (SWL), positive upward. This parameter is useful when simulating the effect of tides or storm-surge sea-level variations without having to alter the substructure geometry information. This parameter must be set to zero if you are using a WAMIT model (HasWAMIT = TRUE).

4.3.2 Waves

The WAVES section of the input file pertains to the first-order (linear Airy) wave theory, used by both the strip-theory and potential-flow solutions. The wave spectrum settings in this section only pertain to the first-order wave frequency components. When second-order terms are optionally enabled—see the 2ND-ORDER WAVES and 2ND-ORDER FLOATING PLATFORM FORCES sections below—the second-order terms are calculated using the first-order wave-component amplitudes and extra energy is added to the wave spectrum (at the difference and sum frequencies).

WaveMod specifies the incident wave kinematics model. The options are:

- 0: none = still water
- 1: regular (periodic) waves
- 1P#: regular (periodic) waves with user-specified phase, for example 1P20.0 for regular waves with a 20° phase (without P#, the phase will be random, based on WaveSeed; 0° phase represents a cosine function, starting at the peak and decreasing in time
- 2: Irregular (stochastic) waves based on the JONSWAP or Pierson-Moskowitz frequency spectrum
- 3: Irregular (stochastic) waves based on a white-noise frequency spectrum
- 4: Irregular (stochastic) waves based on a user-defined frequency spectrum from routine UserWaveSpectrm(); see Appendix D for compiling instructions
- 5: GH Bladed wave data (option has been disabled for this release)
Option 4 requires that the *UserWaveSpectrum()* subroutine of the *Waves.f90* source file be implemented by the user, and will require recompiling either the stand-alone HydroDyn program or FAST. Option 5 requires the availability of several input files, all of which have the root name given by the *GHWvFile* parameter, but the option has been disabled for this release.

This version does not include the ability to model stretching incident wave kinematics to the instantaneous free surface; you must set *WaveStMod* = 0.

*WaveTMax* sets the length of the incident wave kinematics time series, but it also determines the frequency step used in the inverse Fourier transform, from which the time series are derived ($\Delta \omega = 2\pi/WaveTMax$). If *WaveTMax* is less than the total simulation time, HydroDyn implements repeating wave kinematics that have a period of *WaveTMax*. *WaveDT* determines the time step for the wave kinematics time series, but it also determines the maximum frequency in the inverse Fourier transform ($\omega_{max} = \pi/WaveDT$). When modeling irregular sea states, we recommend that *WaveTMax* be set to at least 1 hour (3600 s) and that *WaveDT* be a value in the range between 0.1 and 1.0 s to ensure sufficient resolution of the wave spectrum and wave kinematics. When HydroDyn is coupled to FAST, *WaveDT* may be specified arbitrarily independently from the glue code time step of FAST. (The wave kinematics and hydrodynamic loads will be interpolated in time as necessary.)

The wave height (crest-to-trough, twice the amplitude) for regular waves and the significant wave height for irregular waves is set using *WaveHs*. The wave period for regular waves and the peak-spectral wave period for irregular waves is controlled with the *WaveTp* parameter.

*WavePkShp* is the peak-shape parameter of JONSWAP irregular wave spectrum. Set *WavePkShp* to DEFAULT to obtain the value recommended in the IEC 61400-3 Annex B, derived based on the peak-spectral period and significant wave height [IEC, 2009]. Set *WavePkShp* to 1.0 for the Pierson-Moskowitz spectrum.

*WvLowCOff* and *WvHiCOff* control the lower and upper cut-off frequencies (in rad/s) of the first-order wave spectrum; the first-order wave-component amplitudes are zeroed below and above these cut-off frequencies, respectively. *WvLowCOff* may be set lower than the low-energy limit of the first-order wave spectrum to minimize computational expense. Setting a proper upper cut-off frequency (*WvHiCOff*) also minimizes computational expense and is important to prevent nonphysical effects when approaching the breaking-wave limit and to avoid nonphysical wave forces at high frequencies (i.e., at short wavelengths) when using a strip-theory solution.

*WaveDir* is the mean wave propagation heading direction (in degrees), and must be in the range (-180,180]. A heading of 0 corresponds to wave propagation in the positive X-axis direction. A heading of 90 corresponds to wave propagation in the positive Y-axis direction.

*WaveDirMod* specifies the wave directional spreading model. Setting *WaveDirMod* to 0 disables directional spreading, resulting in long-crested sea states propagating in the *WaveDir* direction. Setting *WaveDirMod* to 1 enables the modeling of short-crested sea states, with a mean propagation direction of *WaveDir*, through the commonly used cosine spreading function ($\cos^2(S)$) to define the directional spreading spectrum, based on the spreading coefficient ($S$) defined via *WaveDirSpread*. The wave directional spreading spectrum is discretized with an equal-energy method using *WaveNDir* number of equal-energy bins. *WaveNDir* is an odd-
valued integer greater or equal to 1 (1 or 3 or 5…), but HydroDyn may slightly increase the
specified value of WaveNDir to ensure that there is the same number of wave components within
each direction bin; setting WaveNDir = 1 is equivalent to setting WaveDirMod = 0. The range
of the directional spread (in degrees) is defined via WaveDirSpread. The equal-energy method
assumes that the directional spreading spectrum is the product of a frequency spectrum and a
spreading function i.e. $S(\omega,\beta) = S(\omega)D(\beta)$. Directional spreading is not permitted when using
Newman’s approximation of the second-order difference-frequency potential-flow loads.

WaveSeed(1) and WaveSeed(2) combined determine the initial seed (starting point) for the
internal pseudorandom number generator needed to derive the wave kinematics from the wave
frequency and direction spectra. If you want to run different time-domain realizations for given
boundary conditions (of significant wave height, and peak-spectral period, etc.), you should
change one or both seeds between simulations. While the phase of each wave frequency and
direction component of the wave spectrum is always based on a uniform distribution (except
when using the 1P# WaveMod option), the amplitude of the wave frequency spectrum can also
be randomized (following a normal distribution) by setting WaveNDAmp to TRUE. Setting
WaveNDAmp to FALSE means that the amplitude of the wave frequency spectrum always
matches the target spectrum.

Input parameter GHWvFile is not used in this release.

You can generate up to 9 wave elevation outputs. NWaveElev determines the number (between
0 and 9), and the whitespace-separated lists of WaveElevxi and WaveElevyi determine the
locations of these NWaveElev number of points on the SWL plane in the global inertial-frame
coordinate system.

4.3.3 2nd-Order Waves

The 2ND-ORDER WAVES section of the input file allows the option of adding second-order
contributions to the wave kinematics used by the strip-theory solution. When second-order terms
are optionally enabled, the second-order terms are calculated using the first-order wave-
component amplitudes and extra energy is added to the wave spectrum (at the difference and
sum frequencies). The second-order terms cannot be computed without also including the first-
order terms from the WAVES section above. Enabling the second-order terms allows one to
capture some of the nonlinearities of real surface waves, permitting more accurate modeling of
sea states and the associated wave loads at the expense of greater computational effort (mostly at
HydroDyn initialization).

While the cut-off frequencies in this section apply to both the second-order wave kinematics
used by strip theory and the second-order diffraction loads in potential-flow theory, the second-
order terms themselves are enabled separately. The second-order wave kinematics used by strip
theory are enabled in this section while the second-order diffraction loads in potential-flow
theory are enabled in the 2ND-ORDER FLOATING PLATFORM FORCES section below.

While the second-order effects are included when enabled, the wave elevations output from
HydroDyn will only include the second-order terms when the second-order wave kinematics are
enabled in this section.
To use second-order wave kinematics in the strip-theory solution, set \( WvDiffQTF \) and/or \( WvSumQTF \) to TRUE. When \( WvDiffQTF \) is set to TRUE, second-order difference-frequency terms, calculated using the full difference-frequency QTF, are incorporated in the wave kinematics. When \( WvSumQTF \) is set to TRUE, second-order sum-frequency terms, calculated using the full sum-frequency QTF, are incorporated in the wave kinematics. The full difference- and sum-frequency wave kinematics QTFs are implemented analytically following [Sharma and Dean, 1981], which extends Stokes second-order theory to irregular multidirectional waves. A setting of FALSE disregards the second-order contributions to the wave kinematics in the strip-theory solution.

\( WvLowCOffD \) and \( WvHiCOffD \) control the lower and upper cut-off frequencies (in rad/s) of the second-order difference-frequency terms; the second-order difference-frequency terms are zeroed below and above these cut-off frequencies, respectively. The cut-offs apply directly to the physical difference frequencies, not the two individual first-order frequency components of the difference frequencies. When enabling second-order potential-flow theory, a setting of \( WvLowCOffD = 0 \) is advised to avoid eliminating the mean-drift term (second-order wave kinematics do not have a nonzero mean). \( WvHiCOffD \) need not be set higher than the peak-spectral frequency of the first-order wave spectrum \( (\omega_p = 2\pi/WaveTp) \) to minimize computational expense.

Likewise, \( WvLowCOffS \) and \( WvHiCOffS \) control the lower and upper cut-off frequencies (in rad/s) of the second-order sum-frequency terms; the second-order sum-frequency terms are zeroed below and above these cut-off frequencies, respectively. The cut-offs apply directly to the physical sum frequencies, not the two individual first-order frequency components of the sum frequencies. \( WvLowCOffS \) need not be set lower than the peak-spectral frequency of the first-order wave spectrum \( (\omega_p = 2\pi/WaveTp) \) to minimize computational expense. Setting a proper upper cut-off frequency \( (WvHiCOffS) \) also minimizes computational expense and is important to (1) ensure convergence of the second-order summations, (2) avoid unphysical “bumps” in the wave troughs, (3) prevent nonphysical effects when approaching the breaking-wave limit, and (4) avoid nonphysical wave forces at high frequencies (i.e., at short wavelengths) when using a strip-theory solution.

Because the second-order terms are calculated using the first-order wave-component amplitudes, the second-order cut-off frequencies \( (WvLowCOffD, WvHiCOffD, WvLowCOffS, \) and \( WvHiCOffS) \) are used in conjunction with the first-order cut-off frequencies \( (WvLowCOff \) and \( WvHiCOff) \) from the WAVES section. However, the second-order cut-off frequencies are not used by Newman’s approximation of the second-order difference-frequency potential-flow loads, which are derived solely from first-order effects.

### 4.3.4 Current

You can include water velocity due to a current model by setting \( CurrMod = 1 \). If \( CurrMod \) is set to zero, then the simulation will not include current. \( CurrMod = 2 \) requires that the \( UserCurrent() \) subroutine of the \( Current.f90 \) source file be implemented by the user, and will require recompiling either the stand-alone HydroDyn program or FAST. Current induces steady hydrodynamic loads through the viscous-drag terms (both distributed and lumped) of strip-theory members. Current is not used in the potential-flow solution.
HydroDyn’s standard current model includes three sub-models: near-surface, sub-surface, and depth-independent. All three currents are vector summed, along with the wave particle kinematics velocity.

The sub-surface current model follows a power law,

$$U_{SS}(Z) = U_{0SS} \left( \frac{Z + d}{d} \right)^{1/7},$$

where $Z$ is the local depth below the SWL (negative downward), $d$ is the water depth (equal to $WtrDpth + MSL2SWL$), and $U_{0SS}$ is the current velocity at SWL, corresponding to $CurrSSV0$. The heading of the sub-surface current is defined using $CurrSSDir$, following the same convention as $WaveDir$.

The near-surface current model follows a linear relationship down to a reference depth such that,

$$U_{NS}(Z) = U_{0NS} \left( \frac{Z + h_{ref}}{h_{ref}} \right), Z \in \left[ -h_{ref}, 0 \right] \text{ otherwise, } U_{NS}(Z) = 0,$$

where $h_{ref}$ is the reference depth corresponding to $CurrNSRef$, and must be positive valued. $U_{0NS}$ is the current velocity at SWL, corresponding to $CurrNSV0$. The heading of the near-surface current is defined using $CurrNSDir$, following the same convention as $WaveDir$.

The depth-independent current velocity everywhere equals $CurrDIV$. This current has a heading direction $CurrDIVDir$, following the same convention as $WaveDir$.

### 4.3.5 Floating Platform

This and the next few sections of the input file have “Floating Platform” in the title, but the input parameters control the potential-flow model, regardless of whether the substructure is floating or not.

If the load contributions from potential-flow theory are to be used, set $HasWAMIT$ to TRUE and include the root name for the WAMIT-related output files in $WAMITFile$. These files consist of the .I, .3, .hst and second-order files. These are written by the WAMIT program and should not include any file headers. When the linear state-space model is used in place of convolution, the .ss file generated by SS_Fitting must have the same root name as the other WAMIT-related files (see $RdinMod$ below). If $HasWAMIT$ is FALSE, the remaining parameters in this section are ignored.

The output files from WAMIT are in a standard nondimensional form that HydroDyn will dimensionalize internally upon input. $WAMITULEN$ is the characteristic body length scale used to redimensionalize the WAMIT output. The body motions and forces in these files are in relation to the WAMIT reference point (WRP) in HydroDyn, which for the undisplaced substructure is the same as the origin of the global inertial-frame coordinate system (0,0,0). The
.hst file contains the 6x6 linear hydrostatic restoring (stiffness) matrix of the platform. The .l file contains the 6x6 frequency-dependent hydrodynamic added-mass and damping matrix of the platform from the radiation problem. The .3 file contains the 6x1 frequency- and direction-dependent first-order wave-excitation force vector of the platform from the linear diffraction problem. While HydroDyn expects hydrodynamic coefficients derived from WAMIT, if you are not using WAMIT, it is recommended that you reformat your data according to the WAMIT format (including nondimensionalization) before inputting them to HydroDyn. Information on the WAMIT format is available from Chapter 4 of the WAMIT User's Guide [Lee, 2006].

$PtfmVol0$ is the displaced volume of water when the platform is in its undisplaced position. This value should be set equal to the value computed by WAMIT as output in the WAMIT .out file. $PtfmCOBxt$ and $PtfmCOByt$ are the $X$ and $Y$ offsets of the center of buoyancy from the WRP.

HydroDyn has two methods for calculating the radiation memory effect. Set $RdtnMod$ to 1 for the convolution method, 2 for the linear state-space model, or 0 to disable the memory effect calculation. For the convolution method, $RdtnTMax$ determines how long to track the memory effect (truncating the convolutions at $t = RdtnTMax$, where $t$ is the current simulation time), but it also determines the frequency step used in the cosine transform, from which the time-domain radiation kernel (radiation impulse-response function) is derived. A $RdtnTMax$ of 60 s is usually more than sufficient because the radiation kernel decays to zero after a short amount of time; setting $RdtnTMax$ much greater than this will cause HydroDyn to run significantly slower. ($RdtnTMax$ does not need to match or exceed the total simulation length.) Setting $RdtnTMax$ to 0 s disables the memory effect, akin to setting $RdtnMod$ to 0. For the convolution method, $RdtnDT$ is the time step for the radiation calculations (numerical convolutions), but also determines the maximum frequency in the cosine transform. For the state-space model, $RdtnDT$ is the time step to use for time integration of the linear state-space model. In this version of HydroDyn, $RdtnDT$ must match the glue code (FAST/driver program) simulation time step; the DEFAULT keyword can be used for this.

