Substructure Flexibility and Member-Level Load Capabilities for Floating Offshore Wind Turbines in OpenFAST

Preprint

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NOTICE

SUBSTRUCTURE FLEXIBILITY AND MEMBER-LEVEL LOAD CAPABILITIES FOR FLOATING OFFSHORE WIND TURBINES IN OPENFAST

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ABSTRACT

OpenFAST is an open-source, physics-based engineering tool applicable to the load analysis of land-based and offshore wind turbines, including floating offshore wind turbines. The substructure for a floating wind turbine has historically been modeled in OpenFAST as a rigid body with hydrodynamic loads lumped at a point, which enabled the tool to predict the global response of the floating substructure but not the structural loads within its individual members. This limitation is an impediment to designing floating substructures—especially newer designs that are more streamlined, flexible, and cost-effective. This paper presents the development plan of new capabilities in OpenFAST to model floating substructure flexibility and member-level loads, including the functional requirements and modeling approaches needed to understand and apply them correctly.

Keywords: Floating offshore wind turbine (FOWT), substructure flexibility, member-level loads, functional requirements, aero-hydro-servo-elastics, OpenFAST

1 INTRODUCTION

To support innovative, optimized, reliable, and cost-effective floating offshore wind turbine (FOWTs) designs, the wind industry and research communities rely on physics-based engineering software (i.e., design tools) capable of predicting the coupled dynamic loads and responses of the wind system. OpenFAST (formerly known as FAST), developed by the National Renewable Energy Laboratory (NREL) via support from the U.S. Department of Energy, is a state-of-the-art, open-source engineering tool [1]. For FOWTs, OpenFAST models the important physical phenomena and system couplings, including the environmental excitation (wind, waves, and current) and full-system dynamic response (rotor, drivetrain, nacelle, tower, substructure, moorings, and controller) under both normal (for fatigue) and extreme (for ultimate) loading conditions.

The substructure of a FOWT has historically been modeled in OpenFAST as a rigid body with hydrodynamic loads lumped at a point, which enabled the tool to predict the global response of the floating substructure but not the structural loads within its individual members. To enable the design and optimization of the floating substructures—especially next-generation floating wind technologies that show promise to be streamlined, flexible, and cost-effective—substructure flexibility and member-level load calculations are being implemented in OpenFAST. This implementation is part of a larger effort at NREL to develop an open-source, multifidelity systems-analysis capability for floating offshore wind turbine analysis and optimization that captures the relevant physics and costs that drive designs and trade-offs.

To meet the modeling needs of most FOWT support structures—ranging from spar buoys, semisubmersibles, tension-leg platforms, and hybrid combinations of these—functional requirements for the new capability were established by reviewing existing FOWT prototypes and proposed concepts and comparing their structural configurations and resulting physics-based modeling needs to the modeling capabilities already available in OpenFAST as well as new capabilities that can be implemented within the time frame and funding available for the current effort. We assessed the floating support structure—including the tower, substructure, and mooring systems—of the various FOWT technologies rather than innovations in the wind turbine itself, which are outside the scope of the current effort. We selected functional requirements that meet the modeling needs of most FOWT support structures, and we identified a few functional requirements that are important for only some FOWTs that will require future development. We considered only modeling approaches that will maintain computational efficiency so that OpenFAST will still

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be applicable to running the thousands of load-case simulations necessary for FOWT design and optimization.

Note that in addition to OpenFAST, other physics-based engineering software tools have also been developed in the wind community to model the coupled dynamic responses of FOWTs, and most of these also treat the floating substructure rigidly. Recent work by Borg et al. [2] extended the Horizontal Axis Wind turbine simulation Code 2nd generation (HAWC2) to consider the substructure flexibility of large-volume floaters through a generalized-modes approach. The approach presented here differs from [2] because large-volume bodies in floating substructures of FOWTs are expected to be quite rigid, whereas the hydrodynamic interactions between multiple large-volume bodies and the flexibility of slender members are expected to be more significant. The approach presented here can be seen as a broader and open-source implementation of the approach taken by Luan et al. [3] in Simo/Riflex/AeroDyn.

