HydroDyn User's Guide and Theory Manual

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1 Nomenclature

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

$\vec{\alpha}_S$	Rotational structural acceleration, 3x1 vector
Δt_{RD}	Time step for the radiation memory effect calculations
ζ	Wave elevation time series
π	Mathematical constant, pi
ω	frequency (rad/s)
$\vec{\omega}_S$	Rotational structural velocities, 3x1 vector, currently not used
ρ_f	Density of the flooding/ballast fluid
ρ_{MG}	Density of marine growth
ρ_W	Water density
$\vec{a}_f$	Linear acceleration of the fluid, 3x1 vector
$\vec{a}_s$	Linear acceleration of the structure, 3x1 vector
A	Area of super member
AM	Added-mass, 6x6 matrix
AM_F	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
$\vec{F}_0$	Additional preload, 3x1 vector
$\vec{F}_{AM}$	Total added mass forces from all contributing effects
$\vec{F}_{AM\_F}$	Added mass forces due to filled/ballasted fluid
$\vec{F}_{AM\_M}$	Added mass forces due to

$\vec{F}_{AM\_MG}$	Added mass forces due to marine growth
$\vec{F}_j$	Total forces and moments applied to node j, 6x1 vector
$\vec{F}_{ADD}$	Total loads due to preload, additional stiffness, and additional damping terms, 6x1 vector
$\vec{F}_B$	Buoyancy forces and moments applied to node, 6x1 vector
$\vec{F}_D$	Drag forces and moments applied to node, 6x1 vector
$\vec{F}_{F\_B}$	Buoyancy forces and moments due to flooding applied to node, 6x1 vector
$\vec{F}_{HS}$	Hydrostatic forces applied to the platform reference node, 6x1 vector
$\vec{F}_I$	Inertial forces and moments applied to node, 6x1 vector
$\vec{F}_{MG}$	Marine growth-related forces and moments applied to node, 6x1 vector
$\vec{F}_{RD}$	Radiation memory-effect force applied to platform reference point, 6x1 vector
$\vec{F}_W$	Incident-wave excitation force applied to platform reference point, 6x1 vector
$\vec{F}_{glb}^i$	Point buoyancy forces at the end cap of the ith member which connects to the super member
$\vec{F}_W$	Incident-wave excitation force applied to platform reference point, 6x1 vector
$\vec{F}_{WRP}$	Total loads at the WAMIT reference point from potential flow theory, 6x1 vector
g	Gravity, unsigned magnitude
h_{ref}	Reference depth for the near-surface current model
i	member or element index
$\hat{i}$	Unit vector along the local x-axis
$\hat{I}$	Unit vector along the global X-axis
j	node index, imaginary number constant
$\hat{j}$	Unit vector along the local y-axis
$\hat{J}$	Unit vector along the global Y-axis
$\hat{k}$	Unit vector along the local z-axis
K	Radiation kernel from potential flow theory, 6x6 matrix
$\hat{K}$	Unit vector along the global Z-axis
kg	Kilograms
L_m	Length of master cylinder of a super member
L_{s_i}	Length of the ith slave cylinder of a super member
m	Meters
M	Number of members connected to a given joint
n	the nth time step
$\hat{n}_i$	Outward facing normal for member the ith member. Parallel to the local $\hat{k}$ axis
N	Newtons
p_{dyn}	Fluid dynamic pressure
R	Outer radius of structural member
R_m	Outer radius of the super member's master cylinder

R_{s_i}	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_{MG_m}	Marine-growth thickness on the master cylinder
$t_{MG_{s_i}}$	Marine-growth thickness on i^{th} slave cylinder of a super member
t_{Ms}	Thickness of structural member at element start
t_{MG}	Marine-growth thickness
$U_{0_{NS}}$	Reference current velocity for the near-surface current model
$U_{0_{SS}}$	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
$\vec{v}_{rel}$	Relative velocity, $\vec{v}_{rel} = \vec{v}_f - \vec{v}_s$ 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
$\lfloor x \quad y \quad z \rfloor^T$	Position in the local, member coordinate system
$\lfloor X \quad Y \quad Z \rfloor^T$	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 multi-physics engineering 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 hybrid combination of the two. Waves generated internally within HydroDyn can be regular (periodic) or irregular (stochastic) and long-crested (unidirectional) or short-crested (with wave energy spread across a range of directions). Wave elevations or full wave kinematics can also be generated externally and used within HydroDyn. Internally, HydroDyn generates waves analytically for finite depth using first-order (linear Airy) or first- plus second-order wave theory [Sharma and Dean, 1981] with the option to include directional spreading, but wave kinematics are only computed in the domain between the flat seabed and still-water level (SWL) and no wave stretching or higher order wave theories are included. The second-order hydrodynamic implementations 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. The potential-flow solution involves either frequency-to-time-domain transforms or fluid-impulse theory (FIT). In the former, 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 (Froude-Kriloff and scattering). 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 use of FIT is not yet documented in this manual.

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 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 should 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 standalone 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 standalone 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 Standalone HydroDyn Archive

You can download the standalone HydroDyn archive from our web server at *https://nwtc.nrel.gov/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.
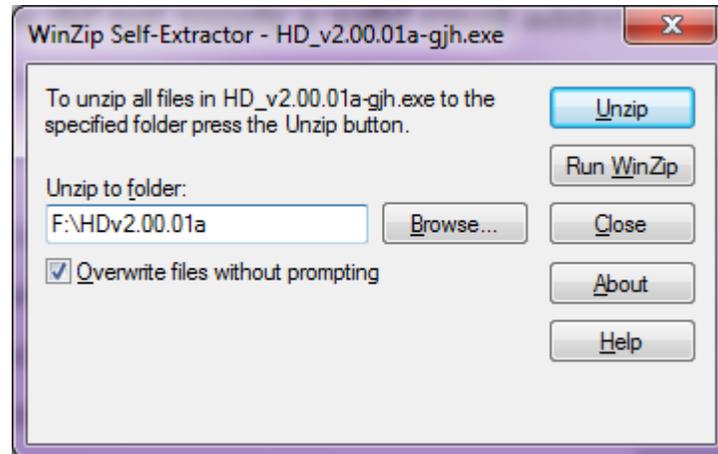
The archive contains the **bin**, **CertTest**, **Compiling**, **Documentation**, and **Source** folders. The **bin** folder includes the *HydroDynDriver_win32.exe*, which is used to execute the standalone HydroDyn program. The **CertTest** folder contains a collection of sample HydroDyn input files. 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 standalone *HydroDynDriver_win32.exe* with either Visual Studio or 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 *https://nwtc.nrel.gov/FAST8*. The file has a name similar to *FAST_v8.12.00.exe*, but may have a different version number. Run the downloaded self-extracting archive (*.exe*) to expand the archive into a 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 Standalone HydroDyn

The standalone HydroDyn program, *HydroDynDriver_win32.exe*, simulates hydrodynamic responses of your input model, without coupling to FAST. Unlike the coupled version, the standalone 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 standalone 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.

>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.

>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 enable or disable 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 standalone 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 standalone 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 $9.80665 \frac{m}{s^2}$. **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 file path, 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 1. WAMIT Inputs Time-Series Data File Contents

Column Number	Input	Units
1	Time step value	s
2-4	Translational displacements along *X*, *Y*, and *Z*	m
5-7	Rotational displacements about *X*, *Y*, and *Z* (small angle	$radians$

	assumptions apply)	
8-10	Translational velocities along X, Y, and Z	$\dfrac{m}{s}$
11-13	Rotational velocities about X, Y, and Z	$\dfrac{radians}{s}$
14-16	Translational accelerations along X, Y, and Z	$\dfrac{m}{s^2}$
17-19	Rotational accelerations about X, Y, and Z	$\dfrac{radians}{s^2}$

In a similar fashion, the input motions for the Morison members (strip-theory model) are set to zero if **MorisonInputsMod** = 0. If you select **MorsionInputsMod** = 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 standalone HydroDyn does not check for physical consistency between motions specified for the WRP and Morison members in the driver file .

Setting **WaveElevSeriesFlag** 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 $X = 0$, $Y = 0$ i.e., (0,0)) 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** × **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).

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 (**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.

The file is organized into several functional sections. Each section corresponds to an aspect of the hydrodynamics model or the submerged substructure. A sample HydroDyn primary input file is given in Appendix A.

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.

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/m^3. **WtrDpth** specifies the water depth (depth of the flat seabed), based on the reference MSL, and must be a value greater than zero. **MSL2SWL** is the offset between the MSL and 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 is unused with **WaveMod** = 6 and must be set to zero if you are using a potential-flow model (**PotMod** = 1 or 2).