### 4.3.6 2nd-Order Floating Platform Forces

The 2ND-ORDER FLOATING PLATFORM FORCES section of the input file allows the option of adding second-order contributions to the potential-flow solution. When second-order terms are optionally enabled, the second-order terms are calculated using the first-order wave-component amplitudes and extra energy is added to the wave spectrum (at the difference and sum frequencies). The second-order terms cannot be computed without also including the first-order terms from the FLOATING PLATFORM section above. Enabling the second-order terms allows one to capture some of the nonlinearities of real surface waves, permitting more accurate modeling of sea states and the associated wave loads at the expense of greater computational effort (mostly at HydroDyn initialization).

While the cut-off frequencies in the 2ND-ORDER WAVES section above apply to both the second-order wave kinematics used by strip theory and the second-order diffraction loads in potential-flow theory, the second-order terms themselves are enabled separately. The second-order wave kinematics used by strip theory are enabled in the 2ND-ORDER WAVES section above while the second-order diffraction loads in potential-flow theory are enabled in this section. While the second-order effects are included when enabled, the wave elevations output
from HydroDyn will only include the second-order terms when the second-order wave kinematics are enabled in the 2ND-ORDER WAVES section above.

The second-order difference-frequency potential-flow terms can be enabled in one of three ways. To compute only the mean-drift term, set \textit{MnDrift} to a nonzero value; to estimate the mean- and slow-drift terms using Standing et al.’s extension to Newman’s approximation, based only on first-order effects, set \textit{NewmanApp} to a nonzero value; or to compute the mean- and slow-drift terms using the full difference-frequency QTF set \textit{DiffQTF} to a nonzero value. Valid values of \textit{MnDrift} are 0, 7, 8, 9, 10, 11, or 12 corresponding to which WAMIT output file the mean-drift terms will be calculated from. Valid values of \textit{NewmanApp} are 0, 7, 8, 9, 10, 11, or 12 corresponding to which WAMIT output file the Newman’s approximation will be calculated from. Newman’s approximation cannot be used in conjunction with directional spreading (\textit{WaveDirMod} must be 0) and the second-order cut-off frequencies do not apply to Newman’s approximation. Valid values of \textit{DiffQTF} are 0, 10, 11, or 12 corresponding to which WAMIT output file the full difference-frequency potential-flow solution will be calculated from. Only one of \textit{MnDrift}, \textit{NewmanApp}, and \textit{DiffQTF} can be nonzero; a setting of 0 disregards the second-order difference-frequency contributions to the potential-flow solution.

The .7 WAMIT file refers to the mean-drift loads (diagonal of the difference-frequency QTF) in all 6 DOFs derived from the control-surface integration method based on the first-order solution. The .8 WAMIT file refers to the mean-drift loads (diagonal of the difference-frequency QTF) only in surge, sway, and roll derived from momentum integration based on the first-order solution. The .9 WAMIT file refers to the mean-drift loads (diagonal of the difference-frequency QTF) in all six DOFs derived from the pressure integration method based on the first-order solution. For the difference-frequency terms, 10, 11, and 12 refer to the WAMIT .10d, .11d, and .12d files, corresponding to the full QTF of (.10d) loads in all 6 DOFs associated with the quadratic interaction of first-order quantities, (.11d) total (quadratic plus second-order potential) loads in all 6 DOFs derived by the indirect method, and (.12d) total (quadratic plus second-order potential) loads in all 6 DOFs derived by the direct method, respectively.

The second-order sum-frequency potential-flow terms can only be enabled using the full sum-frequency QTF, by setting \textit{SumQTF} to a nonzero value. Valid values of \textit{SumQTF} are 0, 10, 11, or 12 corresponding to which WAMIT output file the full sum-frequency potential-flow solution will be calculated from; a setting of 0 disregards the second-order sum-frequency contributions to the potential-flow solution. For the sum-frequency terms, 10, 11, and 12 refer to the WAMIT .10s, .11s, and .12s files, corresponding to the full QTF of (.10s) loads in all 6 DOFs associated with the quadratic interaction of first-order quantities, (.11s) total (quadratic plus second-order potential) loads in all 6 DOFs derived by the indirect method, and (.12s) total (quadratic plus second-order potential) loads in all 6 DOFs derived by the direct method, respectively.

### 4.3.7 Floating Platform Force Flags

This release requires that all platform force flags be set to TRUE. Future releases will allow you to turn on/off one or more of the six platform force components.

### 4.3.8 Platform Additional Stiffness and Damping

The vectors and matrices of this section are used to generate additional loads on the platform (in addition to other hydrodynamic terms calculated by HydroDyn), per the following equation.
\[ \vec{F}_{Add} = \vec{F}_0 - [C] \ddot{\vec{q}} - [B] \vec{q} - [B_{quad}] ABS(\dot{\vec{q}}) \dot{\vec{q}}, \]

where \( \vec{F}_0 \) corresponds to the AddF 6x1 static load (preload) vector, \([C]\) corresponds to the AddClIn 6x6 linear restoring (stiffness) matrix, \([B]\) corresponds to the AddBlIn 6x6 linear damping matrix, \([B_{quad}]\) corresponds to the AddBQuad 6x6 quadratic drag matrix, and \( \ddot{\vec{q}} \) corresponds to the WRP 6x1 (six-DOF) displacement vector (three translations and three rotations), where the overdot refers to the first time-derivative.

These terms can be used, e.g., to model a linearized mooring system, to augment strip-theory members with a linear hydrostatic restoring matrix (see Section 6.6.3), or to “tune” HydroDyn to match damping to experimental results, such as free-decay tests. While likely most useful for floating systems, these matrices can also be used for fixed-bottom systems; in both cases, the resulting load is applied at the WRP, which when HydroDyn is coupled to FAST, get applied to the platform in ElastoDyn (bypassing SubDyn for fixed-bottom systems). See Section 6 for addition modeling considerations where these terms are necessary.

### 4.3.9 Axial Coefficients

This and the next several sections of the input file control the strip-theory model for both fixed-bottom and floating substructures.

HydroDyn computes lumped viscous-drag, added-mass, fluid-inertia, and static pressure loads at member ends (joints). The hydrodynamic coefficients for the lumped the lumped loads at joints are referred to as “axial coefficients” and include viscous-drag coefficients, \( AxCd \), added-mass coefficients, \( AxCa \), and dynamic-pressure coefficients, \( AxCp \). \( AxCa \) influences both the added-mass loads and the scattering component of the fluid-inertia loads. Any number of separate axial coefficient sets, distinguished by \( AxCoefID \), may be specified by setting \( NAxCoef > 1 \).

Axial viscous-drag loads will be calculated for all specified member joints. Axial added-mass, fluid-inertia, and static-pressure loads will only be calculated for member joints of members not modeled with WAMIT (\( PropWAMIT = \text{FALSE} \)). Axial loads are only calculated at user-specified joints. Axial loads are not calculated at joints HydroDyn may automatically create as part its solution process. For example, if you want axial effects at a marine-growth boundary (where HydroDyn automatically adds a joint), you must explicitly set a joint at that location.

### 4.3.10 Member Joints

The strip-theory 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 nodes, \( NJoints \) must be exactly zero or greater than or equal to 2. Each joint listed in the table is identified by a unique integer, \( JointID \). The \((X,Y,Z)\) coordinate of each joint is specified in the global inertial-frame coordinate system via \( Jointxi \), \( Jointyi \), and \( Jointzi \), respectively. \( JointAxID \) corresponds to an entry in the AXIAL COEFFICIENTS table and sets the axial coefficients for a joint. This version of HydroDyn cannot calculate joint overlap when multiple members meet at a common joint; therefore \( JointOvrlp \) must be set to 0. Future releases will enable joint overlap calculations.
Modeling a fixed-bottom substructure embedded into the seabed (e.g., through piles or suction buckets) requires that the lowest member joint(s) lie below the water depth. Placing a joint at or above the water depth results in static pressure loads being applied.

4.3.11 Member Cross-Sections
Members in HydroDyn are assumed to be straight circular (and possibly tapered) cylinders. Apart from the hydrodynamic coefficients, the circular cross-section properties needed for the hydrodynamic load calculations are member outer diameter, \( PropD \), and member thickness, \( PropThck \). You will need to create an entry in this table, distinguished by \( PropSetID \), for each unique combination of these two 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 4.3.13 below. \( PropD \) determines the static buoyancy loads exterior to a member, as well as the area used in the viscous-drag calculation and the volume used in the added-mass and fluid-inertia calculations. \( PropThck \) determines the interior volume for fluid-filled (flooded/ballasted) members.

4.3.12 Hydrodynamic Coefficients
HydroDyn computes distributed viscous-drag, added-mass, fluid-inertia, and static buoyancy loads along members.

The hydrodynamic coefficients for the distributed strip-theory loads are specified using any of three models, which we refer to as the simple model, a depth-based model, and a member-based model. All of these models require the specification of both transverse and axial hydrodynamic coefficients for viscous drag, added mass, and dynamic pressure (axial viscous drag is not yet available). The added-mass coefficient influences both the added-mass loads and the scattering component of the fluid-inertia loads. There are separate set of hydrodynamic coefficients both with and without marine growth. A given element will either use the marine growth or the standard version of a coefficient, but never both. Note that input members are split into elements per Section 7.5.2, one of the splitting rules guarantees the previous statement is true. Which members have marine growth is defined by the MARINE GROWTH table of Section 4.3.15. You can specify only one model type, \( MCoefMod \), for any given member in the MEMBERS table. However, different members can specify different coefficient models.

In the hydrodynamic coefficient input parameters, \( Cd \), \( Ca \), and \( Cp \) refer to the viscous-drag, added-mass, and dynamic-pressure coefficients, respectively, \( MG \) identifies the coefficients to be applied for members with marine growth (the standard values are identified without \( MG \)), and \( Ax \) identifies the axial coefficients to be applied for tapered members (the transverse coefficients are identified without \( Ax \)). It is noted that for the transverse coefficients, \( C_p + C_A = C_M \), the inertia coefficient.

While the strip-theory solution assumes circular cross sections, the hydrodynamic coefficients can include shape corrections; however, there is no distinction made in HydroDyn between different transverse directions.
4.3.12.1 Simple Model

This table consists of a single complete set of hydrodynamic coefficients as follows: SimplCd, SimplCdMG, SimplCa, SimplCaMG, SimplCp, SimplCpMG, SimplAxCa, SimplAxCaMG, SimplAxCp, and SimplAxCpMG. These hydrodynamic coefficients are referenced in the members table of Section 4.3.13 by selecting MCoefMod = 1.

4.3.12.2 Depth-Based Model

The depth-based coefficient model allows you to specify a series of depth-dependent coefficients. NCoefDpth is the user-specified number of depths and determines the number of rows in the subsequent table. Currently, this table requires that the rows are ordered by increasing depth, Dpth; this is equivalent to a decreasing global Z-coordinate. The hydrodynamic coefficients at each depth are as follows: DpthCd, DpthCdMG, DpthCa, DpthCaMG, DpthCp, DpthCpMG, DpthAxCa, DpthAxCaMG, DpthAxCp, and DpthAxCpMG. Members use these hydrodynamic coefficients by setting MCoefMod = 2. The HydroDyn module will interpolate coefficients for a node whose Z-coordinate lies between table Z-coordinates.

4.3.12.3 Member-Based Model

The member-based coefficient model allows you to specify a hydrodynamic coefficients for each particular member. NCoefMembers is the user-specified number of members with member-based coefficients and determines the number of rows in the subsequent table. The hydrodynamic coefficients for a member distinguished by MemberID are as follows: MemberCd1, MemberCd2, MemberCdMG1, MemberCdMG2, MemberCa1, MemberCa2, MemberCaMG1, MemberCaMG2, MemberCp1, MemberCp2, MemberCpMG1, MemberCpMG2, MemberAxCa1, MemberAxCa2, MemberAxCaMG1, MemberAxCaMG2, MemberAxCp1, MemberAxCp2, MemberAxCpMG1, and MemberAxCpMG2, where 1 and 2 identify the starting and ending joint of the member, respectively. Members use these hydrodynamic coefficients by setting MCoefMod = 3.

4.3.13 Members

NMembers is the user-specified number of members and determines the number of rows in the subsequent table. For each member distinguished by MemberID, MJointID1 specifies the starting joint and MJointID2 specifies the ending joint, corresponding to an identifier (JointID) from the MEMBER JOINTS table. Likewise, MPropSetID1 corresponds to the starting cross-section properties and MPropSetID2 specify the ending cross-section properties, allowing for tapered members. MDivSize determines the maximum spacing (in meters) between simulation nodes where the distributed loads are actually computed; the smaller the number, the finer the resolution and longer the computational time. Section 7.5.2 discusses the difference between the user-supplied discretization and the simulation discretization. Each member in your model will have hydrodynamic coefficients, which are specified using one of the three models (MCoefMod). Model 1 uses a single set of coefficients found in the SIMPLE HYDRODYNAMIC COEFFICIENTS section. Model 2 is depth-based, and is determined via the table found in the DEPTH-BASED HYDRODYNAMIC COEFFICIENTS section. Model 3 specifies coefficients for a particular member, by referring to the MEMBER-BASED HYDRODYNAMIC COEFFICIENTS section. The PropWAMIT flag indicates whether the corresponding member coincides with the body represented by the potential-flow solution.
When $PropWAMIT = \text{TRUE}$, only viscous-drag loads, and ballasting loads will be computed for that member.

### 4.3.14 Filled Members

Members—whether they are also modeled with potential-flow or not—may be fluid-filled, meaning that they are flooded and/or ballasted. Fluid-filled members introduce interior buoyancy that subtracts from the exterior buoyancy and a mass. Both distributed loads along a member and lumped loads at joints are applied. The volume of fluid in the member is derived from the outer diameter and thickness of the member and a fluid-filled free-surface level. The fluid in the member is assumed to be compartmentalized such that it does not slosh. Rotational inertia of the fluid in the member is ignored. A member’s filled configuration is defined by the filled-fluid density and the free-surface level. Filled members that have the same configuration are collected into fill groups.

$NFillGroups$ specifies the number of fluid-filled member groups and determines the number of rows in the subsequent table. $FillNumN$ specifies the number of members in the fill group. $FillMList$ is a list of $FillNumN$ whitespace-separated $MemberIDs$. $FillFSLoc$ specifies the $Z$-height of the free-surface (0 for MSL). $FillDens$ is the density of the fluid. If $FillDens = \text{DEFAULT}$, then $FillDens = \text{WtrDens}$.