The subsequent sections present a summary of the existing FOWT support structure modeling capability in OpenFAST, followed by the new functional requirements (including which FOWTs these functional requirements pertain to) and modeling approaches to address these functional requirements that are currently being implemented in the OpenFAST source code. The modeling approaches are described qualitatively, leaving the mathematical details for a subsequent paper. Functional requirements not considered are summarized at the end. Unfortunately, the implementation at the time of this writing had not yet been completed enough to produce results. Results will be presented in future work to highlight the functionality and verify the implementation.

The upgrades to OpenFAST involve further development of the SubDyn structural dynamics module for substructures, the HydroDyn hydrodynamics module, and their coupling to the ElastoDyn wind turbine structural dynamics module within the OpenFAST glue (driver) code. Although SubDyn was originally developed for bottom-fixed substructures, the module is upgraded here for application to FOWTs (HydroDyn already applies to both fixed and FOWTs). See Figure 1 for an overview of OpenFAST and its modules.

2 EXISTING FOWT SUPPORT STRUCTURE MODELING CAPABILITY IN OPENFAST

This section describes the existing modeling capabilities in OpenFAST for FOWT support structures to distinguish them from the new functional requirements and modeling approaches being implemented. The existing capabilities include [1]:
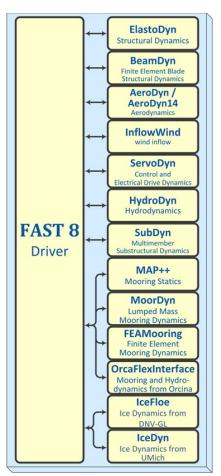
FIGURE 1. OPENFAST AND ITS MODULES

- A flexible tubular monotower atop a rigid substructure—modeled in ElastoDyn as a modal-based flexible tower element with two fore-aft and two side-to-side modes, including geometric nonlinearities such as gravitational destiffening, cantilevered to a rigid platform with six degrees of freedom (DOF); rotations employ small-angle approximations with nonlinear corrections that maintain orthogonality, which permits moderately sized rotational displacements.[2]
- Aerodynamic loads and tower influence on rotor aerodynamic loads for a tubular monotower—modeled in AeroDyn using the viscous drag term from strip theory and upwind and downwind flow corrections.
- Tuned mass dampers (TMDs) installed in the tower—modeled in ServoDyn as two independent, one-DOF, mass-spring-damping elements that act in the fore-aft and side-to-side directions or one single omnidirectional, two-DOF TMDs, together with passive, semi-active, or active control.
- Waves—modeled in HydroDyn with linear (Airy) plus second-order [4] wave theory, including:
  o Regular and irregular sea states
  o Second-order (difference and sum frequency) effects to excite floating platform natural frequencies

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[2] The tower centerline could be offset from the platform centerline.