4.3.2 Waves

The WAVES section of the input file controls the internal generation of first-order waves or the use of externally generated waves, 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 *UserWaveSpctrm()*; see Appendix D for compiling instructions
- 5: Externally generated wave-elevation time series
- 6: Externally generated full wave-kinematics time series

Option 4 requires that the *UserWaveSpctrm()* subroutine of the *Waves.f90* source file be implemented by the user, and will require recompiling either the standalone HydroDyn program or FAST. Option 5 allows the use of externally generated wave-elevation time series, from which the hydrodynamic loads in the potential-flow solution or the wave kinematics used in the strip-theory solution are derived internally. Option 6 allows the use of full externally generated wave kinematics for use with the strip-theory solution (but not the potential-flow solution). With options 5 and 6, the externally generated wave data is provided through input files, all of which have the root name given by the *WvKinFile* parameter below.

This version does not include the ability to model stretching of internally generated 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 FFT, from which the internal wave time series are derived ($\Delta\omega$ = 2π/*WaveTMax*). If *WaveTMax* is less than the total simulation time, HydroDyn implements repeating wave kinematics that have a period of *WaveTMax*; *WaveTMax* must not be less than the total simulation time when *WaveMod* = 5. *WaveDT* determines the time step for the wave kinematics time series, but it also determines the maximum frequency in the inverse FFT (ω_{max} = π/*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 will be interpolated in time as necessary); *WaveDT* must equal the glue code time step of FAST when *WaveMod* = 6.

For internally generated waves, the wave height (crest-to-trough, twice the amplitude) for regular waves and the significant wave height for irregular waves is set using *WaveHs* (only used when *WaveMod* = 1, 2, or 3). The wave period for regular waves and the peak-spectral wave period for irregular waves is controlled with the *WaveTp* parameter (only used when *WaveMod* = 1 or 2). *WavePkShp* is the peak-shape parameter of JONSWAP irregular wave spectrum (only used when *WaveMod* = 2). 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 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. *WvLowCOff* and *WvHiCOff* are unused when *WaveMod* = 0, 1, or 6.

WaveDir (unused when *WaveMod* = 0 or 6) 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. And a heading of 90 corresponds to wave propagation in the positive Y-axis direction. *WaveDirMod* specifies the wave directional spreading model (only

used when ***WaveMod*** = 2, 3, or 4). Setting ***WaveDirMod*** to 0 disables directional spreading, resulting in long-crested (plane-progressive) 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^{2S}) 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 ***WavedSeed(2)*** (unused when ***WaveMod*** = 0, 5, or 6) combined determine the initial seed (starting point) for the internal pseudorandom number generator needed to derive the internal 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. ***WaveNDAmp*** is only used with ***WaveMod*** = 2, 3, or 4.

When using externally generated wave data (***WaveMod*** = 5 or 6), input parameter ***WvKinFile*** should be set to the root name of the input file(s) (without extension) containing the data.

Using externally generated wave-elevation time series (***WaveMod*** = 5) requires a text-formatted input data file with the extension *.Elev* containing two columns of data—the first is time (starting at zero) (in s) and the second is the wave elevation at (0,0) (in m), separated by whitespace. Header lines (identified as those not beginning with a number) are ignored. The time series must be at least ***WaveTMax*** in length and not less than the total simulation time and the time step must match ***WaveDT***. The wave-elevation time series specified is assumed to be of first order and long-crested, but is not checked for physical correctness. 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 wave-component amplitudes derived from the provided wave-elevation time series and extra energy is added to the wave spectrum (at the difference and sum frequencies).

Using full externally generated wave kinematics (***WaveMod*** = 6) requires eight text-formatted input data files, all without headers. Seven files with extensions *.Vxi, .Vyi, .Vzi, .Axi, .Ayi, .Azi,* and *.DynP* correspond to the *X, Y,* and *Z* velocities (in m/s) and accelerations (in m/s^2) in the global inertial-frame coordinate system and the dynamic pressure (in Pa) time series. Each of these files must have exactly ***WaveTMax***/***DT*** rows and *N* whitepace-separated columns, where *N*

is the total number of internal HydroDyn analysis nodes (corresponding exactly to those written to the HydroDyn summary file). Time is absent from the files, but is assumed to go from zero to **WaveTMax** – **WaveDT** in steps of **WaveDT**. To use this feature, it is the burden of the user to generate wave kinematics data at each of HydroDyn's time steps and analysis nodes. HydroDyn will not interpolate the data; as such, when HydroDyn is coupled to FAST, **WaveDT** must equal the glue code time step of FAST. A numerical value (including 0) in a file is assumed to be valid data (with 0 corresponding to 0 m/s, 0 m/s^2, or 0 Pa); a nonnumeric string will designate that the node is outside of the water at that time step (above the instantaneous water elevation or below the seabed)—externally generated wave kinematics used with **WaveMod** = 6 are not limited to the domain between a flat seabed and SWL and may consider wave stretching, higher-order wave theories, or an uneven seabed. All seven files must have nonnumeric strings in the same locations within the file. The eighth file, with extension *.Elev*, must contain the wave elevation (in m) at each of the **NWaveElev** points on the SWL where wave elevations can be output—see below; this data is required for output purposes only and is not used by HydroDyn for other means. This file must have exactly **WaveTMax**/**DT** rows and **NWaveElev** whitepace-separated columns and only valid numeric data is allowed (the file will have **NWaveElev** + (**WaveElevNX** × **WaveElevNY**) columns when HydroDyn is operated in standalone mode). The data in these files is not processed (filtered, etc.) or checked for physical correctness (other than for consistency in the location of the nonnumeric strings). Full externally generated wave kinematics (**WaveMod** = 6) cannot be used in conjunction with the potential-flow solution.

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 (unused when **WaveMod** = 0 or 6) 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 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.

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 standalone 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 or when **WaveMod** = 6.

HydroDyn's standard current model includes three sub-models: near-surface, sub-surface, and depth-independent, as illustrated in Figure 1. All three currents are vector summed, along with the wave particle kinematics velocity.
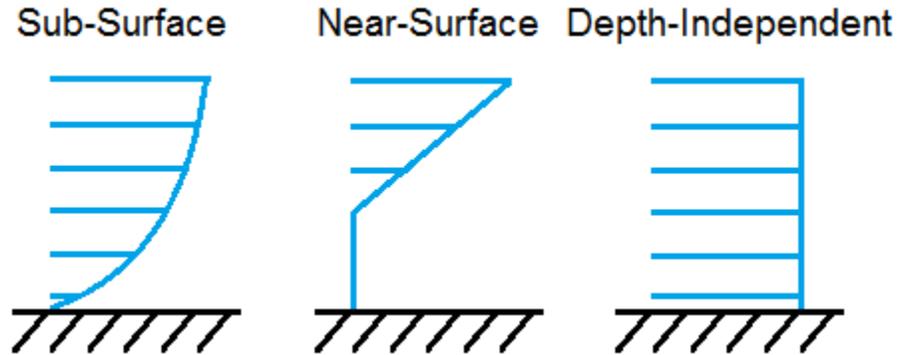
Figure 1. Standard Current Sub-Models

The sub-surface current model follows a power law,

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

where Z is the local depth below the SWL (negative downward), d is the water depth (equal to **WtrDpth** + **MSL2SWL**), and $U_{0_{SS}}$ 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,

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

where h_{ref} is the reference depth corresponding to **CurrNSRef**, and must be positive valued. $U_{0_{NS}}$ 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 **CurrDIDir**, 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. The potential-flow solution cannot be used in conjunction with nonzero **MSL2SWL** or **WaveMod** = 6.

If the load contributions from potential-flow theory are to be used, set **PotMod** to 1 for the use of frequency-to-time-domain transforms based on WAMIT output or 2 for the use of FIT (FIT is not yet documented in this manual). With **PotMod** = 1, include the root name (without extensions) for the WAMIT-related output files in **PotFile**. These files consist of the *.1*, *.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 placed of convolution, the *.ss* file generated by SS_Fitting must have the same root name as the other WAMIT-related files (see **RdtnMod** below). The remaining parameters in this section are only used when **PotMod** = 1.