### 4.3.15 Marine Growth

Members not also modeled with potential-flow theory may be modeled with marine growth. Marine growth causes three effects. First, marine growth introduces a static weight and mass to a member, applied as distributed loads along the member. Second, marine growth increases the outer diameter of a member, which impacts the diameter used in the viscous-drag, added-mass, fluid-inertia, and static buoyancy load calculations. Third, the hydrodynamic coefficients for viscous drag, added mass, and dynamic pressure are specified distinctly for marine growth. Rotational inertia of the marine growth is ignored and marine growth is not added to member ends.

Marine growth is specified using a depth-based table with $NMGDepths$ rows. This table must have exactly zero or at least 2 rows. The columns in the table include the local depth, $MGDpth$, the marine growth thickness, $MGThck$, and marine growth density, $MGDens$. Marine growth for a particular location in the substructure geometry is added by linearly interpolating between the marine-growth table entries. The smallest and largest values of $MGDpth$ define the marine growth region. Outside this region the marine growth thickness is set to zero. If you want sub-regions of zero marine growth thickness within these bounds, you must generate depth entries which explicitly set $MGThck$ to zero. The hydrodynamic coefficient tables contain coefficients with and without marine growth. If $MGThck = 0$ for a particular node, the coefficients not associated with marine growth are used.

### 4.3.16 Member Output List

HydroDyn can output distributed load and wave kinematic quantities at up to 9 locations on up to 9 different members, for a total of 81 possible local member output locations. $NMOutputs$ specifies the number of members. You must create a table entry for each requested member. Within a table entry, $MemberID$ is the ID specified in the MEMBERS table, and $NOutLoc$
specifies how many output locations are generated for this member. NodeLocs specifies those locations as a normalized distance from the starting joint (0.0) to the ending joint (1.0) of the member. If the chosen location does not align with a calculation node, the results at the two surrounding nodes will be linearly interpolated. The outputs specified in the OUTPUT CHANNELS section determines which quantities are actually output at these locations.

4.3.17 Joint Output List

HydroDyn can output lumped load and wave kinematic quantities at up to 9 different joints. JOutLst contains a list of NJOutputs number of JointIDs. The outputs specified in the OUTPUT CHANNELS section determines which quantities are actually output at these joints.

4.3.18 Output

Specifying HDSum = TRUE causes HydroDyn to generate a summary file with name OutRootname.HD.sum. OutRootName is either specified in the HYDRODYN section of the driver input file when running HydroDyn standalone, or by the FAST program when running a coupled simulation. See section 5.3 for summary file details.

For this version, OutAll must be set to FALSE. In future versions, setting OutAll = TRUE will cause HydroDyn to auto-generate outputs for every joint and member in the input file.

If OutSwitch is set to 1, outputs are sent to a file with the name OutRootname.HD.out. If OutSwitch is set to 2, outputs are sent to the calling program (FAST) for writing. If OutSwitch is set to 3, both file outputs occur. In standalone mode, setting OutSwitch to 2 results in no output file being produced.

The OutFmt and OutSFmt parameters control the formatting for the output data and the channel headers, respectively. HydroDyn currently does not check the validity of these format strings. They need to be valid Fortran format strings. Since the OutSFmt is used for the column header and OutFmt is for the channel data, in order for the headers and channel data to align properly, the width specification should match. For example,

"E511.4" OutFmt
"A11" OutSFmt

4.3.19 Output Channels

This section controls output quantities generated by HydroDyn. 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”, HydroDyn will multiply the value for that channel by –1 before writing the data. The parameters are not necessarily written in the order they are listed in the input file. HydroDyn 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 HydroDyn to quit scanning for more lines of channel names. Member- and joint-related quantities are generated for the requested MEMBER OUTPUT LIST and JOINT OUTPUT LIST. If HydroDyn encounters an unknown/invalid channel name, it
warns the users but will remove the suspect channel from the output file. Please refer to Appendix C for a complete list of possible output parameters.
5 Output Files

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

5.1 Echo Files

If you set the *Echo* flag to TRUE in the HydroDyn driver file or the primary HydroDyn input file, the contents of those files will be echoed to a file with the naming conventions, *OutRootName*.dvr.ech for the driver input file and *OutRootName*.HD.ech for the primary HydroDyn input file. *OutRootName* is either specified in the HYDRODYN section of the driver input file, or by the FAST program. The echo files are helpful for debugging your input files. The contents of an echo file will be truncated if HydroDyn encounters an error while parsing an input file. The error usually corresponds to the line after the last successfully echoed line.

5.2 Wave-Elevations File

Setting *WaveElevSeriesFlag* in the driver file to TRUE enables the outputting of a grid of wave elevations to a text-based file with the name *OutRootName*.WaveElev.out. The grid consists of *WaveElevNX* by *WaveElevNY* wave elevations (centered at \( X = 0, Y = 0 \)) with a \( dX \) and \( dY \) spacing in the global inertial-frame coordinate system. These wave elevations are distinct and output separately from the wave elevations determined by *NWaveElev* in the HydroDyn primary input file, such that the total number of wave elevation outputs is \( NWaveElev + (WaveElevNX \times WaveElevNY) \). The wave-elevation output file *OutRootName*.WaveElev.out contains the total wave elevation, which is the sum of the first- and second-order terms (when the second-order wave kinematics are optionally enabled).

5.3 Summary File

HydroDyn generates a summary file with the naming convention, *OutRootName*.HD.sum if the *HDSum* parameter is set to TRUE. This file summarizes key information about your hydrodynamics model, including buoyancy, substructure volumes, marine growth weight, the simulation mesh and its properties, first-order wave frequency components, and the radiation kernel.

When the text refers to an index, it is referring to a given row in a table. The indexing starts at 1 and increases consecutively down the rows.

5.3.1 WAMIT-model volume and buoyancy information

This section summarizes the buoyancy of the potential-flow-model platform in its undisplaced configuration. For a hybrid potential-flow/strip-theory model, these buoyancy values must be added to any strip-theory member buoyancy reported in the subsequent sections to obtain the total buoyancy of the platform.

5.3.2 Substructure Volume Calculations

This section contains a summary of the total substructure volume, the submerged volume, volume of any marine growth, and fluid-filled (flooded/ballasted) volume for the substructure in its undisplaced configuration. Except for the fluid-filled volume value, the reported volumes are
only for members that have the PropWAMIT flag set to FALSE. The flooded/ballasted volume applies to any fluid-filled member, regardless of its PropWAMIT flag.

5.3.3 Integrated Buoyancy Loads
This section details the buoyancy loads of the undisplaced substructure when summed about the WRP (0,0,0). The external buoyancy includes the effects of marine growth, and only applies to members whose PropWAMIT flag is set to FALSE. The internal buoyancy is the negative effect on buoyancy due to flooding or ballasting and is independent of the PropWAMIT flag.

5.3.4 Integrated Marine Growth Weights
This section details the marine growth weight loads of the undisplaced substructure when summed about the WRP (0,0,0).

5.3.5 Simulation Node Table
This table details the undisplaced nodal information and properties for the simulation mesh. The node index is provided in the first column. The second column maps the node to the input joint index (not to be confused with the JointID). If a value of -1 is found in this column, the node is an interior node and results from an input member being split somewhere along its length due to the requirements of the MDivSize parameter in the primary input file members table. See Section 7.5.2 for the member splitting rules used by HydroDyn. The third column indicates if this node is part of a Super Member (JointOvrlp = 1). The next column tells you the corresponding input member index (not to be confused with the MemberID). Nxi, Nyi, and Nzi, provide the (X,Y,Z) coordinates in the global inertial-frame coordinate system. InpMbrDist provides the normalized distance to the node from the start of the input member. R is the outer radius of the member at the node (excluding marine growth), and t is the member wall thickness at the node. dRdZ is the taper of the member at the node, tMG is the marine growth thickness, and MGDens is the marine growth density. PropWAMIT indicates whether the element attached to this node is modeled using potential-flow theory. If FilledFlag is TRUE, then FillDens gives the filled fluid density and FillFSLoc indicates the free-surface height (Z-coordinate). Cd, Ca, Cp, AxCa, AxCp, JAxCd, JAxCa, and JAxCp are the viscous-drag, added-mass, dynamic-pressure, axial added-mass, axial dynamic-pressure, end-effect axial viscous-drag, end-effect axial added-mass, and end-effect axial dynamic-pressure coefficients, respectively. NConn gives the number of elements connected to node, and Connection List is the list of element indexes attached to the node.

5.3.6 Simulation Element Table
This section details the undisplaced simulation elements and their associated properties. A suffix of 1 or 2 in a column heading refers to the element’s starting or ending node, respectively. The first column is the element index. node1 and node2 refer to the node index found in the node table of the previous section. Next are the element Length and exterior Volume. This exterior volume calculation includes any effects of marine growth. MGVolume provides the volume contribution due to marine growth. The cross-sectional properties of outer radius (excluding marine growth), marine growth thickness, and wall thickness for each node are given by R1, tMG1, t1, R2, tMG2, and t2, respectively. MGDens1 and MGDens2 are the marine growth density at node 1 and 2. PropWAMIT indicates if the element is modeled using potential-flow theory. If the element is fluid-filled (has flooding or ballasting), FilledFlag is set to T for
TRUE. **FillDensity** and **FillFSLoc** are the filled fluid density and the free-surface location’s Z-coordinate in the global inertial-frame coordinate system. **FillMass** is calculated by multiplying the **FillDensity** value by the element’s interior volume. Finally, the element hydrodynamic coefficients are listed. These are the same coefficients listed in the node table (above).

### 5.3.7 Summary of User-Requested Outputs

The summary file includes information about all requested member and joint output channels.

#### 5.3.7.1 Member Outputs

The first column lists the data channel’s string label, as entered in the OUTPUT CHANNELS section of the HydroDyn input file. \(X_i, Y_i, Z_i\), provide the output’s undisplaced spatial location in the global inertial-frame coordinate system. The next column, **InpMbrIndx**, tells you the corresponding input member index (not to be confused with the **MemberID**). Next are the coordinates of the starting \(（StartX_i, StartY_i, StartZ_i）\) and ending \(（EndX_i, EndY_i, EndZ_i）\) nodes of the element containing this output location. **Loc** is the normalized distance from the starting node of this element.

#### 5.3.7.2 Joint Outputs

The first column lists the data channel’s string label, as entered in the OUTPUT CHANNELS section of the HydroDyn input file. \(X_i, Y_i, Z_i\), provide the output’s undisplaced spatial location in the global inertial-frame coordinate system. **InpJointID** specifies the **JointID** for the output as given in the MEMBER JOINTS table of the HydroDyn input file.

### 5.3.8 The Wave Number and Complex Values of the Wave Elevations as a Function of Frequency

This section provides the frequency-domain description (in terms of a Discrete Fourier Transform or DFT) of the first-order wave elevation at \((0,0)\) on the free surface. The first column, \(m\), identifies the index of each wave frequency component. The finite-depth wave number, frequency, and direction of the wave component are given by \(k\), \(\Omega\), and **Direction**, respectively. The last two columns provide the real (\(REAL(DFT[WaveElev])\)) and imaginary (\(IMAG(DFT[WaveElev])\)) components of the DFT of the first-order wave elevation. The DFT produces includes both the negative- and positive-frequency components. The negative-frequency components are complex conjugates of the positive frequency components because the time-domain wave elevation is real-valued. The relationships between the negative- and positive-frequency components of the DFT are given by \(k(-\omega) = -k(\omega)\) and \(H(-\omega) = H(\omega)^*\), where \(H\) is the DFT of the wave elevation and \(^*\) denotes the complex conjugate.

### 5.3.9 Radiation Memory Effect Convolution Kernel

HydroDyn computes the radiation kernel used by the convolution method for calculating the radiation memory effect through the cosine transform of the 6x6 frequency-dependent hydrodynamic damping matrix from the radiation problem. The resulting time-domain radiation kernel (radiation impulse-response function)—which is a 6x6 time-dependent matrix—is provided in this section. \(n\) and \(t\) give the time-step index and time, which are followed by the elements (\(K_{11}, K_{12}, \text{etc.}\)) of the radiation kernel associated with that time. Because the frequency-dependent hydrodynamic damping matrix is symmetric, so is the radiation kernel; thus, only the diagonal and upper-triangular portion of the matrix are provided. The radiation
kernel should decay to zero after a short amount of time, which should aid in selecting an appropriate value of $RdtmTMax$.

5.4 Results File
The HydroDyn time-series results are written to a text-based file with the naming convention $\text{OutRootName.HD.out}$ when $\text{OutSwtch}$ is set to either 1 or 3. If HydroDyn is coupled to FAST and $\text{OutSwtch}$ is set to 2 or 3, then FAST will generate a master results file that includes the HydroDyn 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 time step. The data channels are specified in the OUTPUT CHANNELS section of the input file. The column format of the HydroDyn-generated file is specified using the $\text{OutFmt}$ and $\text{OutSFmt}$ parameter of the input file.
6 Modeling Considerations

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

Please refer to the theory of Section 7 for detailed information about HydroDyn’s coordinate systems, and the implementation approach we have followed in HydroDyn.

6.1 Waves

Waves in HydroDyn can be regular (periodic) or irregular (stochastic) and long-crested (unidirectional) or short-crested (with wave energy spread across a range of directions). HydroDyn treats waves using first-order (linear Airy) or first- plus second-order wave theory [Sharma and Dean, 1981] with the option to include directional spreading, but no wave stretching or higher order wave theories are included. Modeling unidirectional sea states is often overly conservative in engineering design. Enabling the second-order terms allows one to capture some of the nonlinearities of real surface waves, permitting more accurate modeling of sea states and the associated wave loads at the expense of greater computational effort (mostly at HydroDyn initialization). The magnitude and frequency content of second-order hydrodynamic loads can excite structural natural frequencies, leading to greater ultimate and fatigue loads than can be predicted solely using first-order theory. Sum-frequency effects are important to the loading of stiff fixed-bottom structures and for the springing and ringing analysis of TLPs. Difference-frequency (mean-drift and slow-drift) effects are important to the analysis of compliant structures, including the motion analysis and mooring loads of catenary-moored floating platforms (spar buoys and semi-submersibles).

When modeling irregular sea states, we recommend that \( \text{WaveTMax} \) be set to at least 1 hour (3600 s) and that \( \text{WaveDT} \) be a value in the range between 0.1 and 1.0 s to ensure sufficient resolution of the wave spectrum and wave kinematics. When HydroDyn is coupled to FAST, \( \text{WaveDT} \) may be specified arbitrarily independently from the glue code time step of FAST. (The wave kinematics and hydrodynamic loads will be interpolated in time as necessary.)