- o Wave directional spreading.
- Sea currents—modeled in HydroDyn with steady International Electrotechnical Commission subsurface, near surface, and depth-independent current models, vector-summed with the wave kinematics velocity [5].
- Hydrodynamic loads via a hybrid combination of slender members (dominated by viscous effects) and/or large-volume bodies (where radiation and diffraction are important):
  - o Slender members—modeled in HydroDyn with strip theory using extensions to the relative form of the Morison equation based on undisturbed wave and current kinematics at the undisplaced platform position, including:
    - ▪ Distributed inertia, added mass, and viscous drag
    - ▪ Distributed axial loads on tapered members
    - ▪ Distributed static buoyancy loads
    - ▪ Concentrated loads at member ends.
  - o Large-volume bodies—modeled in HydroDyn with potential-flow theory involving frequency-to-time-domain transforms based on a frequency-domain wave-body interaction solution solved by a preprocess (e.g., from WAMIT [6] or an equivalent frequency-domain wave-body interaction preprocess), including:
    - ▪ Lumped hydrostatics
    - ▪ Lumped diffraction (wave excitation) at the undisplaced platform position
    - ▪ Lumped radiation (added mass and damping), including free-surface "memory effects"
    - ▪ Second-order effects through Newman's approximation or full difference- and sum-frequency quadratic transfer functions.
- Flooded and ballasted members—modeled in HydroDyn with strip theory
- Marine growth—modeled in HydroDyn with strip theory
- Station-keeping systems—modeled quasi-statically using an analytical model in the MAP++ module, dynamically using a lumped-mass approach in the MoorDyn module, or dynamically using a finite-element approach in the FEAMooring module, including:
  - o Taut or catenary mooring system
  - o Multisegmented interconnections
  - o Buoyancy
  - o Elastic stretching
  - o Seabed friction
  - o Clump weights and buoyancy tanks
  - o Nonlinear geometric restoring.
- Coupling between the flexible tower motion and the aerodynamic loads, coupling between the rigid floating platform motion and the hydrodynamic loads, and coupling between the rigid floating platform motion and the mooring reaction loads—modeled in the OpenFAST glue code as follows:
  - o AeroDyn receives the motions of the flexible tower from ElastoDyn, and ElastoDyn receives the aerodynamic loads from AeroDyn at each coupling time step.

- o HydroDyn receives the motions (including accelerations) of the rigid platform from ElastoDyn, and ElastoDyn receives the hydrodynamic loads from HydroDyn at each coupling time step.
- o The mooring module (MAP++, MoorDyn, or FEAMooring) receives the position of the fairleads from ElastoDyn, and ElastoDyn receives the reaction loads (tensions) at each fairlead from the mooring module at each coupling time step.
- In addition to nonlinear time-domain simulation, full-system linearization analysis capability is available to extract state-space matrices for the state and output equations as a linear function of the states and inputs about an operating point [7].

Although previously applicable only to bottom-fixed wind turbines, SubDyn models the structural dynamics of multimember substructures using the following modeling approach:
- A linear frame finite-element beam model with cantilevered beam interconnections
- The nodes of the SubDyn model are split into boundary nodes and internal nodes. For the internal nodes, a Craig-Bampton (C-B) reduction to capture lower frequency modes dynamically is combined with a static-improvement method (SIM) to capture modes not considered in the C-B reduction quasi-statically, which greatly reduces the number of degrees of freedom and computational time needed to obtain an accurate solution.
- Coupling between the flexible substructure and the wind turbine and coupling between the flexible substructure and hydrodynamic loads are modeled in the OpenFAST glue code as follows:
  - o SubDyn receives the motions (including accelerations) of the boundary nodes at the top of the substructure (transition piece), which is coincident with the tower-base/platform from ElastoDyn, and ElastoDyn receives the substructure reaction loads from SubDyn at each coupling time step. It is also possible to model the entire support structure with SubDyn such that the coupling to ElastoDyn is at the yaw bearing/nacelle (eliminating the tower and rigid platform from ElastoDyn), but geometric nonlinearities are then absent from the support structure dynamics.
  - o HydroDyn receives the motions (including accelerations) of the flexible substructure from SubDyn, and SubDyn receives the hydrodynamic loads from HydroDyn at each coupling time step.
- The boundary nodes at the bottom of the substructure are rigidly fixed to the seabed or connected to the seabed with a stiffness matrix.

3 NEW FUNCTIONAL REQUIREMENTS FOR FOWT SUPPORT STRUCTURES

To enable the design and optimization of floating substructures—including the next-generation floating wind technologies that show promise to be streamlined, flexible, and cost-effective—substructure flexibility and member-level load

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calculations are being implemented in OpenFAST. The new functional requirements that are being addressed are identified as follows. (Functional requirements that are important for only some FOWT concepts were also identified, but they are beyond the scope of the current effort, and they are summarized at the end of this paper.) Table 1 summarizes which functional requirements are important to various FOWT concepts; several FOWT concepts with unique attributes are identified separately, whereas other FOWT concepts that are similar enough to each other and can be considered under the generic categories of "spar buoy," "semisubmersible," and "tension-leg platform" (TLP) are grouped together. As examples, specific functional requirements are identified for the TetraSpar shown in Figure 2 and for the OC4-DeepCwind semisubmersible [8] shown in Figure 3. The identified functional requirements are separated by those associated with structural dynamics and those associated with hydrodynamics; however, coupling between these and coupling between the substructure and the wind turbine is also implied.