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 *.1* 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 (***PotMod*** = 1). 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 ***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 ***NewmanApp*** to a nonzero value; or to compute the mean- and slow-drift terms using the full difference-frequency QTF set ***DiffQTF*** to a nonzero value. Valid values of ***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 ***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 (***WaveDirMod*** must be 0) and the second-order cut-off frequencies do not apply to Newman's approximation. Valid values of ***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 ***MnDrift***, ***NewmanApp***, and ***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 the momentum conservation principle 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 ***SumQTF*** to a nonzero value. Valid values of ***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.

$$\vec{F}_{Add} = \vec{F}_0 - [C]\vec{q} - [B]\dot{\vec{q}} - \left[B_{quad}\right] ABS\left(\dot{\vec{q}}\right)\dot{\vec{q}},$$

where $\vec{F}_0$ corresponds to the **AddF0** 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 $\vec{q}$ 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 6.8.3), 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 potential flow (**PropPot** = 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 two. 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 **MProSetID2** 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 **PropPot** flag indicates whether the corresponding member coincides with the body represented by the potential-flow solution. When **PropPot** = 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. **FillNumM** specifies the number of members in the fill group. **FillMList** is a list of **FillNumM** whitespace-separated **MemberID**s. **FillFSLoc** specifies the Z-height of the free-surface (0 for MSL). **FillDens** is the density of the fluid. If **FillDens** = DEFAULT, then **FillDens** = **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 **OutSwtch** is set to 1, outputs are sent to a file with the name **OutRootname**.*HD.out*. If **OutSwtch** is set to 2, outputs are sent to the calling program (FAST) for writing. If **OutSwtch** 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,

```
"ES11.4"     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 HydroDyn primary 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 HydroDyn primary 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*** × ***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 **PropPot** flag set to FALSE. The flooded/ballasted volume applies to any fluid-filled member, regardless of its **PropPot** 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 **PropPot** flag is set to FALSE. The internal buoyancy is the negative effect on buoyancy due to flooding or ballasting and is independent of the **PropPot** 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 all internal analysis nodes used by the HydroDyn model. 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. **PropPot** 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. **PropPot** 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. ***Xi***, ***Yi***, ***Zi***, 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 (***StartXi***, ***StartYi***, ***StartZi***) and ending (***EndXi***, ***EndYi***, ***EndZi***) 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. ***Xi***, ***Yi***, ***Zi***, 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, but is not written when ***WaveMod*** = 0 or 6. 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

In the potential-flow solution based on frequency-to-time-domain transforms, 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 (***K11***, ***K12***, 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 **RdtnTMax**.

5.4 Results File

The HydroDyn time-series results are written to a text-based file with the naming convention **OutRootName**.*HD.out* when **OutSwtch** is set to either 1 or 3. If HydroDyn is coupled to FAST and **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 output time step. The data channels are specified in the OUTPUT CHANNELS section of the HydroDyn primary input file. The column format of the HydroDyn-generated file is specified using the **OutFmt** and **OutSFmt** parameter of the primary 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 generated internally within HydroDyn can be regular (periodic) or irregular (stochastic) and long-crested (unidirectional) or short-crested (with wave energy spread across a range of directions). Internally, HydroDyn generates waves analytically for finite depth using first-order (linear Airy) or first- plus second-order wave theory [Sharma and Dean, 1981] with the option to include directional spreading, but wave kinematics are only computed in the domain between the flat seabed and SWL and 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 **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.)

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—**WvLowCOff** and **WvHiCOff** for the low- and high-frequency cut-offs of first-order wave components, **WvLowCOffD** and **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. **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 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 with internally generated wave data, 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.

Wave elevations or full wave kinematics can also be generated externally and used within HydroDyn.

WaveMod = 5 allows the use of externally generated wave-elevation time series, which is useful if you want HydroDyn to simulate specific wave transient events where the wave-elevation time series is known a priori e.g. to match wave-elevation measurements taken from a wave tank or open-ocean test. Internally, HydroDyn will compute an FFT of the provided wave-elevation time series to store the amplitudes and phases of each frequency component, and use those in place of a wave energy spectrum and random seeds to internally derive the hydrodynamic loads in the potential-flow solution or the wave kinematics used in the strip-theory solution. The wave-elevation time series specified is assumed to be of first order and long-crested, but is not checked for physical correctness. The time series must be at least **WaveTMax** in length and not less than the total simulation time and the time step must match **WaveDT**. When second-order terms are optionally enabled, the second-order terms are calculated using the wave-component

amplitudes derived from the provided wave-elevation time series and extra energy is added to the wave energy spectrum (at the difference and sum frequencies). Using higher order wave data may produce erroneous results; alternatively, **WvLowCOff** and **WvHiCOff** can be used to filter out energy outside of the first-order wave energy range. The wave-elevation time series output by HydroDyn will only match the specified time series identically if the second-order terms are disabled and the cut-off frequencies are outside the range of wave energy.

WaveMod =6 allows the use of full externally generated wave kinematics for use with the strip-theory solution (but not the potential-flow solution), completely bypassing HydroDyn's internal wave models. This feature is useful if you want HydroDyn to make use of wave kinematics data derived outside of HydroDyn a priori e.g. from a separate numerical tool, perhaps bypassing some of HydroDyn's internal wave modeling limitations. To use this feature, it is the burden of the user to generate wave kinematics data at each of HydroDyn's time steps and analysis nodes. HydroDyn will not interpolate the data; as such, when HydroDyn is coupled to FAST, **WaveDT** must equal the glue code time step of FAST. Before generating the wave kinematics data externally, users should identify all of the internal analysis nodes by running HydroDyn and generating the summary file—see Section 5.3. The fluid domain at each time step are specified by the use of numeric values and nonnumeric strings in the wave data input files. The wave kinematics data specified are not limited to the domain between a flat seabed and SWL and may consider wave stretching, higher-order wave theories, or an uneven seabed. The specified wave kinematics data are not processed (filtered, etc.) or checked for physical correctness. The wave kinematics output by HydroDyn should match the specified data identically.

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, flat 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, a higher resolution near the water free surface is required to capture hydrodynamic loading as waves oscillate about 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 **PropPot** = FALSE, the Z-coordinate is in the range [−**WtrDpth**,**MSL2SWL**], and the element the node is connected to is in the water. When **WaveMod** = 6, the domain is determined by the use of numeric values and nonnumeric strings in the wave data input files.

6.3.1.2 Viscous Drag

These loads are generated at a node as long as the Z-coordinate is in the range [−**WtrDpth**, **MSL2SWL**] and the element the node is connected to is in the water. When **WaveMod** = 6, the domain is determined by the use of numeric values and nonnumeric strings in the wave data input files.

6.3.1.3 Filled Buoyancy, Filled Mass Inertia

These loads are generated at a node as long as the Z-coordinate is in the range [−**WtrDpth**, **FillFSLoc**] and the element the node is connected to is in the filled fluid.

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 **PropPot** = FALSE and the Z-coordinate is in the range [−**WtrDpth**,**MSL2SWL**]. When **WaveMod** = 6, the domain is determined by the use of numeric values and nonnumeric strings in the wave data input files.

6.3.2.2 Axial Drag

These loads are generated at a node as long as the Z-coordinate is in the range [−**WtrDpth**,**MSL2SWL**]. When **WaveMod** = 6, the domain is determined by the use of numeric values and nonnumeric strings in the wave data input files.

6.3.2.3 Filled Buoyancy

These loads are generated at a node as long as the Z-coordinate is in the range [−**WtrDpth**,**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 frequency-to-time-domain-based 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 6.8.3), 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 only, strip-theory (Morison) only, or a hybrid model containing both.

Potential-flow theory based on frequency-to-time-domain transforms is enabled when *PotMod* is set to 1. In this case, you must run WAMIT (or equivalent) in a pre-processing step and HydroDyn will use the WAMIT output files—see Section 6.8.4 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 **PotMod** 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 **PotMod** is TRUE and you have defined one or more strip-theory members. The potential-flow 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 potential-flow model by setting the **PropPot** flag for each member. As detailed in Section 7.5.1, the state of the **PropPot** 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 6.8.3 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, ρ 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, **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.

$$
AddCLin = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \rho g A_0 & \rho g \iint_{A_0} y\,dA & -\rho g \iint_{A_0} x\,dA & 0 \\