Wave directional spreading is implemented in HydroDyn via the equal-energy method, which assumes that the directional spreading spectrum is the product of a frequency spectrum and a spreading function i.e. \( S(\omega, \beta) = S(\omega)D(\beta) \). Directional spreading is not permitted when using Newman’s approximation of the second-order difference-frequency potential-flow loads.

When second-order terms are optionally enabled, the second-order terms are calculated using the first-order wave-component amplitudes and extra energy is added to the wave spectrum (at the difference and sum frequencies). The second-order terms cannot be computed without also including the first-order terms.

It is important to set proper wave cut-off frequencies to minimize computational expense and to ensure that the wave kinematics and hydrodynamic loads are realistic. HydroDyn gives the user six user-defined cut-off frequencies—\( \text{WvLowCOff} \) and \( \text{WvHiCOff} \) for the low- and high-frequency cut-offs of first-order wave components, \( \text{WvLowCOffD} \) and \( \text{WvHiCOffD} \) for the low-and high-frequency cut-offs of second-order difference-frequency wave components, and
**WvLowCOffS** and **WvHiCOffS** for low- and high-frequency cut-offs of second-order sum-frequency wave components—none of which have default settings. The second-order cut-offs apply directly to the physical difference and sum frequencies, not the two individual first-order frequency components of the difference and sum frequencies. Because the second-order terms are calculated using the first-order wave-component amplitudes, the second-order cut-off frequencies are used in conjunction with the first-order cut-off frequencies. However, the second-order cut-off frequencies are not used by Newman’s approximation of the second-order difference-frequency potential-flow loads, which are derived solely from first-order effects.

For the first-order wave-component cut-off frequencies, **WvLowCOff** may be set lower than the low-energy limit of the first-order wave spectrum to minimize computational expense. Setting a proper upper cut-off frequency (**WvHiCOff**) also minimizes computational expense and is important to prevent nonphysical effects when approaching of the breaking-wave limit and to avoid nonphysical wave forces at high frequencies (i.e., at short wavelengths) when using a strip-theory solution.

When enabling second-order potential-flow theory, a setting of **WvLowCOffD** = 0 is advised to avoid eliminating the mean-drift term (second-order wave kinematics do not have a nonzero mean). **WvHiCOffD** need not be set higher than the peak-spectral frequency of the first-order wave spectrum (\(\omega_p = 2\pi/WaveTp\)) to minimize computational expense. Setting a proper upper cut-off frequency (**WvHiCOffS**) also minimizes computational expense and is important to (1) ensure convergence of the second-order summations, (2) avoid unphysical “bumps” in the wave troughs, (3) prevent nonphysical effects when approaching of the breaking-wave limit, and (4) avoid nonphysical wave forces at high frequencies (i.e., at short wavelengths) when using a strip-theory solution.

For all models, if you want to run different time-domain incident wave realizations for given boundary conditions (of significant wave height, and peak-spectral period, etc.), you should change one or both wave seeds (**WaveSeed(1)** and **WavedSeed(2)**) between simulations.

You can generate up to 9 wave elevation outputs (at different points on the SWL plane) when HydroDyn is coupled to FAST or a large grid of wave elevations when running HydroDyn standalone. While the second-order effects are included when enabled, the wave elevations output from HydroDyn will only include the second-order terms when the second-order wave kinematics are enabled.

### 6.2 Strip-Theory Model Discretization

A user will define the geometry of a structure modeled with strip theory in HydroDyn using joints and members. Members in HydroDyn are assumed to be straight circular (and possibly tapered) cylinders. Members can be further subdivided using **MDivSize**, which HydroDyn will internally use to subdivide members into multiple elements (and nodes). HydroDyn may further refine the geometry at the free surface, seabed, marine-growth region, and filled-fluid free surface. The rules HydroDyn uses for refinement may be found in Section 7.5.2.

Due to the exponential decay of hydrodynamic loads with depth, HydroDyn requires higher resolution near the water free surface to capture hydrodynamic loading as waves oscillate about
the still water level (SWL). It is recommended, for instance, 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 HydroDyn is coupled to SubDyn through FAST for the analysis of fixed-bottom systems, it is recommended that the length ratio between elements of HydroDyn and SubDyn not exceed 10 to 1.

6.3 Domain for Strip-Theory Hydrodynamic Load Calculations

Part of the automated geometry refinement mentioned in the above section deals with splitting of input members into sub-elements such that both of the resulting nodes at the element ends lie within the discrete domains described in the following sections.

6.3.1 Distributed Loads

6.3.1.1 Inertia, Added Mass, Buoyancy, Marine-Growth Weight, Marine-Growth Mass Inertia

These loads are generated at a node as long as \( \text{PropWAMIT} = \text{FALSE} \), the \( Z \)-coordinate is in the range \([-\text{WtrDpth}, \text{MSL2SWL}]\), and the element the node is connected to is in the water.

6.3.1.2 Filled Buoyancy, Filled Mass Inertia

These loads are generated at a node as long as the \( Z \)-coordinate is in the range \([-\text{WtrDpth}, \text{FillFSLoc}]\) and the element the node is connected to is in the filled fluid.

6.3.1.3 Viscous Drag

These loads are generated at a node as long as the \( Z \)-coordinate is in the range \([-\text{WtrDpth}, \text{MSL2SWL}]\) and the element the node is connected to is in the water.

6.3.2 Lumped Loads

Lumped loads at member ends (axial effects) are only calculated at user-specified joints, and not at joints HydroDyn may automatically create as part its solution process (see Section 7.5.2 for differences between the input-file discretization and the simulation discretization). For example, if you want axial effects at a marine-growth boundary, you must explicitly set a joint at that location.

6.3.2.1 Added Mass, Inertia, Buoyancy

These loads are generated at a node as long as \( \text{PropWAMIT} = \text{FALSE} \) and the \( Z \)-coordinate is in the range \([-\text{WtrDpth}, \text{MSL2SWL}]\).

6.3.2.2 Axial Drag

These loads are generated at a node as long as the \( Z \)-coordinate is in the range \([-\text{WtrDpth}, \text{MSL2SWL}]\).

6.3.2.3 Filled Buoyancy

These loads are generated at a node as long as the \( Z \)-coordinate is in the range \([-\text{WtrDpth}, \text{FillFSLoc}]\)
6.4 Strip-Theory Hydrodynamic Coefficients

The strip-theory solution of HydroDyn is dependent, among other factors, on user-specified hydrodynamic coefficients, including viscous-drag coefficients, $Cd$, added-mass coefficients, $Ca$, and dynamic-pressure coefficients, $Cp$, for transverse and axial ($Ax$) loads distributed along members and for axial lumped loads at member ends (joints). There are no default settings for these coefficients in HydroDyn. In general, these coefficients are dependent on many factors, including Reynold’s number (Re), Keulegan-Carpenter number (KC), surface roughness, substructure geometry, and location relative to the free surface, among others. In practice, the coefficients are (1) selected from tables derived from measurements of flow past cylinders, (2) calculated through high-fidelity computational fluid dynamics (CFD) solutions, or (3) tuned to match experimental results. A value of 1.0 is a plausible guess for all coefficients in the absence of any other information.

While the strip-theory solution assumes circular cross sections, the hydrodynamic coefficients can include shape corrections; however, there is no distinction made in HydroDyn between different transverse directions.

Please note that added-mass coefficients in HydroDyn influence both the added-mass loads and the scattering component of the fluid-inertia loads. For the coefficients associated with transverse loads distributed along members, note that $C_p + C_A = C_M$, the inertia coefficient. For the distributed loads along members, there are separate set of hydrodynamic coefficients both with and without marine growth ($MG$).

6.5 Impact of Substructure Motions on Loads

In general, HydroDyn assumes that structural motions of the substructure are small, such that (1) small-angle assumptions apply to structural rotations, (2) the potential-flow solution can be split into uncoupled hydrostatic, radiation, and diffraction solutions, and (3) the hydrodynamic loads dependent on wave kinematics (both from diffraction loads in the potential-flow solution and from the fluid-inertia and viscous-drag loads in the strip-theory solution) can be computed using wave kinematics solved at the undisplaced position of the substructure (the wave kinematics are not recomputed at the displaced position). Nevertheless, HydroDyn uses the substructure motions in the following calculations:

- The structural displacements of the WRP are used in the calculation of the hydrostatic loads (i.e., the change in buoyancy with substructure displacement) in the potential-flow solution.
- The structural velocities and accelerations of the WRP are used in the calculation of the wave-radiation loads (i.e., the radiation memory effect and added mass) in the potential-flow solution.
- The structural displacements and velocities of the WRP are used in the calculation of the additional platform loads (via the Platform Additional Stiffness and Damping).
- The structural velocities of the substructure nodes are used in the calculation of the viscous-drag loads in the strip-theory solution (e.g., the relative form of Morison’s equation is applied).
• The structural accelerations of the substructure nodes are used in the calculation of the added-mass, marine-growth mass inertia, and filled-fluid mass inertia loads in the strip-theory solution.

• When coupled to FAST, the hydrodynamic loads computed by HydroDyn are applied to the displaced position of the substructure (i.e., the displaced platform in ElastoDyn and/or the displaced substructure in SubDyn), but are based on wave kinematics at the undisplaced position.

6.6 Platform Additional Stiffness and Damping

HydroDyn allows the user to apply additional loads to the platform (in addition to other hydrodynamic terms calculated by HydroDyn), by including a 6x1 static load vector (preload) \((AddF0)\), a 6x6 linear restoring matrix \((AddCLin)\), a 6x6 linear damping matrix \((AddBLin)\), and a 6x6 quadratic drag matrix \((AddBQuad)\). These terms can be used, e.g., to model a linearized mooring system, to augment strip-theory members with a linear hydrostatic restoring matrix (see Section 6.6.3), or to “tune” HydroDyn to match damping to experimental results, such as free-decay tests. While likely most useful for floating systems, these matrices can also be used for fixed-bottom systems; in both cases, the resulting load is applied at the WRP, which when HydroDyn is coupled to FAST, get applied to the platform in ElastoDyn (bypassing SubDyn for fixed-bottom systems).

6.7 Fixed-Bottom Substructures

When modeling a fixed-bottom system, the use of a strip-theory (Morison) only model is recommended. When HydroDyn is coupled to FAST, SubDyn is used for the substructure structural dynamics.

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. For example, if the water depth is set to 20 m, and you are modeling a fixed-bottom monopile, then the bottom-most joint needs to have a \(Z\)-coordinate such that \(Z < -20\) m. This configuration avoids having HydroDyn apply static pressure loads on the bottom of the structure.

Gravity-based foundations should be modeled such that the lowest joint(s) are located exactly at the prescribed water depth. In other words, the lowest \(Z\)-coordinate should be set to \(Z = -20\) m if the water depth is set to 20 m. This configuration allows for static pressure loads to be applied at the bottom of the gravity-base structure.

6.8 Floating Platforms

When modeling a floating system, you may use potential-flow theory (via a WAMIT preprocess) only, strip-theory (Morison) only, or a hybrid model containing both.

Potential-flow theory is enabled when \(HasWAMIT\) is set to TRUE. In this case, HydroDyn will look for WAMIT input files—see Section 6.6.4 for guidance. For a potential-flow-only model, do not create any strip-theory joints or members in the input file. The WAMIT model should account for all of the members in the floating substructure, and Morison’s equation is neglected in this case.
For a strip-theory-only model, set HasWAMIT to FALSE and create one or more strip-theory members in the input file. Marine growth and nonzero MSL2SWL (the offset between still-water and mean-sea level) may only be included in strip-theory-only models.

A hybrid model is formed when both HasWAMIT is TRUE and you have defined one or more strip-theory members. The WAMIT model created can consider all of the Morison members in the floating substructure, or just some. Specify whether certain members of the structure are considered in the WAMIT model by setting the PropWAMIT flag for each member. As detailed in Section 7.5.1, the state of the PropWAMIT flag for a given member determines which components of the strip-theory equations are applied.

When using either the strip-theory-only or hybrid approaches, filled fluid (flooding or ballasting) may be added to the strip-theory members. Also, the hydrostatic restoring matrix must be entered manually for the strip-theory members—see Section 6.6.3 for guidance.

Please note that current-induced water velocity only induces hydrodynamic loads in HydroDyn through the viscous-drag terms (both distributed and lumped) of strip-theory members. Current is not used in the potential-flow solution. Thus, modeling the effects of current requires the use of a strip-theory-only or hybrid approach.

6.8.1 Undisplaced Position for Floating Systems

The HydroDyn model (geometry, etc.) is defined about the undisplaced position of the substructure. For floating systems, it is important for solution accuracy for the undisplaced position to coincide with the static-equilibrium position in the platform-heave (vertical) direction in the absence of loading from wind, waves, and current. As such, the undisplaced position of the substructure should be defined such that the external buoyancy from displaced water balances with the weight of the system (including the weight of the rotor-nacelle assembly, tower and substructure) and mooring system pretension following the equation below. In this equation, $\rho$ is the water density, $g$ is gravity, $V_0$ is the undisplaced volume of the floating platform (found in the HydroDyn summary file), $m_{total}$ is the total mass of the system (found in the ElastoDyn summary), and $T_{Mooring}$ is the mooring system pretension (found in e.g. the MAP summary file). The effects of marine growth, filled fluid (flooding and/or ballasting), and the additional static force ($AddFX0$) should also be taken into consideration in this force balance, where appropriate.

$$\rho g V_0 - m_{total}g - T_{Mooring} = 0$$

6.8.2 Initial Conditions for Floating Systems

Because the initial conditions used for dynamic simulations typically have an effect on the response statistics during the beginning of the simulation period, an appropriate amount of initial data should be eliminated from consideration in any post-processing analysis. This initial condition solution is more important for floating offshore wind turbines because floating systems typically have long natural periods of the floating substructure and low damping. The appropriate time to eliminate should be chosen such that initial numeric transient effects have sufficiently decayed and the floating substructure has reached a quasi-stationary position. To decrease this initial time in each simulation, it is suggested that the initial conditions of the model (especially
blade-pitch angle, rotor speed, substructure surge, and substructure pitch in ElastoDyn) be initialized according to the specific prevalent wind, wave, current, and operational conditions.

### 6.8.3 Hydrostatic Restoring for Strip-Theory Members of Floating Systems

One notable absence from the list calculations in HydroDyn that make use of substructure motions—see Section 6.3—is that the substructure buoyancy in the strip-theory solution is not recomputed based on the displaced position of the substructure. While the change in buoyancy is likely negligible for fixed-bottom systems, for floating systems modeled using a strip-theory solution, the change in buoyancy with displacement is likely important and should not be neglected. In this latter case, the user should manually calculate the 6x6 linear hydrostatic restoring matrix associated with the strip-theory members and enter this as the additional linear restoring (stiffness) matrix, $\text{AddCLin}$. (The static buoyancy of the strip-theory members is automatically calculated and applied within HydroDyn.)