3.1 Structural Dynamics
- Flexibility/member-level loads—structural flexibility is important for slender and/or low-stiffness members (such as pontoons, braces, and thin columns, including those of the TetraSpar and OC4-DeepCwind semisubmersible) because load transfer from the wind turbine, hydrodynamics, or mooring system might excite natural frequencies of these members. Structural flexibility is also important for multimember substructures that are statically indeterminate, where member-level loads cannot be determined without considering the flexibility of the structural members. Member-level load calculation is important for properly sizing the structural members.
- Pretensioned cables—several FOWT support structures (such as the SWAY, SCDnezzy, and SpiderFLOAT) maintain strength despite their slender design through pretensioned cables interconnecting various structural members. The TetraSpar uses cables to support a hanging ballast.
- Rigid links—unlike slender members, the structural flexibility of large-volume members is negligible (because

of their high natural frequencies that are not excited by loading), so these members can be considered rigid. Several FOWT concepts interconnect slender and large-volume members (such as the offsets columns of the OC4-DeepCwind semisubmersible), so considering rigid links between members is necessary.
- Pin joints—the TetraSpar substructure minimizes structural loading by interconnecting members using pin joints (where no moment is transferred in one direction) rather than fixed (cantilevered) connections (where three moments are transferred).
- Universal joints—similar to the TetraSpar, the SpiderFLOAT substructure minimizes structural loading by interconnecting members using universal joints (where no moment is transferred in two directions) rather than fixed (cantilevered) connections (where three moments are transferred).

3.2 Hydrodynamics
- Member-level hydrostatics—for slender members with structural flexibility, the distribution of member-level buoyancy loads, including the change in buoyancy loads with displacement, is necessary to properly calculate member-level loads and hydrostatic restoring.
- Multiple large-volume bodies—some FOWT substructures have several large-volume bodies; hydrodynamic radiation and diffraction interaction effects could be important between these bodies, but it is important to apply the hydrodynamic loads separately on each body so that the structural loads on flexible, slender members that interconnect them can be calculated.
- Local pressure on large-volume bodies—although large-volume bodies tend to be structurally rigid, it is necessary to calculate the hydrodynamic pressure distribution on these bodies to enable their structural design (which would likely take place in a three-dimensional shell or solid finite-element analysis using standard commercial software distinct from, and as a postprocess of, the OpenFAST simulation).

TABLE 1. IMPORTANCE OF NEW MODELING FUNCTIONALITY TO VARIOUS FOWT CONCEPTS

New Functionality	Generic Spar	Generic Semi	Generic TLP	TetraSpar	SBM	IDEOL	Advanced Spar	SWAY	X1 Wind	SCDnezzy-1	SCDnezzy-2	ECO-TLP	SpiderFLOAT
	E.g.: *Hywind *Kabashima	E.g.: *WindFloat *VolturnUS *Fukushima *V-Shaped	E.g.: *GICON *Pelastar *Blue H										
Structural Dynamics													
Flexibility/member-level loads	X	X	X	X	X		X	X	X	X	X		X
Pretensioned cables				X				X	X	X	X		X
Rigid links		X	X		X		X		X				
Pin joints				X									
Universal joints													X
Hydrodynamics													
Member-level hydrostatics	X	X	X	X	X		X	X	X	X	X		X
Multiple large-volume bodies		X	X		X		X		X				
Local pressure on large bodies		X	X		X	X	X		X			X	