0 & 0 & \rho g \iint_{A_0} y\,dA & \rho g \iint_{A_0} y^2\,dA + \rho g V_0 z_b - m_{mg} g z_{mg} - m_f g z_f & -\rho g \iint_{A_0} xy\,dA & -\rho g V_0 x_b + m_{mg} g x_{mg} + m_f g x_f \\
0 & 0 & -\rho g \iint_{A_0} x\,dA & -\rho g \iint_{A_0} xy\,dA & \rho g \iint_{A_0} x^2\,dA + \rho g V_0 z_b - m_{mg} g z_{mg} - m_f g z_f & -\rho g V_0 y_b + m_{mg} g y_{mg} + m_f g y_f \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix},
$$

where:

ρ	water density, kg/m^3
g	gravity, m/s^2
A_0	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, $\iint_{A_0} y\,dA = 0$, $\iint_{A_0} xy\,dA = 0$, $y_b = 0$, $y_{mg} = 0$, and $y_f = 0$ if the $x - z$ plane of the

platform is a symmetry plane. Likewise, $\iint_{A_0} x\,dA = 0$, $\iint_{A_0} xy\,dA = 0$, $x_b = 0$, $x_{mg} = 0$, 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 using *PotMod* = 1. 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 contains 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 contains 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
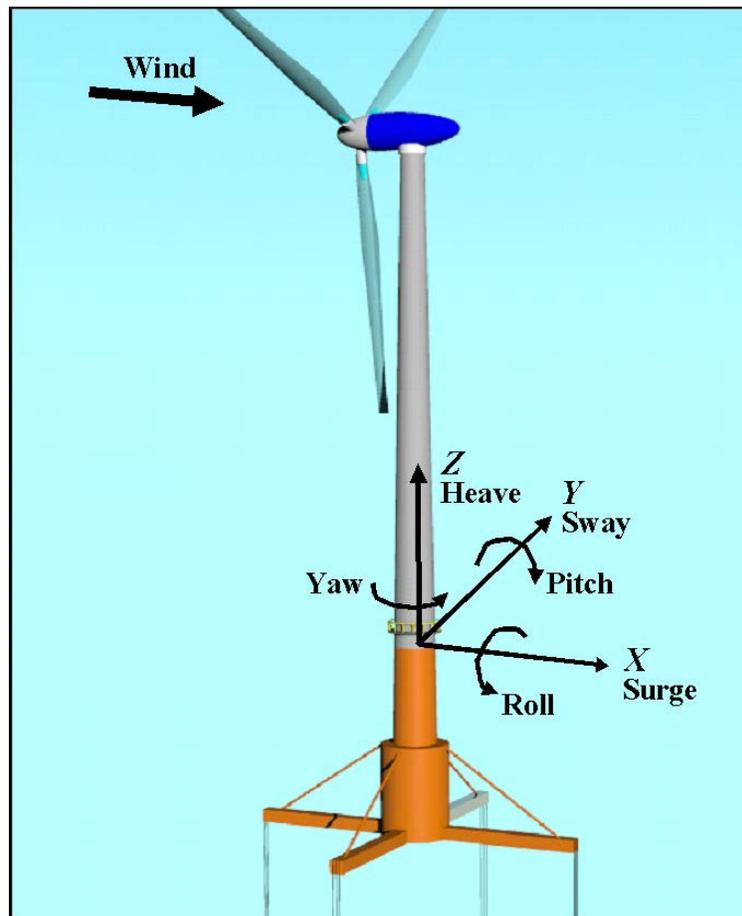
7.1.1 Global coordinate system: (X,Y,Z)

- 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:

$$\begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix} = [C] \begin{Bmatrix} r\cos\theta \\ r\sin\theta \\ z \end{Bmatrix} + \begin{Bmatrix} \dfrac{X_s + X_e}{2} \\ \dfrac{Y_s + Y_e}{2} \\ \dfrac{Z_s + Z_e}{2} \end{Bmatrix}$$

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:

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

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 $Y_e < Y_s \; Y_e < Y_s$ then

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

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 (ζ) 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:

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

This equation represents the wave elevation as an inverse Fourier transform of the desired two-sided power spectral density, $S_\zeta^{2-sided}$ where j is an imaginary number and ω 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 [Jonkman, 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.

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

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_{ref} (in [IEC, 2009], h_{ref} is set at 20 m).

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

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:

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

where

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

$$\vec{F}_W = \frac{1}{N}\sum_{k=-\frac{N}{2}-1}^{\frac{N}{2}} W[k]\sqrt{\frac{2\pi}{\Delta t}S_\zeta^{2-Sided}(\omega)}\, X(\omega,\beta)\Big|_{\omega=k\Delta\omega}\, e^{j\frac{2\pi kn}{N}}$$

$$\vec{F}_{HS} = \rho g V_0\left(\{\delta\}_3 + y^{CB}\{\delta\}_4 - x^{CB}\{\delta\}_5\right) - C^{Hydrostatic}x$$

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}:

$$\vec{F}_{RD_n} = -\Delta t_{RD}\sum_{i=n-N_{RD}}^{n-1} K_{n-i-1}\dot{x}_i$$

The state for time step n is simply the structural velocities for the previous N_{RD} time steps. Or,

$$x_n^d = \begin{Bmatrix} \dot{x}_{n-1} \\ \dot{x}_{n-2} \\ \vdots \\ \dot{x}_{n-N_{RD}} \end{Bmatrix}$$

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

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

The radiation step size, Δt_{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:

$$\vec{F} = \vec{F}_I + \vec{F}_D + \vec{F}_B + \vec{F}_{MG} + \vec{F}_{F\_B} + \vec{F}_{AM\_M} + \vec{F}_{AM\_MG} + \vec{F}_{AM\_F}$$

where F_I is the inertia force, F_D the drag force, F_B the buoyancy force, F_{MG} the weight of the marine growth, F_{F_B} the force due to fluid ballasting, F_{AM_M} the added mass of the structure, F_{AM_MG} the added mass due to marine growth, and 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, $\vec{F}_B$, and $\vec{F}_{F\_B}$, 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:

$$\vec{F} = \vec{F}_D + \vec{F}_{F\_B} + \vec{F}_{AM\_F}$$

7.5.1.1.1 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-Kriloff 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).

$$\vec{F}_I = \begin{Bmatrix} \left[(C_P + C_A)\rho_W \pi (R+t_{MG})^2 \left(\vec{a}_f - (\vec{a}_f \bullet \hat{k})\hat{k} \right) + \left\{ C_{P_{Ax}} 2\pi(R+t_{MG})\frac{\partial R}{\partial z} p_{dyn} + C_{A_{Ax}}\rho_W 2\pi(R+t_{MG})^2 \left| \frac{\partial R}{\partial z} \right| (\vec{a}_f \bullet \hat{k}) \right\} \hat{k} \right] \\ 0 \\ 0 \\ 0 \end{Bmatrix}$$

where $\dfrac{\partial R}{\partial z} = \dfrac{(R^e + t^e_{mg}) - (R^s + t^s_{mg})}{(Z^e - Z^s)}$

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.

7.5.1.1.2 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.

$$\vec{F}_D = \begin{Bmatrix} C_D\rho_W (R+t_{MG}) \left\| \vec{v}_{rel} - (\vec{v}_{rel} \bullet \hat{k})\hat{k} \right\|_2 \left(\vec{v}_{rel} - (\vec{v}_{rel} \bullet \hat{k})\hat{k} \right) \\ 0 \\ 0 \\ 0 \end{Bmatrix}$$

7.5.1.1.3 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.

$$\vec{F}_B = \rho_w g \left\{ \begin{array}{l} C \left\{ \begin{array}{c} C_{31}\pi \left(R+t_{MG}\right)^2 \\ C_{32}\pi \left(R+t_{MG}\right)^2 \\ -2\pi \left(R+t_{MG}\right)\dfrac{\partial R}{\partial z} Z \end{array} \right\} \\[2em] C \left\{ \begin{array}{c} -C_{32}\pi \dfrac{\partial R}{\partial z}\left(R+t_{MG}\right)^3 \\ +C_{31}\pi \dfrac{\partial R}{\partial z}\left(R+t_{MG}\right)^3 \\ 0 \end{array} \right\} \end{array} \right\}$$

7.5.1.1.4 Marine Growth Weight

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 ρ_{MG} its density.

$$\vec{F}_{MG} = \left\{ \begin{array}{c} 0 \\ 0 \\ -\rho_{mg} g \pi \left(\left(R+t_{MG}\right)^2 - R^2 \right) \\ 0 \\ 0 \\ 0 \end{array} \right\}$$

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.

$$\vec{F}_{F\_B} = -\rho_f g \left\{ \begin{array}{c} C \left\{ \begin{array}{c} C_{31}\pi(R-t)^2 \\ C_{32}\pi(R-t)^2 \\ -2\pi(R-t)\dfrac{\partial R}{\partial z}(Z-Z_{fs}) \end{array} \right\} \\[2em] C \left\{ \begin{array}{c} -C_{32}\pi\dfrac{\partial R}{\partial z}(R-t)^3 \\ C_{31}\pi\dfrac{\partial R}{\partial z}(R-t)^3 \\ 0 \end{array} \right\} \end{array} \right\}$$

7.5.1.1.6 Hydrodynamic Added Mass

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.

$$AM_M = \rho_W \pi (R+t_{MG})^2 \begin{bmatrix} \left[C_A\left(I-\hat{k}\hat{k}^T\right) - 2C_{A_{Ax}}\left|\dfrac{\partial R}{\partial z}\right|\hat{k}\hat{k}^T \right] & [0] \\ [0] & [0] \end{bmatrix}$$

$$\vec{F}_{AM\_M} = -AM_M \begin{Bmatrix} \vec{a}_s \\ \vec{\alpha}_s \end{Bmatrix}$$

7.5.1.1.7 Added Mass due to Marine Growth

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.

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

$$\vec{F}_{AM\_MG} = -AM_{MG} \begin{Bmatrix} \vec{a}_s \\ \vec{\alpha}_s \end{Bmatrix}$$

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.

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

$$\vec{F}_{AM\_F} = -AM_F \begin{Bmatrix} \vec{a}_s \\ \vec{\alpha}_s \end{Bmatrix}$$

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

$$\vec{F}_I^s = \left\{ C^s \left\{ \begin{array}{c} 0 \\ 0 \\ C_{P_{Ax}} \pi \left(R^s + t_{MG}^s \right)^2 p_{dyn} \end{array} \right\} + \frac{C_{A_{Ax}} \rho_W \vec{V}_n \left(\vec{a}_f \bullet \vec{V}_n \right)}{\sqrt{\left(\vec{V}_n \bullet \vec{V}_n \right)}} \\ 0 \\ 0 \\ 0 \end{array} \right\} \quad (32)$$

$$\vec{F}_I^e = \left\{ -C^e \left\{ \begin{array}{c} 0 \\ 0 \\ C_{P_{Ax}} \pi \left(R^e + t_{MG}^e \right)^2 p_{dyn} \end{array} \right\} + \frac{C_{A_{Ax}} \rho_W \vec{V}_n \left(\vec{a}_f \bullet \vec{V}_n \right)}{\sqrt{\left(\vec{V}_n \bullet \vec{V}_n \right)}} \\ 0 \\ 0 \\ 0 \end{array} \right\} \quad (33)$$

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

The terms in $\vec{F}_I^s$ and $\vec{F}_I^e$ involving $C_{A_{Ax}}$ 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

$$\vec{A}_n = \sum_i^M A_i \hat{n}_i$$

$$\vec{F}_D = \left\{ \begin{array}{c} \dfrac{C_{D_{Ax}} \rho_W \vec{A}_n \left\| \vec{v}_{rel} \bullet \vec{A}_n \right\|_2 \left(\vec{v}_{rel} \bullet \vec{A}_n \right)}{4 \left(\vec{A}_n \bullet \vec{A}_n \right)} \\ 0 \\ 0 \\ 0 \end{array} \right\} \quad (31)$$

Equation 31 is the total lumped drag at a joint, since the simulation mesh consists of M co-located lumped nodes, $\vec{F}_D$ is actually $\dfrac{\vec{F}_D}{M}$, for each simulation node.

7.5.1.2.3 Buoyancy

$$\vec{F}_B^s = \rho_w g \left\{ \begin{array}{c} C_s \left\{ \begin{array}{c} 0 \\ 0 \\ -Z^s \pi \left(R^s + t_{MG}^s \right)^2 \end{array} \right\} \\ \left[-\dfrac{\pi}{4} C_{32} \left(R^s + t_{MG}^s \right)^4 \right] \\ C_s \left\{ \dfrac{\pi}{4} C_{31} \left(R^s + t_{MG}^s \right)^4 \right\} \\ 0 \end{array} \right\} (35)$$

$$\vec{F}_B^e = \rho_w g \left\{ \begin{array}{c} C_e \left\{ \begin{array}{c} 0 \\ 0 \\ Z^e \pi \left(R^e + t_{MG}^e \right)^2 \end{array} \right\} \\ \left[\dfrac{\pi}{4} C_{32} \left(R^e + t_{MG}^e \right)^4 \right] \\ C_e \left\{ -\dfrac{\pi}{4} C_{31} \left(R^e + t_{MG}^e \right)^4 \right\} \\ 0 \end{array} \right\} (36)$$

7.5.1.2.4 Ballasting

$$\vec{F}_{F\_B}^s = -\rho_f g \left\{ \begin{array}{c} C^s \left\{ \begin{array}{c} 0 \\ 0 \\ -\left(Z^s - Z^{fs} \right) \pi \left(R^s - t_M^s \right)^2 \end{array} \right\} \\ \left[-\dfrac{\pi}{4} C_{32} \left(R^s - t_M^s \right)^4 \right] \\ C^s \left\{ \dfrac{\pi}{4} C_{31} \left(R^s - t_M^s \right)^4 \right\} \\ 0 \end{array} \right\}, \qquad (37)$$

$$\vec{F}^e_{F\_B} = -\rho_f g \left\{ \begin{array}{c} C^e \left\{ \begin{array}{c} 0 \\ 0 \\ \left(Z^e - Z^{fs} \right) \pi \left(R^e - t^e_M \right)^2 \end{array} \right\} \\ \dfrac{\pi}{4} C_{32} \left(R^e - t^e_M \right)^4 \\ C^e \left\{ -\dfrac{\pi}{4} C_{31} \left(R^e - t^e_M \right)^4 \right\} \\ 0 \end{array} \right\}$$

7.5.1.2.5 Hydrodynamic Added Mass

$$\vec{F}_{AM} = \left\{ \begin{array}{c} \dfrac{-C_{A_{Ax}} \rho_W \vec{V}_n \left(\vec{a}_s \bullet \vec{V}_n \right)}{\sqrt{\left(\vec{V}_n \bullet \vec{V}_n \right)}} \\ 0 \\ 0 \\ 0 \end{array} \right\}$$

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 $\dfrac{\vec{F}_{AM}}{M}$, 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:

    o The element is filled and the free-surface elevation lies within the element; add node at free-surface elevation.

- o The element crosses the **MSL2SWL** elevation; add node at **MSL2SWL** elevation.

- o The element crosses the flat seabed; add node at seabed elevation.

- o 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 could be implemented 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).

- Enable auto-generation of all possible output channels (*OutAll* = TRUE).

- Add outputs pertaining to the total hydrodynamic applied loads at nodes along members and at joints.

- 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.

- Add convective fluid acceleration terms.

- Allow for wave directional spreading to include energy spectra that varies with direction (requires changing from the equal-energy method).

- 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.

- 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.

IEC 61400-3 Ed.1, *Wind Turbines – Part 3: Design Requirements for Offshore Wind Turbines*, International Electrotechnical Commission (IEC), 2009.

Jonkman, J. M., *Dynamic modeling and load analysis of an offshore floating wind turbine*, Ph.D. Thesis. Department of Aerospace Engineering Sciences, University of Colorado, Boulder, CO, 2007; NREL/TP-500-41958. Golden, CO: National Renewable Energy Laboratory.

Lee, C. H. and Newman, J. N., WAMIT® User Manual, Versions 6.3, 6.3PC, 6.3S, 6.3S-PC, Chestnut Hill, MA: WAMIT, Inc., 2006.

Sharma, N. and Dean. R., "Second-order directional seas and associated wave forces," Society of Petroleum Engineers Journal, 4:129-140, 1981.

Appendix A. OC4 Semi-submersible Input File