In its most general form, the 6x6 linear hydrostatic restoring matrix of a floating platform is given by the equation below.

\[
\text{AddCLin} = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & \rho g A_y & \rho g \int y dA & -\rho g \int x dA & 0 & 0 \\
0 & 0 & \rho g \int y dA & \rho g \int x^2 dA + \rho g V_z z_b - m_{mg} g z_{mg} - m_f g z_f & -\rho g \int y dA & -\rho g V_z z_b + m_{mg} g z_{mg} + m_f g z_f \\
0 & 0 & -\rho g \int x dA & -\rho g \int y dA & \rho g \int x^2 dA + \rho g V_z z_b - m_{mg} g z_{mg} - m_f g z_f & -\rho g V_z z_b + m_{mg} g z_{mg} + m_f g z_f \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix},
\]

where:
- $\rho$ water density, kg/m$^3$
- $g$ gravity, m/s$^2$
- $A_y$ undisplaced waterplane area of platform, m$^2$
- $V_0$ undisplaced volume of platform, m$^3$
- $(x_b, y_b, z_b)$ coordinates of the center of buoyancy of the undisplaced platform, m
- $m_{mg}$ total mass of marine growth, kg
- $(x_{mg}, y_{mg}, z_{mg})$ coordinates of the center of mass of the undisplaced marine growth mass, m
- $m_f$ total mass of ballasting/flooding, kg
- $(x_f, y_f, z_f)$ coordinates of the center of mass of the undisplaced filled fluid (flooding or ballasting) mass, m

The equation above can be simplified when the floating platform has one or more planes of symmetry. That is, $\int y dA = 0$, $\int y dA = 0$, $y = 0$, $y_{mg} = 0$, and $y_f = 0$ if the $x-z$ plane of the platform is a symmetry plane. Likewise, $\int x dA = 0$, $\int x dA = 0$, $x = 0$, $x_{mg} = 0$, and $x_f = 0$ if the $y-z$ plane of the platform is a symmetry plane.
The undisplaced coordinates of the center of buoyancy, \((x_b, y_b, z_b)\), center of marine-growth mass, \((x_{mg}, y_{mg}, z_{mg})\), and center of filled-fluid mass, \((x_f, y_f, z_f)\), are in the global inertial-frame coordinate system. Most of these parameters can be derived from data found in the HydroDyn summary file. While the equation above makes use of several area integrals, the integrals can often be easily estimated by hand for platforms composed of one or more circular members piercing the waterplane (still-water free surface).

The waterplane area of the undisplaced platform, \(A_0\), affects the hydrostatic load because the displaced volume of the fluid changes with changes in the platform displacement. Similarly, the location of the center of buoyancy of the platform affects the hydrostatic load because its vector position changes with platform displacement and because the cross product of the buoyancy force with the vector position produces hydrostatic moments about the WRP. \(A_0\), \(V_0\), and \((x_b, y_b, z_b)\) should be based on the external volume of the platform, including marine-growth thickness. The marine-growth mass and filled-fluid mass also have a direct effect of the hydrostatic restoring because of the moments produced about the WRP.

In classical marine hydrostatics, the effects of body weight are often lumped with the effects of hydrostatics when defining the hydrostatic-restoring matrix; for example, when it is defined in terms of metacentric heights. However, when HydroDyn is coupled to FAST, the body-weight terms (other than the marine-growth and filled-fluid mass within HydroDyn) are automatically accounted for by ElastoDyn, and so, are not included here.

### 6.8.4 Floating Systems Modeled with Potential Flow

Frequency-dependent hydrodynamic coefficients are needed before running the potential-flow solution in HydroDyn. An external pre-processing tool should be used to generate the appropriate frequency-dependent hydrodynamic coefficients. The naming in this manual has focused on WAMIT [Lee, 2006], but other frequency-domain wave-body interaction panel codes can be used that produce similar data. However, in the end, the WAMIT format is what is expected by HydroDyn.

For the first-order potential-flow solution, HydroDyn requires data from the WAMIT files with .1, .3, and .hst extensions. When creating these files, one should keep in mind:

- The .1 file must contain the 6×6 added-mass matrix at infinite frequency (period = zero). Additionally, the .1 file must contain the 6×6 damping matrix over a large range from low frequency to high frequency (the damping should approach zero at both ends of the range). A range of 0.0 to 5.0 rad/s with a discretization of 0.05 rad/s is suggested.
- The .3 file must contain the first-order wave-excitation (diffraction) loads (3 forces and 3 moments) per unit wave amplitude across frequencies and directions where there is wave energy. A range of 0.0 to 5.0 rad/s with a discretization of 0.05 rad/s is suggested and the direction should be specified across the desired range—the full direction range of (-180 to 180) degrees with a discretization of 10 degrees is suggested. While the .3 file contains both the magnitude/phase and real/imaginary components of the first-order wave-excitation loads, only the latter are used by HydroDyn.
- The .hst file should account for the restoring provided by buoyancy, but not the restoring provided by body mass or moorings. (The hydrostatic file is not frequency dependent.) An important thing to keep in mind is that the pitch and roll restoring of a floating body depends on the vertical distance between the center of buoyancy and center of mass of the body. In WAMIT, the vertical center of gravity (VCG) is used to determine the pitch and roll restoring associated with platform weight, and WAMIT will include these effects in the restoring matrix that it outputs (the .hst file). However, the ElastoDyn module of FAST intrinsically accounts for the platform weight’s influence on the pitch and roll restoring if the platform weight and center-of-mass location are defined appropriately. To avoid double booking these terms, it is important to neglect these terms in WAMIT. This can be achieved by setting VCG to zero when solving the first-order problem in WAMIT.

The second-order WAMIT files only need to pre-calculated if a second-order potential-flow option is enabled in HydroDyn. For the second-order mean-drift solution, or for Standing et al.’s extension to Newman’s approximation to the mean- and slow-drift solution, HydroDyn requires WAMIT files with .7, .8, .9, .10d, .11d, or .12d extensions. For the second-order full difference-frequency solution of the mean- and slow-drift terms, HydroDyn requires WAMIT files with .10d, .11d, or .12d extension. For the second-order full sum-frequency solution, HydroDyn requires WAMIT files with .10s, .11s, or .12s extensions. When creating any of these files, one should keep in mind:

- The second-order frequency-domain solution is dependent on first-order body motions, whose accuracy is impacted by properly setting the 6×6 rigid-body mass matrix and center of gravity of the complete floating wind system and the 6×6 mooring system restoring matrix. So, while the body center of gravity and mooring stiffness should be zeroed when creating the first-order WAMIT files, they should not be zeroed when creating the second-order WAMIT files. (Thus, obtaining the first-order and second-order WAMIT files requires distinct WAMIT runs.)

- The .7, .8, and .9 files contain the diagonal of the difference-frequency QTF, based on the first-order potential-flow solution. The files contain the second-order mean-drift loads (3 forces and 3 moments) per unit wave amplitude squared at each first-order wave frequency and pair of wave directions, across a range of frequencies and a range of direction pairs. While the .7, .8, and .9 files contain both the magnitude/phase and real/imaginary components of the second-order wave-excitation loads, only the latter are used by HydroDyn.

- The .10d, .11d, and .12d, or .10s, .11s, and .12s files contain the full difference- and sum-frequency QTFs, respectively, based on the first-order or first- plus second-order potential-flow solutions. The files contain the second-order wave-excitation (diffraction) loads (3 forces and 3 moments) per unit wave amplitude squared at each pair of first-order wave frequencies and directions, across a range of frequency and direction pairs. While the .10d, .11d, .12d, .10s, .11s, and .12s files contain both the magnitude/phase and real/imaginary components of the second-order wave-excitation loads, only the latter are used by HydroDyn.

- The frequencies and directions in the WAMIT files do not need to be evenly spaced.
• The discretization of the first set of directions does not need to be the same as the discretization of the second set of directions; however, the matrix of direction pairs must be fully populated (not sparse). Both sets of directions should span across the desired range—the full direction range of (-180 to 180] degrees with a discretization of 10 degrees is suggested.

• The frequencies should span the range where there is first-order wave energy and the frequency discretization should be such that the differences and sums between pairs of frequencies span the range where there is second-order wave energy. A range of 0.25 to 2.75 rad/s with a discretization of 0.05 rad/s is suggested.

• Second-order hydrodynamic theory dictates that difference-frequency QTFs are conjugate symmetric between frequency pairs and sum-frequency QTFs are symmetric between frequency pairs. Due to this symmetry, the QTFs (the $10d$, $11d$, or $12d$, $10s$, $11s$, and $12s$ files) may be upper triangular, lower triangular, a mix of upper and lower triangular terms, or full; however, after applying the symmetry, the matrix of frequency pairs must be fully populated (not sparse). When an element of the QTF is supplied together with its symmetric pairing, HydroDyn will warn the user if the QTF is not properly symmetric.
7 HydroDyn Theory

This is a preliminary draft of the HydroDyn theory and should be considered a work in progress.

Hydrodynamics are modeled using a suitable combination of incident-wave kinematics and hydrodynamic loading models. Hydrodynamic loads result from the integration of the dynamic pressure of the water over the wetted surface of a floating platform. These loads include contributions from inertia (added mass) and linear drag (radiation), buoyancy (restoring), incident-wave scattering (diffraction), sea current, and nonlinear effects.

7.1 Coordinate Systems

7.1.1 Global coordinate system: \((X, Y, Z)\)

- The global axes are represented by the unit vectors \(\hat{I}\), \(\hat{J}\), and \(\hat{K}\).
- The origin is set at the mean sea level, the center of the structure, with Z axis positive upward.
- The positive X axis is along the nominal (zero-degree) wave propagation direction.
- The Y axis can be found assuming a right-handed Cartesian coordinate system.
7.1.2 Structural member local coordinate system: \((x, y, z)\)

- Axes are represented by the unit vectors \(\hat{i}, \hat{j}, \) and \(\hat{k}\).
- The origin is set at the center of the structural member.
- The local \(z\) axis is along the cylinder axis, directed from the start joint to the end joint. The start joint is defined as the joint that has a lower \(Z\) coordinate value. If the two joints have the same \(Z\) coordinate value, then the one that has the lower \(X\) coordinate value is the start point. If the two joints have the same \(Z\) and \(X\) coordinate value, then the one that has the lower \(Y\) coordinate value is the start point.
- The local \(x\) axis is parallel to the global \(XZ\) plane, positive along the nominal wave propagation direction. If the cylinder’s axis is along the global \(X\) direction, then the local \(x\) axis is parallel to the \(XZ\) plane, and positive along the negative global \(Z\) direction.
- The local \(y\) axis can be found assuming a right-handed Cartesian coordinate system.

7.1.3 Local to Global transformation

For regular members, the cylinder expression in global coordinate system can be found as follows:

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = \left[ C \right] \begin{bmatrix}
X_s + X_e \\
Y_s + Y_e \\
Z_s + Z_e
\end{bmatrix} + \begin{bmatrix}
\frac{r \cos \theta}{2} \\
\frac{r \sin \theta}{2} \\
z
\end{bmatrix}
\]

where \((X_s, Y_s, Z_s)\) and \((X_e, Y_e, Z_e)\) are the start and end joints of the member in global coordinate system of the member, and \([C]\) is the direction cosine matrix of the member axis and can be obtained as follows:

\[
[C] = \begin{bmatrix}
\frac{Z_e - Z_s}{L_{xz}} & -\frac{(X_e - X_s)(Y_e - Y_s)}{L_{xz}L} & \frac{X_e - X_s}{L} \\
0 & \frac{L_{xz}}{L} & \frac{Y_e - Y_s}{L} \\
-\frac{X_e + X_s}{L_{xz}} & -\frac{(Z_e - Z_s)(Y_e - Y_s)}{L_{xz}L} & \frac{Z_e - Z_s}{L}
\end{bmatrix}
\]

where \(L_{xz} = \sqrt{(X_e - X_s)^2 + (Z_e - Z_s)^2}\) and \(L = \sqrt{(X_e - X_s)^2 + (Y_e - Y_s)^2 + (Z_e - Z_s)^2}\). When \(X_e = X_s\) and \(Z_e = Z_s\), the \([C]\) matrix can be found as follows:

if \(Y_e < Y_s\) then

\[
\left( X_e + X_s \right) = \left( Y_e + Y_s \right)
\]

\[
\left( Z_e + Z_s \right) = \left( \frac{Y_e - Y_s}{L} \right)
\]

\[
\left( \frac{X_e - X_s}{L} \right) = \left( \frac{Z_e - Z_s}{L} \right)
\]

\[
\left( \frac{Y_e - Y_s}{L} \right)
\]

\[
\left( \frac{Z_e - Z_s}{L} \right)
\]
\[ [C] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix} \]

else

\[ [C] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -1 & 0 \end{bmatrix} \]

### 7.2 Wave Kinematics

The wave kinematics are modeled using Airy wave theory, which can be used to describe either regular or irregular waves. For regular waves, the wave elevation (\( \zeta \)) is represented as a sinusoid with a single amplitude (wave height) and frequency. Airy wave theory also describes how the undisturbed fluid-particle velocities and accelerations decay exponentially with depth. Irregular or random waves can then be represented as a summation or superposition of multiple wave components, as described by an appropriate wave spectrum:

\[
\zeta(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} W(\omega) \sqrt{2\pi S_{\zeta}^{2\text{ - sided}}} e^{j\omega t} d\omega
\]

This equation represents the wave elevation as an inverse Fourier transform of the desired two-sided power spectral density, \( S_{\zeta}^{2\text{ - sided}} \) where \( j \) is an imaginary number and \( \omega \) is an individual wave frequency. \( W(\omega) \) is the Fourier transform of a realization of a white Gaussian noise (WGN) time-series process with zero mean and unit variance (i.e., the so-called “standard normal distribution”). This realization is used to ensure that the individual wave components have a random phase and that the instantaneous wave elevation is normally- (i.e., Gaussian-) distributed with zero mean and with a variance, on average, equal to \( \sigma_{\zeta}^2 = \int_{-\infty}^{\infty} S_{\zeta}^{2\text{ - sided}}(\omega) d\omega \).

Further details about the wave kinematics and how they are computed can be found in [Jenkman, 2007].

### 7.3 Current Model

The current model within HydroDyn is a superposition of three different types of sub-models. These sub-models follow the forms defined in the IEC 61400-3 offshore wind standard [IEC, 2009].