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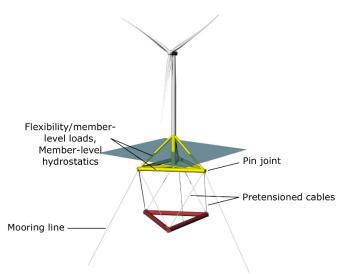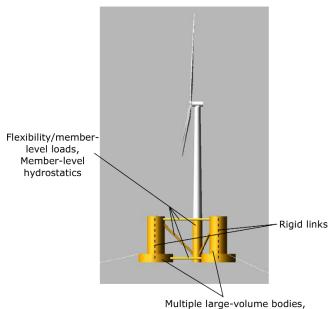**FIGURE 2.** FUNCTIONAL REQUIREMENTS FOR THE TETRASPAR

FIGURE 3. FUNCTIONAL REQUIREMENTS FOR THE OC4-DEEPCWIND SEMISUBMERSIBLE

4 MODELING APPROACHES ADDRESSING THE FUNCTIONAL REQUIREMENTS

Addressing the new functional requirements for FOWT support structures requires modeling upgrades to OpenFAST. The modeling approaches to address these functional requirements that are currently being implemented in the

OpenFAST source code are summarized qualitatively in terms of further development of SubDyn, HydroDyn, and their coupling within the OpenFAST glue code.

4.1 SubDyn

The requirement that the boundary nodes at the bottom of the SubDyn substructure be rigidly connected to the seabed or connected to the seabed with a stiffness matrix is being eliminated, permitting the entire structure to move in six DOF through the existing coupling to the tower base/platform in ElastoDyn. This is being modeled by allowing the boundary nodes at the bottom of the substructure (base reaction nodes) to be disabled and including those nodes in the C-B reduction and SIM.[3]

In addition to the beam finite elements currently implemented, two new element types are being introduced into the linear finite-element formulation:

- Pretensioned spring elements to model pretensioned cables—being modeled with six DOF linear spring elements, representing the three translational DOF at each end of the cable, considering their elastic stretching, (optional) pretension, and mass.
- Rigid elements—being modeled as a massless link that constrains the motion of one joint to be tied to the motion of another joint (acting as a single body), which will eliminate six equations through matrix manipulation.

In addition to the cantilevered beam interconnections currently available, two new joint types for beam interconnection are being added. Each joint is being implemented by adding new degrees of freedom:

- Pin joint—being modeled by adding one equation (for the rotation DOF about the pin) for each beam (minus one) connected to the joint otherwise represented by six equations.
- Universal joint—being modeled by adding two equations (for two rotation DOF about the universal joint) for each beam (minus one) connected to the joint otherwise represented by six equations.

With the introduction of new finite elements and joint types, it is important to ensure that the internal modes do not include rigid-body motion (collapse mechanisms), which will be ensured by testing that the determinant of the stiffness submatrix associated with the internal nodes be nonzero (implying that the stiffness submatrix can be inverted within the C-B reduction).

To enable full-system linearization of the OpenFAST model, including SubDyn, the ability to export the Jacobians of the module-level state and output equations with respect to the states and inputs is being added. (This is straightforward because SubDyn already uses a linear formulation.)

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[3] Note that the C-B reduction in SubDyn is based on the structural mass and stiffness inherent in the SubDyn module. The effects of hydrodynamic added mass and hydrostatic and mooring stiffness are being considered in OpenFAST by coupling the HydroDyn and mooring modules. In practice, it is important that enough C-B modes are retained to ensure that the modal superposition of the retained C-B modes can represent the

true deflection/motion of the substructure, including the hydrodynamic and mooring effects. The method being implemented will not apply to internal modes of the substructure (whereby the boundary nodes are constrained) that are dominated by hydrodynamic added mass and/or hydrostatic and mooring stiffness—e.g., buoyancy cans—which, as a result, cannot be modeled within the SubDyn upgrade.