```
------- HydroDyn v2.03.* Input File --------------------------------------------
NREL 5.0 MW offshore baseline floating platform HydroDyn input properties for the OC4 Semi-submersible.
False        Echo           - Echo the input file data (flag)
---------------------- ENVIRONMENTAL CONDITIONS --------------------------------
        1025 WtrDens        - Water density (kg/m^3)
         200 WtrDpth        - Water depth (meters)
           0 MSL2SWL        - Offset between still-water level and mean sea level (meters) [positive upward; unused when WaveMod=6; must be zero if PotMod=1 or 2]
---------------------- WAVES ---------------------------------------------------
           3 WaveMod        - Incident wave kinematics model {0: none=still water, 1: regular (periodic), 1P#: regular with user-specified phase, 2: JONSWAP/Pierson-Moskowitz …
           0 WaveStMod      - Model for stretching incident wave kinematics to instantaneous free surface {0: none=no stretching, 1: vertical stretching, 2: extrapolation …
        4600 WaveTMax       - Analysis time for incident wave calculations (sec) [unused when WaveMod=0; determines WaveDOmega=2Pi/WaveTMax in the IFFT]
         0.2 WaveDT         - Time step for incident wave calculations     (sec) [unused when WaveMod=0; 0.1<=WaveDT<=1.0 recommended; determines WaveOmegaMax=Pi/WaveDT in the IFFT]
      1.2646 WaveHs         - Significant wave height of incident waves (meters) [used only when WaveMod=1, 2, or 3]
          10 WaveTp         - 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) [unused when WaveMod=0, 1, or 6]
    1.570796 WvHiCOff       - High cut-off frequency or upper frequency limit of the wave spectrum beyond which the wave spectrum is zeroed (rad/s) [unused when WaveMod=0, 1, or 6]
           0 WaveDir        - Incident wave propagation heading direction                        (degrees) [unused when WaveMod=0 or 6]
           0 WaveDirMod     - Directional spreading function {0: none, 1: COS2S}                 (-)      [only used when WaveMod=2, 3, or 4]
           1 WaveDirSpread  - Wave direction spreading coefficient ( > 0 )                       (-)      [only used when WaveMod=2, 3, or 4 and WaveDirMod=1]
           1 WaveNDir       - Number of wave directions                                          (-)      [only used when WaveMod=2, 3, or 4 and WaveDirMod=1; odd number only, …
           0 WaveDirRange   - Range of wave directions (full range: WaveDir +/- 1/2*WaveDirRange) (degrees) [only used when WaveMod=2, 3, or 4 and WaveDirMod=1]
   123456789 WaveSeed(1)    - First  random seed of incident waves [-2147483648 to 2147483647]   (-)      [unused when WaveMod=0, 5, or 6]
  1011121314 WaveSeed(2)    - Second random seed of incident waves [-2147483648 to 2147483647]   (-)      [unused when WaveMod=0, 5, or 6]
       FALSE WaveNDAmp      - Flag for normally distributed amplitudes (flag)                              [only used when WaveMod=2,3, or 4]
          "" WvKinFile      - Root name of externally generated wave data file(s) (quoted string)          [used only when WaveMod=5 or 6]
           1 NWaveElev      - Number of points where the incident wave elevations can be computed (-)      [maximum of 9 output locations]
           0 WaveElevxi     - List of xi-coordinates for points where the incident wave elevations can be output (meters) [NWaveElev points, separated by commas or white space; …
           0 WaveElevyi     - List of yi-coordinates for points where the incident wave elevations can be output (meters) [NWaveElev points, separated by commas or white space; …
---------------------- 2ND-ORDER WAVES ---------------------------------------- [unused with WaveMod=0 or 6]
False        WvDiffQTF      - Full difference-frequency 2nd-order wave kinematics (flag)
False        WvSumQTF       - Full summation-frequency  2nd-order wave kinematics (flag)
           0 WvLowCOffD     - Low  frequency cutoff used in the difference-frequencies (rad/s) [Only used with a difference-frequency method]
         500 WvHiCOffD      - High frequency cutoff used in the difference-frequencies (rad/s) [Only used with a difference-frequency method]
           0 WvLowCOffS     - Low  frequency cutoff used in the summation-frequencies  (rad/s) [Only used with a summation-frequency  method]
         500 WvHiCOffS      - High frequency cutoff used in the summation-frequencies  (rad/s) [Only used with a summation-frequency  method]
---------------------- CURRENT ------------------------------------------------- [unused with WaveMod=6]
           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]
   "DEFAULT" CurrSSDir      - Sub-surface current heading direction (degrees) or DEFAULT (string) [used only when CurrMod=1]
          20 CurrNSRef      - Near-surface current reference depth           (meters) [used only when CurrMod=1]
           0 CurrNSV0       - Near-surface current velocity at still water level (m/s) [used only when CurrMod=1]
           0 CurrNSDir      - Near-surface current heading direction         (degrees) [used only when CurrMod=1]
           0 CurrDIV        - Depth-independent current velocity              (m/s) [used only when CurrMod=1]
           0 CurrDIDir      - Depth-independent current heading direction    (degrees) [used only when CurrMod=1]
---------------------- FLOATING PLATFORM --------------------------------------- [unused with WaveMod=6]
           1 PotMod         - Potential-flow model {0: none=no potential flow, 1: frequency-to-time-domain transforms based on WAMIT output, 2: fluid-impulse theory (FIT)} (switch)
"HydroData/marin_semi"   PotFile     - Root name of potential-flow model data; WAMIT output files containing the linear, nondimensionalized, hydrostatic restoring matrix (.hst…
           1 WAMITULEN      - Characteristic body length scale used to redimensionalize WAMIT output (meters) [only used when PotMod=1]
       13917 PtfmVol0       - Displaced volume of water when the platform is in its undisplaced position (m^3) [only used when PotMod=1; USE THE SAME VALUE COMPUTED BY WAMIT AS…
           0 PtfmCOBxt      - The xt offset of the center of buoyancy (COB) from the platform reference point (meters) [only used when PotMod=1]
           0 PtfmCOByt      - The yt offset of the center of buoyancy (COB) from the platform reference point (meters) [only used when PotMod=1]
           1 RdtnMod        - Radiation memory-effect model {0: no memory-effect calculation, 1: convolution, 2: state-space} (switch) [only used when PotMod=1; STATE-SPACE REQUIRES…
```