The first is a sub-surface current model for currents that are generated by tides, storm surge, atmospheric pressure variations, etc. This model is characterized by a simple 1/7 power law over the water depth, \( d \).

\[
U_{SS}(Z) = U_{0SS} \left( \frac{Z + d}{d} \right)^{\frac{1}{7}}
\]
The second is near-surface currents generated by wind. This model is characterized by a linear
distribution of the velocity with water depth, ending at zero at a prescribed depth, $h_{\text{ref}}$ (in [IEC, 2009], $h_{\text{ref}}$ is set at 20 m).

$$U_{NS}(Z) = U_{0,NS} \left( \frac{Z + h_{\text{ref}}}{h_{\text{ref}}} \right), Z \in [-h_{\text{ref}}, 0], \text{otherwise, } U_{NS}(Z) = 0$$

The third model is a depth-independent model, which sets the current velocity to a constant value
across the water depth.

You can specify a unique heading direction for each of the three current models.

### 7.4 Potential Flow Theory

Three main approaches exist for modeling the hydrodynamic loads within HydroDyn, potential-flow theory, strip theory (via Morison’s equation), or a combination. This section reviews the forces modeled in HydroDyn when using a linear potential flow theory approach.

#### 7.4.1 Modeling Approach

In linear potential-flow theory, the forces and added mass are applied at the platform reference
point. The components are:

$$\vec{F}_{WRP} = \vec{F}_W + \vec{F}_{HS} + \vec{F}_{RD} + \vec{F}_{AM}$$

where

$$\vec{F}_{AM} = -AM_{RP} \vec{a}_p$$

$$\vec{F}_W = \frac{1}{N} \sum_{k=\frac{N}{2}}^{\frac{N}{2}-1} W[k]\sqrt{\frac{2\pi}{\Delta t}} S_{12}^{\text{2-sided}}(\omega) X(\omega, \beta)_{\omega=\omega_0} e^{j2\pi k t \Delta t}$$

$$\vec{F}_{HS} = \rho g V_0 \left( \delta_3 + y^{CB} \delta_4 - x^{CB} \delta_5 \right) - C_{\text{Hydrostatic}} x$$

The general form of the convolution integral is:

$$\vec{F}_{RD} = \int_0^t K(t - \tau) \cdot \dot{x}(\tau) d\tau$$

But we discretize this and only consider a specific amount time history, $N_{RD}$:

$$\vec{F}_{RD} = -\Delta t_{RD} \sum_{i=n-N_{RD}}^{n-1} K_{n-i-1} \dot{x}_i$$
The state for time step \( n \) is simply the structural velocities for the previous \( N_{RD} \) time steps. Or,

\[
x_n^d = \begin{cases} 
\dot{x}_{n-1} \\
\dot{x}_{n-2} \\
\vdots \\
\dot{x}_{n-N_{RD}} 
\end{cases}
\]

Therefore, at time step \( n \), we can compute the \( n+1 \) state, such that,

\[
x_{n+1}^d = \begin{cases} 
\dot{x}_n \\
\dot{x}_{n-1} \\
\vdots \\
\dot{x}_{n-N_{RD}+1} 
\end{cases}
\]

The radiation step size, \( \Delta t_{RD} \), and the radiation kernel, \( K \), are simply module parameters.

### 7.5 Morison’s Equation

Morison’s equation is applicable for calculating the hydrodynamic loads on cylindrical structures when (1) the effects of diffraction are negligible, (2), radiation damping is negligible, and (3) flow separation may occur. The relative form of Morison’s equation accounts for wave loading from incident-wave-induced excitation, radiation-induced added mass, and flow-separation-induced viscous drag. In this section we review the representation of Morison’s equation both when considering distributed forces along the length of the members (at nodes) and point loads at the ends (at the joints).

#### 7.5.1 Modeling Approach

In the present version of HydroDyn, Morison forces are applied only along the portion of the member below the SWL. Wave stretching theory has not yet been implemented. In addition, the forces are applied at the original position of the structure, and not at the instantaneous position.

#### 7.5.1.1 Distributed Loads

For a Morison-only model, the distributed hydrodynamic loads applied along the length of a member are computed as:

\[
\overline{F} = \overline{F}_I + \overline{F}_D + \overline{F}_B + \overline{F}_{MG} + \overline{F}_{F.B} + \overline{F}_{AM.M} + \overline{F}_{AM.MG} + \overline{F}_{AM.F}
\]

where \( \overline{F}_I \) is the inertia force, \( \overline{F}_D \) the drag force, \( \overline{F}_B \) the buoyancy force, \( \overline{F}_{MG} \) the weight of the marine growth, \( \overline{F}_{F.B} \) the force due to fluid ballasting, \( \overline{F}_{AM.M} \) the added mass of the structure, \( \overline{F}_{AM.MG} \) the added mass due to marine growth, and \( \overline{F}_{AM.F} \) the added mass due to fluid ballasting. Details about each of these forces will be provided in the following sections. All of these forces except the buoyancy forces, \( \overline{F}_B \), and \( \overline{F}_{F.B} \), are applied directly to a mesh node.
If a hybrid model is desired, which combines contributions from both potential-flow theory and Morison’s equation, the only components that are considered for Morison’s equation are:

\[
\vec{F} = \vec{F}_D + \vec{F}_{F-B} + \vec{F}_{AM-F}
\]

### 7.5.1.1 Inertial Loads

The inertial force component of Morison’s equation is associated with the fluid acceleration, and includes two terms. The first is the Froude-Krylov term associated with the unsteady pressure field generated by the undisturbed waves. This term can be controlled using the \(C_P\) coefficient, with a value of 1.0 being the default. The second term is the scattering force associated with the disruption of the fluid by the presence of the structure. This term is controlled by the coefficient of added mass, \(C_A\). The equation below gives the full representation of the inertia force, which includes transverse and axial forces (represented by the \(Ax\) subscript).

\[
\vec{F}_I = \left\{ \begin{align*}
(C_P + C_A) \rho_w \pi (R + t_{MG})^2 \left( \vec{a}_f - \left( \vec{a}_f \cdot \hat{k} \right) \hat{k} \right) + \left[ C_{p_w} 2\pi (R + t_{MG}) \frac{\partial R}{\partial z} p_{dyn} + C_{A_w} \rho_w 2\pi (R + t_{MG}) \right] \frac{\partial R}{\partial z} \left( \vec{a}_f \cdot \hat{k} \right) \hat{k} \\
0 \\
0 \\
0 
\end{align*} \right\}
\]

where \(\frac{\partial R}{\partial z} = \frac{(R^e + t_{MG}^e) - (R^e + t_{MG}^s)}{(Z^e - Z^s)}\)

It is noted that \(C_P + C_A = C_M\), the inertia coefficient. \(C_P\) is called the dynamic pressure coefficient. By creating the dynamic pressure coefficient, \(C_M\) and \(C_A\) can be controlled independently.

### 7.5.1.2 Viscous Drag

The second major component of Morison’s equation is the viscous drag force, which is represented in the equation below. The viscous drag force is proportional to the square of relative velocity between the fluid and the structure, and is scaled using the coefficient of drag, \(C_D\).

\[
\vec{F}_D = \begin{bmatrix}
C_D \rho_w (R + t_{MG}) \left\| \vec{v}_{rel} - \left( \vec{v}_{rel} \cdot \hat{k} \right) \hat{k} \right\|_2 \left( \vec{v}_{rel} - \left( \vec{v}_{rel} \cdot \hat{k} \right) \hat{k} \right) \\
0 \\
0 \\
0 
\end{bmatrix}
\]

### 7.5.1.3 Buoyancy

The next term presented is the buoyancy term, which is the force directed along the global Z-axis equal to the weight of the displaced fluid when the platform is in its undisplaced position.
Marine growth is considered in the force equation by adding its weight, as shown below, where $t_{MG}$ is the thickness of the marine growth and $\rho_{MG}$ its density.

$$\bar{F}_{MG} = \rho_{MG}g \begin{bmatrix} C \begin{bmatrix} C_{31}\pi (R + t_{MG})^2 \\ C_{32}\pi (R + t_{MG})^2 \\ -2\pi (R + t_{MG}) \frac{\partial R}{\partial z}Z \\ -C_{32}\pi \frac{\partial R}{\partial z} (R + t_{MG})^3 \\ +C_{31}\pi \frac{\partial R}{\partial z} (R + t_{MG})^3 \\ 0 \end{bmatrix} \end{bmatrix}$$

### 7.5.1.1.5 Ballasting

One can choose to add water ballasting to the individual members. The effect of this ballasting is considered in the equation below, where $Z_{fs}$ is the free-surface height of the ballast fluid in a member.

$$\bar{F}_{MG} = -\rho_{mg}g\pi \begin{bmatrix} 0 \\ 0 \\ -(R + t_{MG})^2 - R^2 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$
The next group of terms is associated with the added mass of the structure, which is proportional to the acceleration of the structure. The added mass is the inertia added to a system because an accelerating body must move some volume of surrounding fluid as it moves through it. In the equations below, both transverse and axial terms are shown.

\[
\begin{align*}
\vec{F}_{F_B} = -\rho_f g C \begin{cases} 
C_{31} \pi (R-t)^2 \\
C_{32} \pi (R-t)^2 \\
-2\pi (R-t) \frac{\partial R}{\partial z}(Z - Z_f)
\end{cases}
\end{align*}
\]

\[
\begin{align*}
\vec{F}_{AM} = -AM_M \begin{bmatrix} \bar{a}_t \\ \bar{a}_s \end{bmatrix}
\end{align*}
\]

7.5.1.1.6 Hydrodynamic Added Mass

If marine growth is applied to the structure, this additional volume will alter the added mass calculation. Here, the influence of the marine growth is captured through an additional term.

\[
AM_{MG} = \rho_{mg} \pi \left( (R + t_{MG})^2 - R^2 \right) \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}
\]

\[
\vec{F}_{AM_MG} = -AM_{MG} \begin{bmatrix} \bar{a}_t \\ \bar{a}_s \end{bmatrix}
\]
7.5.1.1.8 Added Mass due to Ballasting

Similarly, the added mass is altered by the existence of fluid ballasting, which is captured in the following equations.

\[
AM_F = \rho_f \pi \left( R - t_M \right)^2 \begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]

\[
\vec{F}_{AM-F} = -AM_F \begin{bmatrix}
\vec{a}_s \\
\vec{a}_{s} \\
\end{bmatrix}
\]

7.5.1.2 Lumped Loads at member ends

The previous section covered distributed forces along the length of a member. Now, lumped forces at member ends are considered.

When using a Morison-only model, the lumped forces for Morison’s equation at the member ends include the following components:

\[
\vec{F} = \vec{F}_I + \vec{F}_D + \vec{F}_B + \vec{F}_{F-B} + \vec{F}_{AM}
\]

However, if the member is modeled using a hybrid approach combining both potential flow theory and Morison’s equation, only the following terms are considered:

\[
\vec{F} = \vec{F}_D + \vec{F}_{F-B}
\]

The influences of the individual terms in Morison’s equation in a lumped formulation are the same as the description for the distributed forces, but the implementation changes. Whereas the distributed forces considered the projected area and diameter of the member assuming a cylindrical geometry, at the ends the member is considered a flat plate in Morison’s equation.
### 7.5.1.2.1 Inertial Loads

\[
\overrightarrow{F}_I = \begin{cases} 
C \begin{bmatrix} C_{p_n} \pi \left( R^e + t_{MG}^e \right)^2 P_{dyn} & \frac{C_{A_{n,}} \rho_w \overline{V}_n (\overline{a}_f \cdot \overline{V}_n)}{\sqrt{\left( \overline{V}_n \cdot \overline{V}_n \right)}} \end{bmatrix} + 0 \\
- \frac{C_{p_n} \pi \left( R^e + t_{MG}^e \right)^2 P_{dyn}}{0} \\
0 \\
0 \\
0 \end{cases} \]

(32)

where \( \overline{V}_n = \sum_i \frac{2}{3} \pi \left( R^i + t_{MGi} \right)^3 \hat{n}_i \)

The terms in \( \overrightarrow{F}_I^r \) and \( \overrightarrow{F}_I^e \) involving \( C_{A_{n,}} \) must be divided by \( M \) and distributed equally to the start/end node each member at each joint.

### 7.5.1.2.2 Viscous Drag

\[
\overrightarrow{F}_D = \begin{bmatrix} 
C_{D_{A_{n,}}} \rho_w \overline{A}_n \left\| \overline{v}_{rel} \cdot \overline{A}_n \right\| \left( \overline{v}_{rel} \cdot \overline{A}_n \right) \\
4 \left( \overline{A}_n \cdot \overline{A}_n \right) \\
0 \\
0 \\
0 \end{bmatrix} \]

(31)

Equation 31 is the total lumped drag at a joint, since the simulation mesh consists of \( M \) co-located lumped nodes, \( \overrightarrow{F}_D \) is actually \( \overrightarrow{F}_D \frac{F_D}{M} \) for each simulation node.
7.5.1.2.3 Buoyancy

\[
\tilde{F}_B = \rho_s g \begin{cases} 
0 \\
C_s \\
-Z^s \pi \left( R^s + t_M^s \right)^2 \\
-C_{32} \left( \frac{\pi}{4} \left( R^s + t_M^s \right)^4 \right) \\
C_{31} \left( \frac{\pi}{4} \left( R^s + t_M^s \right)^4 \right) \\
0 
\end{cases}
\] (35)

\[
\tilde{F}_B = \rho_s g \begin{cases} 
0 \\
C_e \\
Z^e \pi \left( R^e + t_M^e \right)^2 \\
\frac{\pi}{4} \left( \frac{\pi}{4} \left( R^e + t_M^e \right)^4 \right) \\
\frac{\pi}{4} \left( \frac{\pi}{4} \left( R^e + t_M^e \right)^4 \right) \\
0 
\end{cases}
\] (36)

7.5.1.2.4 Ballasting

\[
\tilde{F}_{F,B} = -\rho_f g \begin{cases} 
0 \\
C^s \\
- \left( Z^s - Z^e \right) \pi \left( R^s - t_M^s \right)^2 \\
-C_{32} \left( \frac{\pi}{4} \left( R^s - t_M^s \right)^4 \right) \\
C_{31} \left( \frac{\pi}{4} \left( R^s - t_M^s \right)^4 \right) \\
0 
\end{cases}
\] (37)
Hydrodynamic Added Mass

\[
\vec{F}_{AM} = \begin{cases} 
    -C_{A_3}\rho_access\vec{V}_n\left(\vec{a}_s \cdot \vec{V}_n\right) \\
    \sqrt{\left(\vec{V}_n \cdot \vec{V}_n\right)} \\
    0 \\
    0 \\
    0 
\end{cases}
\]

This is the total lumped added mass force at a joint, since the simulation mesh consists of M co-located lumped nodes, \(\vec{F}_{AM}\) is actually \(\frac{\vec{F}_{AM}}{M}\), for each simulation node.

Note that \(\hat{n}_i\) is the outward facing normal vector, so, \(\hat{n}_i = -\hat{k}_i\) at the start (s) of a member and \(\hat{n}_i = \hat{k}_i\) at the end (e) of a member.