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4.2 HydroDyn

Buoyancy loads in the strip-theory calculation have previously been distributed properly across the members, but they are calculated only at initialization, independent of the substructure motion. This is being changed so that the buoyancy loads are recalculated every time step based on the instantaneous displacement of the substructure, which means that strip theory will directly capture hydrostatic restoring (without the need for an additional stiffness matrix).[4]

HydroDyn previously allowed for only one large-volume body (or at least the hydrodynamic loads—three forces and three moments—for all large-volume bodies were lumped at a single point). This is being changed to allow for multiple large-volume bodies such that the lumped hydrodynamic loads are applied distinctly to each body. The implementation permits hydrodynamic interaction between each body by including the off-diagonal coupling terms between each set of six DOF/loads using the "N-body" option in WAMIT (or equivalent). It is also possible to neglect this hydrodynamic interaction (by neglecting the off-diagonal coupling terms), i.e., by allowing each body to be modeled separately in WAMIT (or equivalent).

A postprocessor is being developed so that the time-varying pressure distribution on each large-volume body can be computed based on the wave-elevation and body motion time histories together with frequency-to-time domain transforms of the frequency-dependent pressure calculated by WAMIT (or equivalent).10

4.3 OpenFAST Glue Code

Previously, SubDyn had been enabled only for bottom-fixed wind turbines, but this is being changed to allow SubDyn to be enabled for FOWTs.

When SubDyn is enabled for FOWTs, the coupling between the flexible substructure and the wind turbine, the coupling between the flexible substructure and hydrodynamic loads, and the coupling between the flexible substructure and the mooring reaction loads is modeled in the OpenFAST glue code as follows (the first two items are identical to coupling previously available for bottom-fixed offshore wind turbines, but the last item is new):

- SubDyn receives the motions (including accelerations) of the boundary nodes at the top of the substructure (transition piece), which is coincident with the tower base/platform from ElastoDyn, and ElastoDyn receives the substructure reaction loads from SubDyn at each coupling time step. It is also possible to model the entire support structure with SubDyn such that the coupling to ElastoDyn is at the yaw bearing/nacelle (eliminating the tower and rigid platform from ElastoDyn), but geometric nonlinearities are then absent from the support structural dynamics.

- HydroDyn receives the motions (including accelerations) of the flexible substructure from SubDyn, and SubDyn receives the hydrodynamic loads from HydroDyn at each coupling time step.
- The mooring module (MAP++, MoorDyn, or FEAMooring) receives the position of the fairleads from SubDyn, and SubDyn receives the reaction loads (tensions) at each fairlead from the mooring module at each coupling time step.

The existing full-system linearization capability in the OpenFAST glue code for FOWTs is being upgraded to support these couplings, enabling full-system linearization capability for both bottom-fixed and FOWTs, including substructure flexibility and member-level loads.

5 FUNCTIONAL REQUIREMENTS NOT CURRENTLY CONSIDERED

A few functional requirements are important for only some FOWT concepts, but they will require future developments that are beyond the scope of the current effort. These include:

- Buoyancy cans—FOWT concepts such as the SCDnezzy supporting one wind turbine and the SpiderFLOAT use buoyancy cans that are attached to the substructure via a spherical joint (where no moments are transferred at all), resulting in large nonlinear motion of the buoyancy cans.[5]
- Station-keeping systems with turret connections to the substructure—FOWT concepts such as X1 Wind and SCDnezzy use a turret joint (which does not transfer moment in one DOF) between the station-keeping system and substructure to enable passive yaw motion of the FOWT, but the addition of this turret DOF is beyond the scope of this effort. That said, the SWAY concept—which has a single-point mooring connection to the platform—could be modeled with the present method because the existing coupling approach between the mooring module and the substructure does not transfer any moments through a single-point mooring connection to the platform.
- Hydro-elastics of large-volume bodies—the present modeling approach considers structural flexibility using beam elements, but a beam approach might not be suitable to model the structural flexibility of FOWT concepts with large-volume bodies such as the IDEOL barge (if deemed important).
- Structural nonlinearities in the substructure—the present modeling approach assumes that the structural dynamics within the substructure can be treated linearly, which precludes modeling beam buckling or pretensioned cables that go slack. For the TetraSpar, the present modeling approach could predict the onset of a slack event for the cables supporting the hanging ballast (by checking whether

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[4] Note that the hydrostatic restoring term associated with water-plane inertia is being neglected—meaning that the strip-theory members piercing the free surface are assumed to have a high aspect ratio, such that the center of buoyancy term in the hydrostatic restoring dominates the water-plane inertia term.