```
            60   RdtnTMax        - Analysis time for wave radiation kernel calculations (sec) [determines RdtnDOmega=Pi/RdtnTMax in the cosine transform] [only used when PotMod=1; MAKE…
        0.0125   RdtnDT          - Time step for wave radiation kernel calculations (sec) [only used when PotMod=1; DT<=RdtnDT<=0.1 recommended; determines RdtnOmegaMax=Pi/RdtnDT in the…
---------------------- 2ND-ORDER FLOATING PLATFORM FORCES ---------------------- [unused with WaveMod=0 or 6 or PotMod=0 or 2]
             0   MnDrift         - Mean-drift 2nd-order forces computed                                         {0: None; [7, 8, 9, 10, 11, or 12]: WAMIT file to use} [Only one of …
             0   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 …
             0   DiffQTF         - Full difference-frequency 2nd-order forces computed with full QTF            {0: None; [10, 11, or 12]: WAMIT file to use}          [Only one of …
             0   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  -------------------------- [unused with WaveMod=6]
True           PtfmSgF         - Platform horizontal surge translation force (flag) or DEFAULT
True           PtfmSwF         - Platform horizontal sway translation force (flag) or DEFAULT
True           PtfmHvF         - Platform vertical heave translation force (flag) or DEFAULT
True           PtfmRF          - Platform roll tilt rotation force (flag) or DEFAULT
True           PtfmPF          - Platform pitch tilt rotation force (flag) or DEFAULT
True           PtfmYF          - Platform yaw rotation force (flag) or DEFAULT
---------------------- PLATFORM ADDITIONAL STIFFNESS AND DAMPING  ---------------
             0           0           0           0           0           0   AddF0    - Additional preload (N, N-m)
             0           0           0           0           0           0   AddCLin  - Additional linear stiffness (N/m, N/rad, N-m/m, N-m/rad)
             0           0           0           0           0           0
             0           0           0           0           0           0
             0           0           0  1451298897           0           0
             0           0           0           0  1451298897           0
             0           0           0           0           0           0
             0           0           0           0           0           0   AddBLin  - Additional linear damping(N/(m/s), N/(rad/s), N-m/(m/s), N-m/(rad/s))
             0           0           0           0           0           0
             0           0           0           0           0           0
             0           0           0           0           0           0
             0           0           0           0           0           0
             0           0           0           0           0           0   AddBQuad - Additional quadratic drag(N/(m/s)^2, N/(rad/s)^2, N-m(m/s)^2, N-m/(rad/s)^2)
             0           0           0           0           0           0
             0           0           0           0           0           0
             0           0           0           0           0           0
             0           0           0           0           0           0
             0           0           0           0           0           0
---------------------- AXIAL COEFFICIENTS ------------------------------------
             2   NAxCoef         - Number of axial coefficients (-)
AxCoefID  AxCd     AxCa     AxCp
  (-)     (-)      (-)      (-)
   1     0.00     0.00     1.00
   2     9.60     0.00     1.00
---------------------- MEMBER JOINTS --------------------------------------------
            44   NJoints         - Number of joints (-)   [must be exactly 0 or at least 2]
JointID   Jointxi     Jointyi     Jointzi  JointAxID   JointOvrlp   [JointOvrlp= 0: do nothing at joint, 1: eliminate overlaps by calculating super member]
  (-)      (m)         (m)         (m)       (-)       (switch)
   1     0.00000     0.00000   -20.00000      1          0
   2     0.00000     0.00000    10.00000      1          0
   3    14.43376    25.00000   -14.00000      1          0
   4    14.43376    25.00000    12.00000      1          0
   5   -28.86751     0.00000   -14.00000      1          0
   6   -28.86751     0.00000    12.00000      1          0
   7    14.43376   -25.00000   -14.00000      1          0
   8    14.43376   -25.00000    12.00000      1          0
   9    14.43375    25.00000   -20.00000      2          0
  10   -28.86750     0.00000   -20.00000      2          0
  11    14.43375   -25.00000   -20.00000      2          0
  12     9.23760    22.00000    10.00000      1          0
  13   -23.67130     3.00000    10.00000      1          0
```