### 7.5.2 Simulation Discretization

HydroDyn refines the input geometry of joints and members into a resulting set of nodes and elements using the following algorithm:

1. Copy initial input geometry of joints/members to an initial node/element description.
2. For each element, swap the element nodes if they do not satisfy the specifications of Section 7.1.2.
3. For each element, determine if the element needs to be split for any of the following reasons; adding a node and an element to the mesh for each positive test:
   - The element is filled and the free-surface elevation lies within the element; add node at free-surface elevation.
- The element crosses the $MSL2SWL$ elevation; add node at $MSL2SWL$ elevation.
- The element crosses the seabed; add node at seabed elevation.
- The element crosses the upper and/or lower marine-growth elevations; add one or two nodes corresponding to the upper and/or lower marine growth elevations.

4. For each resulting element, if its length is greater than $MDivSize$ for its associated input member, then subdivide into the necessary number of additional elements such that each element’s length is less than or equal to $MDivSize$. Any new nodes created as a part of this subdivision are referred to as “interior nodes”.

5. Finally, for each non-interior node, determine if it connects to more than one element. If so, make N-1 copies of that node, where N is the number of elements connecting to the node. Redefine the connectivity of these connected elements such that the original node and the new nodes connect to only one element.
8 Future Work
This list contains features that we will implement in future releases:

- Enable times-series input motions for Morison members in the standalone HydroDyn (MorisonInputsMod = 2)
- Enable tight-coupling to FAST, including linearization.
- Enable wave stretching (WaveStMod > 0).
- Enable full support for floating platform force flags.
- Enable joint overlap calculations (JointOvrlp = 1).
- Support for user-defined wave time history.
- Enable auto-generation of all possible output channels (OutAll = TRUE).
- Ensure that the output channels are written in the order they are entered.
- Allow for a WAMIT reference point location other than (0,0,0).
- Allow RdtnDT to be independent from the FAST simulation time step
- Add distributed axial viscous-drag loads on tapered members.
- Add rotational inertia terms for fluid-filled members and marine growth.
- Calculate the effective 6x6 added-mass matrix from strip-theory members and place in the HydroDyn summary file.
- Add graphics/animation capability to visualize the substructure geometry and motion, wave elevation, and hydrodynamic loads.
- Further validation with test data.
- Add higher order regular wave kinematics models for fixed-bottom substructures.
- Add breaking wave-impact loads for fixed-bottom substructures.
- Add floating platform hydro-elastics.
- Add pressure mapping for floating platforms.
- Fix the problem whereby HydroDyn can’t be run after compiling with gFortran.
- Added automated computation and use of hydrostatic restoring matrix for strip-theory members.
9 References

This is a preliminary draft of the reference list and should be considered a work in progress.


NREL 5.0 MW offshore baseline floating platform HydroDyn input properties for the OC4 Semi-submersible.
False
- Echo the input file data (flag)

--- ENVIRONMENTAL CONDITIONS ---

1.025 WtRDrph - Water depth (m)
0 MSL2SWL - Offset between still-water level and mean sea level (meters) [positive upward; must be zero if HasWAMIT=TRUE]

--- WAVES ---

3 WaveMod - Incident wave kinematics model {0: none=still water, 1: plane progressive (regular), 1P#: plane progressive with user-specified phase, 2: ...
0.2 WaveDT - Time step for incident wave calculations (sec) [only used when WaveMod=0 or 1]
1.2646 Waves - Significant wave height of incident waves (meters) [used only when WaveMod=1, 2, or 3]
10 Waves - Peak-spectral period of incident waves (sec) [used only when WaveMod=1 or 2]

"DEFAULT" WavePkShp - Peak-shape parameter of incident wave spectrum (-) or DEFAULT (string) [used only when WaveMod=2] [use 1.0 for Pierson-Moskowitz]
0.314159 WvLowCOff - Low cut-off frequency or lower frequency limit of the wave spectrum beyond which the wave spectrum is zeroed (rad/s) [used only when WaveMod=2, 3, or 4]
1.570796 WvHiCOff - High cut-off frequency or upper frequency limit of the wave spectrum beyond which the wave spectrum is zeroed (rad/s) [used only when WaveMod=2, 3, or 4]
0 WaveDir - Incident wave propagation heading direction (degrees) [used only when WaveMod=0 or 5]
0 WaveDirMod - Directional spreading function {0: none, 1: COS2S} (-) [used only when WaveMod=2, 3, 4 and WaveDirMod=1]
1 WaveDirRange - Number of wave directions [odd number only, may be adjusted within HydroDyn]
0 WaveDirRange - Range of wave directions (full range: WaveDir +/- 1/2*WaveDirRange) (degrees) [only used when WaveMod=2,3,4 and WaveDirMod=1]
123456789 WaveSeed - Second random seed of incident waves [-2147483648 to 2147483647] (-) [unused when WaveMod=0 or 5]
1011121314 WaveSeed - First random seed of incident waves [-2147483648 to 2147483647] (-) [unused when WaveMod=0 or 5]
0 WaveDir - Incident wave propagation heading direction (degrees) [used only when WaveMod=0 or 5]
0 WaveDirMod - Directional spreading function {0: none, 1: COS2S} (-) [used only when WaveMod=2, 3, 4 and WaveDirMod=1]
1 WaveDirRange - Number of wave directions [odd number only, may be adjusted within HydroDyn]
0 WaveDirRange - Range of wave directions (full range: WaveDir +/- 1/2*WaveDirRange) (degrees) [only used when WaveMod=2,3,4 and WaveDirMod=1]
123456789 WaveSeed - Second random seed of incident waves [-2147483648 to 2147483647] (-) [unused when WaveMod=0 or 5]
1011121314 WaveSeed - First random seed of incident waves [-2147483648 to 2147483647] (-) [unused when WaveMod=0 or 5]

--- CURRENT ---

0 CurrMod - Current profile model {0: none=no current, 1: standard, 2: user-defined from routine UserCurrent} (switch)
0 CurrSSV0 - Sub-surface current velocity at still water level (m/s) [used only when CurrMod=1]
0 CurrNSV - Near-surface current reference depth (meters) [used only when CurrMod=1]
0 CurrNSV - Near-surface current velocity at still water level (m/s) [used only when CurrMod=1]
0 CurrNSV - Near-surface current heading direction (degrees) or DEFAULT (string) [used only when CurrMod=1]
0 CurrNSV - Near-surface current heading direction (degrees) or DEFAULT (string) [used only when CurrMod=1]
0 CurrDIDir - Depth-independent current heading direction (degrees) [used only when CurrMod=1]
0 CurrDIDir - Depth-independent current heading direction (degrees) [used only when CurrMod=1]

--- FLOTTING PLATFORM ---

TRUE HasWAMIT - Using WAMIT (flag)
"HydroData/marin_semi" WAMITFile - Root name of WAMIT output files containing the linear, nondimensionalized, hydrostatic restoring matrix (.hst extension), ...
1 WAMITULEN - Characteristic body length scale used to redimensionalize WAMIT output (meters)
13917 PtfmVol - Displaced volume of water when the platform is in its undisplaced position (m^3) [USE THE SAME VALUE COMPUTED BY WAMIT AS OUTPUT IN THE .OUT FILE!]
0 PtfmCOBxt - The x coordinate of the center of buoyancy (COB) from the platform reference point (meters)
0 PtfmCOBxt - The y coordinate of the center of buoyancy (COB) from the platform reference point (meters)
1 RadtnMod - Radiation memory-effect model {0: no memory-effect calculation, 1: convolution, 2: state-space} (switch) [STATE-SPACE REQUIRES *.ss INPUT FILE]
RdtnTMax - Analysis time for wave radiation kernel calculations (sec) [determines RdtnDOmega=Pi/RdtnTMax in the cosine transform] [MAKE SURE THIS ...

RdtnDT - Time step for wave radiation kernel calculations (sec) [DT<=RdtnDT<=0.1 recommended] [determines RdtnOmegaMax=Pi/RdtnDT in the cosine transform]

2ND-ORDER FLOATING PLATFORM FORCES

MnDrift - Mean-drift 2nd-order forces computed {0: None; [7, 8, 9, 10, 11, or 12]: WAMIT file to use} [Only one of ...

NewmanApp - Mean- and slow-drift 2nd-order forces computed with Newman's approximation {0: None; [7, 8, 9, 10, 11, or 12]: WAMIT file to use} [Only one of ...

DiffQTF - Full difference-frequency 2nd-order forces computed with full QTF {0: None; [10, 11, or 12]: WAMIT file to use} [Only one of ...

SumQTF - Full summation -frequency 2nd-order forces computed with full QTF {0: None; [10, 11, or 12]: WAMIT file to use}

FLOATING PLATFORM FORCE FLAGS

PtfmSgF - Platform horizontal surge translation force (flag) or DEFAULT

PtfmSwF - Platform horizontal sway translation force (flag) or DEFAULT

PtfmHvF - Platform vertical heave translation force (flag) or DEFAULT

PtfmRF - Platform roll tilt rotation force (flag) or DEFAULT

PtfmPF - Platform pitch tilt rotation force (flag) or DEFAULT

PtfmYF - Platform yaw rotation force (flag) or DEFAULT

PLATFORM ADDITIONAL STIFFNESS AND DAMPING

AddF0 - Additional preload (N, N-m)

AddClin - Additional linear stiffness (N/m, N/rad, N-m/m, N-m/rad)

AddBlin - Additional linear damping(N/(m/s), N/(rad/s), N-m/(m/s), N-m/(rad/s))

AddBQuad - Additional quadratic drag(N/(m/s)^2, N/(rad/s)^2, N-m/(m/s)^2, N-m/(rad/s)^2)

AXIAL COEFFICIENTS

AxCd - Number of axial coefficients (-)

AxCa - Additional preload (N, N-m)

AxCp - Additional linear stiffness (N/m, N/rad, N-m/m, N-m/rad)

AxCq - Additional linear damping(N/(m/s), N/(rad/s), N-m/(m/s), N-m/(rad/s))

AxCd - Additional quadratic drag(N/(m/s)^2, N/(rad/s)^2, N-m/(m/s)^2, N-m/(rad/s)^2)

MEMBER JOINTS

JointID - Number of joints (-) [must be exactly 0 or at least 2]

Jointx1 - Jointy1 - Jointz1 - JointxID - JointyID - JointzID - JointAxID - JointOvrlp [JointOvrlp= 0: do nothing at joint, 1: eliminate overlaps by calculating super member]

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14.43376 25.00000 -14.00000 1 0 0 0
0.00000 0.00000 10.00000 1 0 0 0
-28.86751 0.00000 -14.00000 1 0 0 0
-28.86751 0.00000 12.00000 1 0 0 0
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14.43376 25.00000 -20.00000 2 0 0 0
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**2 NFillGroups - Number of filled member groups (-)** [If FillDens = DEFAULT, then FillDens = WtrDens; FillFSLoc is related to MSLZSWL]

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**0 NMGDepths - Number of marine-growth depths specified (-)**
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**OUTPUT**

- **True**  
  
  - HDSum  
    - Output a summary file [flag]

- **False**  
  
  - OutAll  
    - Output all user-specified member and joint loads (only at each member end, not interior locations) [flag]

- **2**  
  
  - OutSwitch  
    - Output requested channels to: [1=Hydrodyn.out, 2=GlueCode.out, 3=both files]

- "E$11.4e2"  
  
  - OutFmt  
    - Output format for numerical results (quoted string) [not checked for validity!]

- "A11"  
  
  - OutSFmt  
    - Output format for header strings (quoted string) [not checked for validity!]

---

**OUTPUT CHANNELS**

- "Wave1Elev"  
  
  - Wave elevation at the platform reference point (0, 0)

**END of output channels and end of file.** (the word "END" must appear in the first 3 columns of this line)
Appendix B. OC4 Semi-submersible Driver File

HydroDyn Driver file for OC4 Semi-submersible.

Compatible with HydroDyn v2.01.*

TRUE    Echo                - Echo the input file data (flag)

---------------------- ENVIRONMENTAL CONDITIONS -------------------------------

9.80665   Gravity             - Gravity (m/s^2)

---------------------- HYDRODYN -----------------------------------------------

"./OC4Semi.dat"  HDInputFile     - Primary HydroDyn input file name (quoted string)
"./OC4Semi"      OutRootName       - The name which prefixes all HydroDyn generated files (quoted string)
1             NSteps              - Number of time steps in the simulations (-)
0.025        TimeInterval        - TimeInterval for the simulation (sec)

---------------------- WAMIT INPUTS -------------------------------------------

1             WAMITInputsMod    - Inputs model {0: all inputs are zero for every timestep, 1: steadystate inputs, 2: read inputs from a file (InputsFile)} (switch)
""            WAMITInputsFile     - Name of the inputs file if InputsMod = 2 (quoted string)

---------------------- WAMIT STEADY STATE INPUTS  -----------------------------

1.0 2.0 3.0 4.0 5.0 6.0  uWAMITInSteady         - input displacements and rotations at the platform reference point (m, rads)
7.0 8.0 9.0 10.0 11.0 12.0  uDotWAMITInSteady     - input translational and rotational velocities at the platform reference point (m/s, rads/s)
13.0 14.0 15.0 16.0 17.0 18.0 uDotDotWAMITInSteady - input translational and rotational accelerations at the platform reference point (m/s^2, rads/s^2)

---------------------- MORISON INPUTS -----------------------------------------

0             MorisonInputsMod   - Inputs model {0: all inputs are zero for every timestep, 1: steadystate inputs, 2: read inputs from a file (InputsFile)} (switch)
" "          MorisonInputsFile    - Name of the inputs file if InputsMod = 2 (quoted string)

---------------------- MORISON STEADY STATE INPUTS  ---------------------------

1.0 2.0 3.0 4.0 5.0 6.0  uMorisonInSteady       - input displacements and rotations for the morison elements (m, rads)
7.0 8.0 9.0 10.0 11.0 12.0  uDotMorisonInSteady  - input translational and rotational velocities for the morison elements (m/s, rads/s)
13.0 14.0 15.0 16.0 17.0 18.0 uDotDotMorisonInSteady - input translational and rotational accelerations for the morison elements (m/s^2, rads/s^2)

---------------------- Waves multipoint elevation output -----------------------

TRUE  WaveElevSeriesFlag     - T/F flag to calculate the wave elevation field (for movies)
5.0  5.0  WaveElevDX WaveElevDY - WaveElevSeries spacing -- WaveElevDX WaveElevDY
3  3     WaveElevWX WaveElevWY  - WaveElevSeries points -- WaveElevWX WaveElevWY

END of driver input file
Appendix C. List of Output Channels

This is a list of all possible output parameters for the HydroDyn module. The names are grouped by meaning, but can be ordered in the OUTPUT CHANNELS section of the HydroDyn input file as you see fit. $\text{M}\alpha\text{N}\beta$, 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 and $\beta$ is a number in the range $[1,9]$ and corresponds to location $\beta$ in the NodeLocs list of that table entry. $\text{J}\alpha$ refers to joint $\alpha$, where $\alpha$ is a number in the range $[1,9]$ and corresponds to row $\alpha$ in the JOINT OUTPUT LIST table. All outputs are in the global inertial-frame coordinate system.