[5] The structural dynamics of such buoyancy cans cannot be modeled with the substructure dynamics modeling approach currently being implemented, but they could be modeled in future work by an extension to MoorDyn together with coupling to HydroDyn.

the cable tension drops to zero) but not the transient dynamics of the slack event itself (if deemed important).

- Transient dynamics of the installation procedure—FOWT concepts such as the TetraSpar and SBM invoke an installation process that involves a configuration change of the substructure, including adding and/or lowering ballast dynamically. Although the present modeling approach enables analysis of the fully installed configuration of these FOWT concepts, modeling the transient dynamics of the installation procedure (if deemed important) is beyond the scope of this effort.

- Transient dynamics of active ballast system—FOWT concepts such as the WindFloat use an active-ballast system to move water ballast around the substructure to minimize wind turbine inclination. Although the present modeling approach enables analysis of the fixed ballast of the WindFloat, the transient dynamics of the active ballast system itself (if deemed important) are beyond the scope of this effort.

- Aerodynamic loads and tower influence on support structures that are not a tubular monotower—FOWT concepts such as SWAY and X1 Wind have downwind rotors together with a fairing-shaped tower (SWAY) or lattice support structure (X1 Wind) whose aerodynamics cannot currently be modeled by AeroDyn and whose extension are beyond the scope of this effort.

- Slanted towers—FOWT concepts such as SWAY and SCDnezzy incorporate slanted towers, which cannot be modeled in ElastoDyn; however, if geometric nonlinearities are negligible, these towers could be modeled in SubDyn such that the coupling to ElastoDyn is at the yaw bearing/nacelle (eliminating the tower and rigid platform from ElastoDyn).

- Multirotor concepts—FOWT concepts such as the SCDnezzy support multiple rotors, the modeling of which is beyond the scope of this effort.10

6 CONCLUSIONS

This paper presented the development of new capabilities in OpenFAST to model floating substructure flexibility and member-level loads to enable the design and optimization of the next-generation floating wind technologies that show promise to be streamlined, flexible, and cost-effective. Details have been presented on the rationale behind selecting the functional requirements and the modeling approaches needed to understand and apply them correctly.

The upgrades to OpenFAST involve further development of the SubDyn structural-dynamics module for substructures, the HydroDyn hydrodynamics module, and their coupling to the other OpenFAST modules within the glue (driver) code. SubDyn—which models the structural dynamics of substructures using a beam finite-element approach together with a C-B reduction and SIM—was previously available in OpenFAST for fixed-bottom substructures, but it has now been adopted for use in modeling the structural flexibility and member-level loads of floating substructures. In addition to the beam elements and cantilevered interconnections previously available, new element types and interconnections important to floating substructures have been added, including pretensioned cable and rigid-link elements and pin and universal joint interconnections. HydroDyn—which models the first- plus second-order hydrodynamics of substructures using a hybrid combination of strip theory for slender members and potential-flow theory for large-volume members—was extended to include member-level hydrostatics in the strip-theory solution and multiple potential-flow bodies (including optional interaction between these bodies). The glue code—which connects the modules to enable coupled aero-hydro-servo-elastic interactions—was extended to ensure that the new functionality within SubDyn and HydroDyn is properly coupled together with the other OpenFAST modules. The new functionality applies to both nonlinear time-domain solutions and full-system linearization. The mathematical details are left for a subsequent paper.

Unfortunately, the implementation at the time of this writing has not yet been completed enough to produce results. Results will be presented in future work to highlight the functionality and verify the implementation.10

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