```
   14    -23.67130    -3.00000    10.00000    1         0
   15      9.23760   -22.00000    10.00000    1         0
   16     14.43375   -19.00000    10.00000    1         0
   17     14.43375    19.00000    10.00000    1         0
   18      4.04145    19.00000   -17.00000    1         0
   19    -18.47520     6.00000   -17.00000    1         0
   20    -18.47520    -6.00000   -17.00000    1         0
   21      4.04145   -19.00000   -17.00000    1         0
   22     14.43375   -13.00000   -17.00000    1         0
   23     14.43375    13.00000   -17.00000    1         0
   24      1.62500     2.81500    10.00000    1         0
   25     11.43376    19.80385    10.00000    1         0
   26     -3.25000     0.00000    10.00000    1         0
   27    -22.87000     0.00000    10.00000    1         0
   28      1.62500    -2.81500    10.00000    1         0
   29     11.43376   -19.80385    10.00000    1         0
   30      1.62500     2.81500   -17.00000    1         0
   31      8.43376    14.60770   -17.00000    1         0
   32     -3.25000     0.00000   -17.00000    1         0
   33    -16.87000     0.00000   -17.00000    1         0
   34      1.62500    -2.81500   -17.00000    1         0
   35      8.43376   -14.60770   -17.00000    1         0
   36      1.62500     2.81500   -16.20000    1         0
   37     11.43376    19.80385     9.13000    1         0
   38     -3.25000     0.00000   -16.20000    1         0
   39    -22.87000     0.00000     9.13000    1         0
   40      1.62500    -2.81500   -16.20000    1         0
   41     11.43376   -19.80385     9.13000    1         0
   42     14.43376    25.00000   -19.94000    1         0
   43    -28.86751     0.00000   -19.94000    1         0
   44     14.43376   -25.00000   -19.94000    1         0
---------------------- MEMBER CROSS-SECTION PROPERTIES -------------------------
           4   NPropSets       - Number of member property sets (-)
PropSetID    PropD       PropThck
   (-)        (m)          (m)
    1        6.50000      0.03000         ! Main Column
    2       12.00000      0.06000         ! Upper Columns
    3       24.00000      0.06000         ! Base Columns
    4        1.60000      0.01750         ! Pontoons
---------------------- SIMPLE HYDRODYNAMIC COEFFICIENTS (model 1) --------------
    SimplCd   SimplCdMG    SimplCa   SimplCaMG    SimplCp   SimplCpMG   SimplAxCa  SimplAxCaMG  SimplAxCp  SimplAxCpMG
    (-)        (-)         (-)        (-)         (-)        (-)         (-)        (-)         (-)        (-)
    0.00       0.00        0.00       0.00        1.00       1.00        0.00       0.00        1.00       1.00
---------------------- DEPTH-BASED HYDRODYNAMIC COEFFICIENTS (model 2) ---------
           0   NCoefDpth       - Number of depth-dependent coefficients (-)
Dpth     DpthCd    DpthCdMG    DpthCa    DpthCaMG     DpthCp    DpthCpMG    DpthAxCa   DpthAxCaMG     DpthAxCp   DpthAxCpMG
(m)       (-)       (-)        (-)        (-)         (-)        (-)        (-)        (-)           (-)         (-)
---------------------- MEMBER-BASED HYDRODYNAMIC COEFFICIENTS (model 3) --------
          25   NCoefMembers     - Number of member-based coefficients (-)
MemberID   MemberCd1    MemberCd2    MemberCdMG1   MemberCdMG2    MemberCa1    MemberCa2    MemberCaMG1   MemberCaMG2   MemberCp1    MemberCp2    MemberCpMG1   MemberCpMG2  …
   (-)       (-)          (-)          (-)          (-)           (-)          (-)          (-)          (-)           (-)          (-)          (-)          (-)         …
    1        0.56         0.56         0.00         0.00          0.00         0.00         0.00         0.00          0.00         0.00         0.00         0.00        …
    2        0.61         0.61         0.00         0.00          0.00         0.00         0.00         0.00          0.00         0.00         0.00         0.00        …
    3        0.61         0.61         0.00         0.00          0.00         0.00         0.00         0.00          0.00         0.00         0.00         0.00        …
    4        0.61         0.61         0.00         0.00          0.00         0.00         0.00         0.00          0.00         0.00         0.00         0.00        …
    5        0.68         0.68         0.00         0.00          0.00         0.00         0.00         0.00          0.00         0.00         0.00         0.00        …
```

6	0.68	0.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	…
7	0.68	0.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	…
23	0.68	0.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	…
24	0.68	0.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	…
25	0.68	0.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	…
8	0.63	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	…
9	0.63	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	…
10	0.63	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	…
11	0.63	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	…
12	0.63	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	…
13	0.63	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	…
14	0.63	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	…
15	0.63	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	…
16	0.63	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	…
17	0.63	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	…
18	0.63	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	…
19	0.63	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	…
20	0.63	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	…
21	0.63	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	…
22	0.63	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	…

------------------- MEMBERS ---

          25   NMembers   - Number of members (-)

MemberID	MJointID1	MJointID2	MPropSetID1	MPropSetID2	MDivSize	MCoefMod	PropPot	[MCoefMod=1: use simple coeff table, 2: use depth-based coeff table, 3: use member-based …
(-)	(-)	(-)	(-)	(-)	(m)	(switch)	(flag)	
1	1	2	1	1	1.0000	3	TRUE	! Main Column
2	3	4	2	2	1.0000	3	TRUE	! Upper Column 1
3	5	6	2	2	1.0000	3	TRUE	! Upper Column 2
4	7	8	2	2	1.0000	3	TRUE	! Upper Column 3
5	42	3	3	3	1.0000	3	TRUE	! Base Column 1
6	43	5	3	3	1.0000	3	TRUE	! Base Column 2
7	44	7	3	3	1.0000	3	TRUE	! Base Column 3
23	9	42	3	3	1.0000	3	TRUE	! Base column cap 1
24	10	43	3	3	1.0000	3	TRUE	! Base column cap 2
25	11	44	3	3	1.0000	3	TRUE	! Base column cap 3
8	12	13	4	4	1.0000	3	TRUE	! Delta Pontoon, Upper 1
9	14	15	4	4	1.0000	3	TRUE	! Delta Pontoon, Upper 2
10	16	17	4	4	1.0000	3	TRUE	! Delta Pontoon, Upper 3
11	18	19	4	4	1.0000	3	TRUE	! Delta Pontoon, Lower 1
12	20	21	4	4	1.0000	3	TRUE	! Delta Pontoon, Lower 2
13	22	23	4	4	1.0000	3	TRUE	! Delta Pontoon, Lower 3
14	24	25	4	4	1.0000	3	TRUE	! Y Pontoon, Upper 1
15	26	27	4	4	1.0000	3	TRUE	! Y Pontoon, Upper 2
16	28	29	4	4	1.0000	3	TRUE	! Y Pontoon, Upper 3
17	30	31	4	4	1.0000	3	TRUE	! Y Pontoon, Lower 1
18	32	33	4	4	1.0000	3	TRUE	! Y Pontoon, Lower 2
19	34	35	4	4	1.0000	3	TRUE	! Y Pontoon, Lower 3
20	36	37	4	4	1.0000	3	TRUE	! Cross Brace 1
21	38	39	4	4	1.0000	3	TRUE	! Cross Brace 2
22	40	41	4	4	1.0000	3	TRUE	! Cross Brace 3

-------------------- FILLED MEMBERS --

           2   NFillGroups   - Number of filled member groups (-) [If FillDens = DEFAULT, then FillDens = WtrDens; FillFSLoc is related to MSL2SWL]

FillNumM	FillMList			FillFSLoc	FillDens
(-)	(-)			(m)	(kg/m^3)
3	2	3	4	-6.17	1025
3	5	6	7	-14.89	1025

-------------------- MARINE GROWTH ---

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

```
MGDpth     MGThck     MGDens
(m)        (m)        (kg/m^3)
-------------------- MEMBER OUTPUT LIST ---------------------------------
           0   NMOutputs      - Number of member outputs (-) [must be < 10]
MemberID   NOutLoc   NodeLocs [NOutLoc < 10; node locations are normalized distance from the start of the member, and must be >=0 and <= 1] [unused if NMOutputs=0]
  (-)       (-)        (-)
-------------------- JOINT OUTPUT LIST ----------------------------------
           0   NJOutputs      - Number of joint outputs [Must be < 10]
    0      JOutLst       - List of JointIDs which are to be output (-)[unused if NJOutputs=0]
-------------------- 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   OutSwtch       - Output requested channels to: [1=Hydrodyn.out, 2=GlueCode.out, 3=both files]
"ES11.4e2"     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 v2.03.*
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 acccelerations 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 acccelerations 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           WaveElevNX WaveElevNY  - WaveElevSeries points -- WaveElevNX WaveElevNY
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.   MαNβ, refers to output node β of output member α, where α is a number in the range [1,9] and corresponds to row α in the MEMBER OUTPUT LIST table and β is a number in the range [1,9] and corresponds to location β in the *NodeLocs* list of that table entry. Jα refers to output joint α, where α is a number in the range [1,9] and corresponds to row α in the JOINT OUTPUT LIST table. All outputs are in the global inertial-frame coordinate system.