<table>
<thead>
<tr>
<th>Channel Name(s)</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave and Current Kinematics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wave1Elev, Wave2Elev, …, Wave9Elev</td>
<td>(m)</td>
<td>Total (first- plus second-order) wave elevations (up to 9 designated locations)</td>
</tr>
<tr>
<td>Wave1Elv1, Wave2Elv1, …, Wave9Elv1</td>
<td>(m)</td>
<td>First-order wave elevations (up to 9 designated locations)</td>
</tr>
<tr>
<td>Wave1Elv2, Wave2Elv2, …, Wave9Elv2</td>
<td>(m)</td>
<td>Second-order wave elevations (up to 9 designated locations)</td>
</tr>
<tr>
<td>$\text{M}\alpha\text{N}\beta\text{Vxi}$, $\text{M}\alpha\text{N}\beta\text{Vyi}$, $\text{M}\alpha\text{N}\beta\text{Vzi}$</td>
<td>(m/s), (m/s), (m/s)</td>
<td>Total (first- plus second-order) fluid particle velocities at $\text{M}\alpha\text{N}\beta$</td>
</tr>
<tr>
<td>$\text{M}\alpha\text{N}\beta\text{Axi}$, $\text{M}\alpha\text{N}\beta\text{Ayi}$, $\text{M}\alpha\text{N}\beta\text{Azi}$</td>
<td>(m/s²), (m/s²), (m/s²)</td>
<td>Total (first- plus second-order) fluid particle accelerations at $\text{M}\alpha\text{N}\beta$</td>
</tr>
<tr>
<td>$\text{M}\alpha\beta\text{DynP}$</td>
<td>(Pa)</td>
<td>Total (first- plus second-order) fluid particle dynamic pressure at $\text{M}\alpha\beta$</td>
</tr>
<tr>
<td>$\text{J}\alpha\text{Vxi}$, $\text{J}\alpha\text{Vyi}$, $\text{J}\alpha\text{Vzi}$</td>
<td>(m/s), (m/s), (m/s)</td>
<td>Total (first- plus second-order) fluid particle velocities at $\text{J}\alpha$</td>
</tr>
<tr>
<td>$\text{J}\alpha\text{Axi}$, $\text{J}\alpha\text{Ayi}$, $\text{J}\alpha\text{Azi}$</td>
<td>(m/s²), (m/s²), (m/s²)</td>
<td>Total (first- plus second-order) fluid particle accelerations at $\text{J}\alpha$</td>
</tr>
<tr>
<td>$\text{J}\alpha\text{DynP}$</td>
<td>(Pa)</td>
<td>Total (first- plus second-order) fluid particle dynamic pressure at $\text{J}\alpha$</td>
</tr>
<tr>
<td>Total and Additional Loads</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AddFxi, AddFyi, AddFzi, AddMxi, AddMyi, AddMzi</td>
<td>(N), (N), (N), (N·m), (N·m), (N·m)</td>
<td>Forces and moments due to additional preload, stiffness, and damping at the WRP</td>
</tr>
<tr>
<td>HydroFxi, HydroFyi, HydroFzi, HydroMxi, HydroMyi, HydroMzi</td>
<td>(N), (N), (N·m), (N·m), (N·m)</td>
<td>Total integrated hydrodynamic loads from both potential flow and strip theory at the WRP</td>
</tr>
<tr>
<td>Loads from Potential-Flow Solution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WavesFxi, WavesFyi, WavesFzi, WavesMxi, WavesMyi, WavesMzi</td>
<td>(N), (N), (N·m), (N·m), (N·m)</td>
<td>Total (first- plus second-order) wave-excitation loads from diffraction at the WRP</td>
</tr>
<tr>
<td>WavesF1xi, WavesF1yi, WavesF1zi, WavesM1xi, WavesM1zi</td>
<td>(N), (N), (N·m), (N·m), (N·m)</td>
<td>First-order wave-excitation loads from</td>
</tr>
<tr>
<td>WavesM1yi, WavesM1zi</td>
<td>diffraction at the WRP</td>
<td></td>
</tr>
<tr>
<td>WavesF2xi, WavesF2yi, WavesF2zi, WavesM2xi, WavesM2yi, WavesM2zi</td>
<td>(N), (N), (N), (N·m), (N·m)</td>
<td></td>
</tr>
<tr>
<td>HdrStcFxi, HdrStcFyi, HdrStcFzi, HdrStcMxi, HdrStcMyi, HdrStcMzi</td>
<td>Second-order wave-excitation loads from diffraction at the WRP</td>
<td></td>
</tr>
<tr>
<td>RdtnFxi, RdtnFyi, RdtnFzi, RdtnMxi, RdtnMyi, RdtnMzi</td>
<td>Hydrostatic loads at the WRP</td>
<td></td>
</tr>
</tbody>
</table>

### Structural Motions

| WRPSurge, WRPSway, WRPHeave, WRPRoll, WRPPitch, WRPYaw | (m), (m), (rad), (rad) |
| WRPTVxi, WRPTVyi, WRPTVzi, WRPRVxi, WRPRVyi, WRPRVzi | Translational and rotational velocities at the WRP |
| WRPTAxi, WRPTAyi, WRPTAzi, WRPRAx, WRPRAy, WRPRAz | Translational and rotational accelerations at the WRP |

### Distributed Loads (Per Unit Length) on Members

| MoNBSTVxi, MoNBSTVyi, MoNBSTVzi | (m/s), (m/s), (m/s) |
| MoNBSTAxi, MoNBSTAy, MoNBSTAzi | Structural translational velocities at MoNB |
| JaSTVxi, JaSTVyi, JaSTVzi | (m/s), (m/s), (m/s) |

### Lumped Loads at Joints

| JaFDxi, JaFDyi, JaFDzi | (N), (N), (N) |
| JaFDxi, JaFDyi, JaFDzi | Fluid-inertia force at Ja |
| JaFDxi, JaFDyi, JaFDzi | Buoyancy loads at Ja |
| JaFDxi, JaFDyi, JaFDzi | Negative buoyancy loads due to flooding/ballasting at Ja |
| JaFDxi, JaFDyi, JaFDzi | Forces due to marine growth weight at MoNB |
| JaFDxi, JaFDyi, JaFDzi | Hydrodynamic added-mass forces at MoNB |
| JaFDxi, JaFDyi, JaFDzi | Flooding/ballasting mass inertia forces at MoNB |
|JaFDxi, JaFDyi, JaFDzi | Total effective added-mass forces at MoNB |
Appendix D. Compiling Stand-alone HydroDyn

See the FAST documentation for instructions on how to compile HydroDyn coupled to FAST.

*Future versions of the manual will include compiling instructions for building the stand-alone HydroDyn program.*
Appendix E. Major Changes in HydroDyn

HydroDyn when first released was included as an undocumented feature of FAST and packaged with the FAST archive. Since v2.00, the former software called “HydroDyn” has been separated into a distinct module packaged separately from FAST (but still coupled to FAST) and itself has been split into two pieces of software, each following the FAST modularization framework. This appendix outlines significant modifications to HydroDyn made with each public release, starting with v2.00.

V2.02 (September 2014)

Version 2.02 integrates with the FAST v8 software v8.09.00a-bjj.

- **Primary input file changes**
  - 2ND-ORDER WAVES section
    - Removed *WvMnDriftQTF* option
    - Enabled *WvDiffQTF* and *WvSumQTF* options for calculating second-order wave kinematics for use in strip theory
  - 2ND-ORDER FLOATING PLATFORM FORCES section
    - Enabled *MnDrift*, *NewmanApp*, *DiffQTF*, and *SumQTF* options for calculating second-order loads for use in potential-flow theory

- **New or Modified Hydrodynamics**
  - Added second-order wave kinematics for use in strip theory calculations
  - Added second-order load calculations for use in potential-flow theory (second-order hydrodynamic coefficients must be supplied using WAMIT)

- **Output file changes**
  - Added output channels for first- and second-order wave elevation (*Wave1Elv1*, *Wave1Elv2*, etc); changed the existing wave-elevation outputs (*Wave1Elev*, etc) to be the total wave elevation (i.e., the sum of the first- and second-order waves)
  - Added output channels for first- and second-order wave loads from potential-flow calculations (*WavesF1xi*, *WavesF2xi*, etc); changed the existing wave load outputs (*WavesFxi*, etc) to be the total wave load (i.e., the sum of the first- and second-order wave loads)

- **Significant bug Fixes**
  - Fixed bug in the HydroDyn output file when coupled to FAST (multiple lines were output)
  - Fixed bug in output channel handling when compiled with gfortran
  - Minor changes in Morison module to allow for compiling in double precision
  - Fixed bug with multidirectional waves for single wave direction (*WaveNDir* = 1, or *WaveDirSpread* = 0)
v2.01 (June 2014)
Version 2.01 integrates with the FAST v8 software v8.08.00c-bjj.

- **Driver input file changes**
  - Enabled *MorisonInputsMod* option for steady-state Morison inputs
  - Added wave-elevation output section

- **Primary input file changes**
  - ENVIRONMENTAL CONDITIONS section
    - Enabled the *MSL2SWL* parameter
  - WAVES section
    - Added parameters supporting multi-directional waves: *WaveDirMod*, *WaveDirSpread*, *WaveNDir*, *WaveDirRange*
  - Added 2\(^{ND}\)-ORDER WAVES section
  - FLOWING PLATFORM section
    - Added support for *RdtmDT* to be set to “DEFAULT” to match driver code time step
  - Added 2\(^{ND}\)-ORDER FLOWING PLATFORM FORCES section
  - HEAVE COEFFICIENTS section renamed AXIAL COEFFICIENTS
    - Renamed *HvCoefID* to *AxCoefID*
    - Renamed *CdHv* to *AxCd*
    - Renamed *CaHv* to *AxCa*
    - Added axial dynamic-pressure coefficient, *AxCp*
  - SIMPLE HYDRODYNAMIC COEFFICIENTS section
    - Added dynamic-pressure coefficients: *SimplCp*, *SimplCpMG*
    - Added parameters for axial coefficients: *SimplAxCa*, *SimplAxCaMG*, *SimplAxCp*, *SimplAxCpMG*
  - DEPTH-BASED HYDRODYNAMIC COEFFICIENTS section
    - Added dynamic-pressure coefficients: *DpthCp*, *DpthCpMG*
    - Added parameters for axial coefficients: *DpthAxCa*, *DpthAxCaMG*, *DpthAxCp*, *DpthAxCpMG*
  - MEMBER-BASED HYDRODYNAMIC COEFFICIENTS section
    - Added dynamic-pressure coefficients: *MemberCp1*, *MemberCp2*, *MemberCpMG1*, *MemberCpMG2*,
    - Added parameters for axial coefficients: *MemberAxCa1*, *MemberAxCa2*, *MemberAxCaMG1*, *MemberAxCaMG2*,

MemberAxCp1, MemberAxCp2, MemberAxCpMG1, MemberAxCpMG2

- Consolidated the two sections for output channel labels into a single OUTPUT CHANNELS section.
  - Numerous changes and additions to the available channel labels, see Appendix C

- Output file changes
  - Modified file naming convention to match FAST convention
  - Summary file saw several changes
    - Now includes WAMIT-body volume and buoyancy table
    - Existing volume, buoyancy, and weight tables were moved to the start of the file
    - The radiation kernel and wave kinematics tables were moved to the end of the file
    - The node and element tables were altered
    - New wave-elevation outputs file available when using stand-alone HydroDyn
      - All units are now SI (m, N, s)
  - Results file
    - All units are now SI (m, N, s)

- New or Modified Hydrodynamics
  - Added multi-directional waves
  - Combined Froude-Kriloff (dynamic-pressure) loads into the inertial loads
  - Added option whereby if simulation time is greater than WaveTMax, waves repeat
  - Added lumped inertial loads
  - Altered lumped added-mass equation
  - Altered distributed inertial-load equation
  - Altered fluid-domain checks for when to compute hydrodynamic loads
  - Included the platform added-mass loads in the radiation load outputs (RdtmFx, RdtmFyi, etc.)

- Miscellaneous
  - Restructured the calculation of loads due to additional stiffness, damping so they work when HasWAMIT = FALSE
  - Wave elevations can now be output when HasWAMIT = FALSE
• Changed terminology from platform reference point to WAMIT reference point (WRP)
• Added improved error handling when parsing input file

**Significant bug Fixes**

• Fixed bug for regular waves with phase
• Fixed bug in computation of wave kinematics for current cases
• Fixed bug that could prevent filled buoyancy from being computed
• Fixed bug where a model using WAMIT could still report marine-growth volume in the summary file
• Fixed bug with transverse drag calculation: wasn’t including all components of relative velocity
• Fixed bug with computation of lumped added-mass matrix
• Fixed bug in the mesh-mapping of HydroDyn to ElastoDyn
• Fixed bug where dynamic-pressure load terms, and buoyancy, and drag might not be calculated even when $\text{PropWAMIT} = \text{FALSE}$
• Fixed bug with reported units of output channels
• Fixed bug so that WAMIT-related calculations now account for $\text{PtfmCOBxt}$ and $\text{PtfmCOByt}$
• Fixed bug when user set $\text{WaveNDAmp} = \text{TRUE}$ when $\text{WaveMod} = 1$

**v2.00.01 (October 2013)**

The major changes in version 2.00 are:

• Version 2.00 integrates with the [FAST v8 software](https://fastsoftware.com) v8.03-bjj.
• Mooring lines have been removed from HydroDyn. The mooring line modeling is now being handled in a different FAST module. You can however use the additional stiffness and damping matrices to model a mooring line system within HydroDyn.
• Multi-member structures can now be modeled within HydroDyn (applicable e.g. to fixed-bottom tripod and jacket structures, as well as thin members (e.g., braces/spokes) of floating platforms). This modeling implement's Morison's equation for multiple slender cylinders, inclined and tapered members, inertia/drag/added mass/buoyancy/dynamic pressure loads, filled/flooded effects, and marine growth effects.
• Hybrid models with both linear radiation/diffraction calculations and Morison Equation calculations are possible.
• Added a linear state-space-based radiation formulation to be used together with [SS_Fitting](https://fastsoftware.com).
• The new implementation has well-defined data exchange interfaces ([following the FAST modularization framework](https://fastsoftware.com)) which should make integration of HydroDyn into other multi-physics software packages much simpler.