Channel Name(s)	Units	Description
Wave and Current Kinematics		
Wave1Elev, Wave2Elev, …, Wave9Elev	(m)	Total (first- plus second-order) wave elevations (up to 9 designated locations)
Wave1Elv1, Wave2Elv1, …, Wave9Elv1	(m)	First-order wave elevations (up to 9 designated locations)
Wave1Elv2, Wave2Elv2, …, Wave9Elv2	(m)	Second-order wave elevations (up to 9 designated locations)
MαNβVxi, MαNβVyi, MαNβVzi	(m/s), (m/s), (m/s)	Total (first- plus second-order) fluid particle velocities at MαNβ
MαNβAxi, MαNβAyi, MαNβAzi	(m/s^2), (m/s^2), (m/s^2)	Total (first- plus second-order) fluid particle accelerations at MαNβ
MαNβDynP	(Pa)	Total (first- plus second-order) fluid particle dynamic pressure at MαNβ
JαVxi, JαVyi, JαVzi	(m/s), (m/s), (m/s)	Total (first- plus second-order) fluid particle velocities at Jα
JαAxi, JαAyi, JαAzi	(m/s^2), (m/s^2), (m/s^2)	Total (first- plus second-order) fluid particle accelerations at Jα
JαDynP	(Pa)	Total (first- plus second-order) fluid particle dynamic pressure at Jα
Total and Additional Loads		
AddFxi, AddFyi, AddFzi, AddMxi, AddMyi, AddMzi	(N), (N), (N), (N·m), (N·m), (N·m)	Forces and moments due to additional preload, stiffness, and damping at the WRP
HydroFxi, HydroFyi, HydroFzi, HydroMxi, HydroMyi, HydroMzi	(N), (N), (N), (N·m), (N·m), (N·m)	Total integrated hydrodynamic loads from both potential flow and strip theory at the WRP
Loads from Potential-Flow Solution		
WavesFxi, WavesFyi, WavesFzi, WavesMxi, WavesMyi, WavesMzi	(N), (N), (N), (N·m), (N·m), (N·m)	Total (first- plus second-order) wave-excitation loads from diffraction at the WRP

WavesF1xi, WavesF1yi, WavesF1zi, WavesM1xi, WavesM1yi, WavesM1zi	(N), (N), (N), (N·m), (N·m), (N·m)	First-order wave-excitation loads from diffraction at the WRP
WavesF2xi, WavesF2yi, WavesF2zi, WavesM2xi, WavesM2yi, WavesM2zi	(N), (N), (N), (N·m), (N·m), (N·m)	Second-order wave-excitation loads from diffraction at the WRP
HdrStcFxi, HdrStcFyi, HdrStcFzi, HdrStcMxi, HdrStcMyi, HdrStcMzi	(N), (N), (N), (N·m), (N·m), (N·m)	Hydrostatic loads at the WRP
RdtnFxi, RdtnFyi, RdtnFzi, RdtnMxi, RdtnMyi, RdtnMzi	(N), (N), (N), (N·m), (N·m), (N·m)	Radiation loads at the WRP
Structural Motions		
WRPSurge, WRPSway, WRPHeave, WRPRoll, WRPPitch WRPYaw	(m), (m), (m), (rad), (rad), (rad)	Displacements and rotations at the WRP
WRPTVxi, WRPTVyi, WRPTVzi, WRPRVxi, WRPRVyi, WRPVzi	(m/s), (m/s), (m/s), (rad/s), (rad/s), (rad/s)	Translational and rotational velocities at the WRP
WRPTAxi, WRPTAyi, WRPTAzi, WRPRAxi, WRPRAyi, WRPAzi	(m/s^2), (m/s^2), (m/s^2), (rad/s^2), (rad/s^2), (rad/s^2)	Translational and rotational accelerations at the WRP
MαNβSTVxi, MαNβSTVyi, MαNβSTVzi	(m/s), (m/s), (m/s)	Structural translational velocities at MαNβ
MαNβSTAxi, MαNβSTAyi, MαNβSTAzi	(m/s^2), (m/s^2), (m/s^2)	Structural translational accelerations at MαNβ
JαSTVxi, JαSTVyi, JαSTVzi	(m/s), (m/s), (m/s)	Structural translational velocities at Jα
JαSTAxi, JαSTAyi, JαSTAzi	(m/s^2), (m/s^2), (m/s^2)	Structural translational accelerations at Jα
Distributed Loads (Per Unit Length) on Members		
MαNβFDxi, MαNβFDyi, MαNβFDzi	(N/m), (N/m), (N/m)	Viscous-drag force at MαNβ
MαNβFIxi, MαNβFIyi, MαNβFIzi	(N/m), (N/m), (N/m)	Fluid-inertia force at MαNβ
MαNβFBxi, MαNβFByi, MαNβFBzi, MαNβMBxi, MαNβMByi, MαNβMBzi	(N/m), (N/m), (N/m), (N·m/m), (N·m/m), (N·m/m)	Buoyancy loads at MαNβ
MαNβFBFxi, MαNβFBFyi, MαNβFBFzi, MαNβMBFxi, MαNβMBFyi, MαNβMBFzi	(N/m), (N/m), (N/m), (N·m/m), (N·m/m), (N·m/m)	Negative buoyancy loads due to flooding/ballasting at MαNβ
MαNβFMGxi, MαNβFMGyi, MαNβFMGzi	(N/m), (N/m), (N/m)	Forces due to marine growth weight at MαNβ
MαNβFAMxi, MαNβFAMyi, MαNβFAMzi	(N/m), (N/m), (N/m)	Hydrodynamic added-mass forces at MαNβ
MαNβFAGxi, MαNβFAGyi, MαNβFAGzi	(N/m), (N/m), (N/m)	Marine growth mass inertia forces at MαNβ
MαNβFAFxi, MαNβFAFyi, MαNβFAFzi	(N/m), (N/m), (N/m)	Flooding/ballasting mass inertia forces at MαNβ
MαNβFAxi, MαNβFAyi, MαNβFAzi	(N/m), (N/m), (N/m)	Total effective added-mass forces at MαNβ
Lumped Loads at Joints		
JαFDxi, JαFDyi, JαFDzi	(N), (N), (N)	Viscous-drag force at Jα
JαFIxi, JαFIyi, JαFIzi	(N), (N), (N)	Fluid-inertia force at Jα
JαFBxi, JαFByi, JαFBzi, JαMBxi, JαMByi, JαMBzi	(N), (N), (N), (N·m), (N·m), (N·m)	Buoyancy loads at Jα
JαFBFxi, JαFBFyi, JαFBFzi, JαMBFxi, JαMBFyi, JαMBFzi	(N), (N), (N), (N·m), (N·m), (N·m)	Negative buoyancy loads due to flooding/ballasting at Jα
JαFAMxi, JαFAMyi, JαFAMzi	(N), (N), (N)	Hydrodynamic added-mass forces at Jα

Appendix D. Compiling Standalone 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 standalone 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). This appendix outlines significant modifications to HydroDyn made with each public release, starting with v2.00.

V2.03 (October 2015)

Version 2.03 integrates with the FAST v8 software v8.12.00a-bjj.

- **Primary input file changes**
  - Waves section
    - Changed *GHWvFile* option to *WvKinFile*
  - Floating Platform section
    - Changed *HasWAMIT* option to *PotMod* with valid values of 0 or 1
    - Changed *WAMITFile* option to *PotFile*
  - Members section
    - Changed *PropWAMIT* to *PropPot*
- **New or Modified Hydrodynamics**
  - Added *WaveMod* = 5 option: Externally generated wave-elevation time series
    Added *WaveMod* = 6 option: Externally generated full wave-kinematics time series

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 2ND-ORDER WAVES section
  - FLOATING PLATFORM section
    - Added support for *RdtnDT* to be set to "DEFAULT" to match driver code time step
  - Added 2ND-ORDER FLOATING 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*

- o SIMPLE HYDRODYNAMIC COEFFICIENTS section
  - Added dynamic-pressure coefficients: ***SimplCp***, ***SimplCpMG***
  - Added parameters for axial coefficients: ***SimplAxCa***, ***SimplAxCaMG***, ***SimplAxCp***, ***SimplAxCpMG***
- o DEPTH-BASED HYDRODYNAMIC COEFFICIENTS section
  - Added dynamic-pressure coefficients: ***DpthCp***, ***DpthCpMG***
  - Added parameters for axial coefficients: ***DpthAxCa***, ***DpthAxCaMG***, ***DpthAxCp***, ***DpthAxCpMG***
- o 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***
- o 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**
  - o Modified file naming convention to match FAST convention
  - o 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 standalone HydroDyn
    - All units are now SI (m, N, s)
  - o Results file
    - All units are now SI (m, N, s)

- **New or Modified Hydrodynamics**
  - o Added multi-directional waves
  - o Combined Froude-Kriloff (dynamic-pressure) loads into the inertial loads

- o Added option whereby if simulation time is greater than ***WaveTMax***, waves repeat
- o Added lumped inertial loads
- o Altered lumped added-mass equation
- o Altered distributed inertial-load equation
- o Altered fluid-domain checks for when to compute hydrodynamic loads
- o Included the platform added-mass loads in the radiation load outputs (***RdtnFxi***, ***RdtnFyi***, etc.)

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

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

v2.00.01 (October 2013)

The major changes in version 2.00 are:

- Version 2.00 integrates with the FAST v8 software 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.

- The new implementation has well-defined data exchange interfaces (following the FAST modularization framework) which should make integration of HydroDyn into other multi-physics software packages much simpler.