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State of the Art in Floating Wind Turbine Design Tools

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State of the Art in Floating Wind Turbine Design Tools

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ABSTRACT

This paper presents an overview of the simulation codes available to the offshore wind industry that are capable of performing integrated dynamic calculations for floating offshore wind turbines. It provides a description of the modelling techniques employed by each of the different codes, and analyzes the strengths and weaknesses of these methods. A review of the testing and validation activities performed for a number of the design tools is also included. Conclusions are presented about the development needs and future verification activities required for these codes.

KEY WORDS: Offshore; floating wind turbine; integrated design tools; state of the art; numerical simulation; testing; validation

INTRODUCTION

The offshore wind industry has experienced significant growth in recent years, and continues to expand worldwide. Nearly all of the offshore wind turbines installed to date are located in North European Seas and are mounted on fixed-bottom support structures in water depths of 35 m or less. There are a limited number of suitable shallow water sites available in offshore locations for countries currently active in offshore wind. Much of the global offshore wind resource is in locations where the water is much deeper than it is at the sites of current installations. The offshore resources also exist where fixed-bottom support structures are not feasible, for instance off the coasts of the United States, China, Japan, Spain, Portugal, and Norway. The possibility of mounting wind turbines on floating support structures opens up the potential to use such deepwater resources. The economic potential of floating offshore wind turbines (FOWTs) is demonstrated in Musial et al. (2004). Realization of this potential, however, requires cost-effective floating wind turbine designs that can compete with other energy sources.

The design and manufacturing of optimized and cost-effective floating wind turbines requires reliable and sophisticated design tools that can model the dynamics and response of floating wind turbine platforms in a comprehensive and fully integrated manner. Currently, several sophisticated simulation codes are capable of modelling floating offshore wind turbines. This paper presents an overview of the current status of these codes, together with a description of the various modelling techniques employed by the different codes, and an analysis of the strengths and weaknesses of these methods. The testing and validation of these design tools is also reviewed, and conclusions are drawn about the development needs and future verification activities required to ensure that the tools continue to improve the accuracy of their loading and response predictions, thus providing the confidence required for detailed floating platform design.

PREVIOUS RESEARCH

Frequency-domain methods commonly are used in the offshore oil and gas industries to analyze and design floating structures. These methods also have been employed in a number of instances for the preliminary design of floating wind turbines. Bulder et al. (2002) used linear frequency-domain hydrodynamic techniques to find response amplitude operators (RAOs) to investigate a tri-floater concept. Lee (2005) used a similar process to analyze a tension-leg platform (TLP) design. Vijfhuizen (2006) used frequency-domain analysis to design a barge for a 5-MW turbine, including a wave energy device. Wayman (2006) performed calculations in the frequency domain to model various TLP and barge designs. Sclavounos et al. (2007) performed a parametric design study of floating wind turbine concepts and mooring systems using a coupled linear dynamic analysis in the frequency domain.

There are numerous advantages to design calculations in the frequency domain. For example, the studies discussed above were useful in demonstrating the initial technical feasibility of floating wind turbines. They showed that turbines could be designed so that the natural frequencies are placed away from the wave-energy spectrum to minimize dynamic response. Frequency-domain calculations, however, also have important limitations. They cannot capture nonlinear dynamic characteristics and cannot model transient loading events—both of which are important for wind turbines because the nonlinear dynamics introduced through transient events and control system actions are significant for loads analysis. Matha (2009) performed a standard frequency-domain analysis for a floating wind turbine and showed that some couplings between the platform motion and the flexible tower and blades were not taken into account. This factor could lead to natural frequencies being wrongly predicted and critical system resonances not being identified. This result underscores the importance of performing calculations for floating wind turbines in the time domain. For the purposes of this paper, therefore, frequency-domain design tools are not considered and all the codes presented are based on a time-domain analysis.

SUMMARY OF EXISTING DESIGN TOOLS

A number of design tools available to the offshore wind industry have the capability to model floating offshore wind turbines in a coupled time-domain dynamic analysis. This section presents the methods employed by those design tools known by the authors, and includes four categories: structural dynamics, aerodynamics, hydrodynamics and mooring lines. The summaries presented here apply to the design tool capabilities available at the time of writing; future development is planned for most codes to expand their capabilities.

The computational speeds of the various codes will depend on numerous factors. These include the discretization chosen by the user, the code features enabled, and the precise details of the coupling scheme (in the case of coupled codes). Without a full knowledge of these variables a direct comparison of the computational speeds of the presented codes is not possible. However it can be said in general that the computational speeds will be slower for codes with more complex coupling schemes.

FAST with AeroDyn and HydroDyn by NREL The FAST code is a publicly available simulation tool for horizontal-axis wind turbines that was developed by the National Renewable Energy Laboratory (NREL), largely by Jonkman (2007). The FAST code was developed for the dynamic analysis of conventional fixed-bottom wind turbines, but has been extended with additional modules and to enable coupled dynamic analysis of floating wind turbines.

Structural dynamics. The FAST code uses a combined modal and multibody system dynamics (MBS) representation. The wind turbine blades and tower are modelled using linear modal representation assuming small deflections, with two flapwise bending modes and one edgewise bending mode per blade and two fore-aft and two side-to-side bending modes for the tower. The finite element method (FEM) pre-processor BModes (Bir, 2005) is used to calculate the mode shapes of the blades and tower. The floating platform upon which the tower is cantilevered has full six degree-of-freedom (DOF) rigid-body motion. The drivetrain is modelled using an equivalent linear spring and damper.

Aerodynamics. The aerodynamic subroutine package AeroDyn is used to calculate aerodynamic forces in FAST. This model uses quasi-steady blade-element/momentum (BEM) theory or a generalized dynamic inflow model. Both of these models include the effects of axial and tangential induction. The BEM aerodynamic calculations include tip and hub losses according to Prandtl and skewed-wake corrections. Dynamic stall is considered using the Beddoes-Leishman model. Further details can be found in Laino and Hansen (2002).

Hydrodynamics. The hydrodynamic subroutine package HydroDyn is used to calculate applied hydrodynamic forces in FAST. Wave kinematics is calculated using Airy wave theory with free-surface corrections. The hydrodynamic loading includes contributions from linear hydrostatic restoring, nonlinear viscous drag contributions from Morison's equation, added mass and damping contributions from linear wave radiation (including free-surface memory effects), and incident wave excitation from linear diffraction. Full details are given in Jonkman (2009). The linearized radiation and diffraction problems are solved in the frequency domain for a platform of arbitrary shape using WAMIT (Wave Analysis at Massachusetts Institute of Technology), a three-dimensional (3D) panel-based program for computing wave loads and motions of offshore structures (Lee, 1995). The resulting hydrodynamic coefficients are used in HydroDyn.

Mooring lines. The FAST code uses a quasi-static mooring system module to represent the nonlinear mooring-line restoring forces. This module accounts for the apparent weight of the mooring line in fluid, the elastic stretching of the mooring line,and the seabed friction of each line. For a given platform displacement, the module solves for the tensions within each mooring line by assuming that each cable is in static equilibrium at that instant, and uses the resulting tensions to solve the dynamic equations of motion for the remainder of the system. Full details of the quasi-static mooring line module are given in Jonkman (2009).

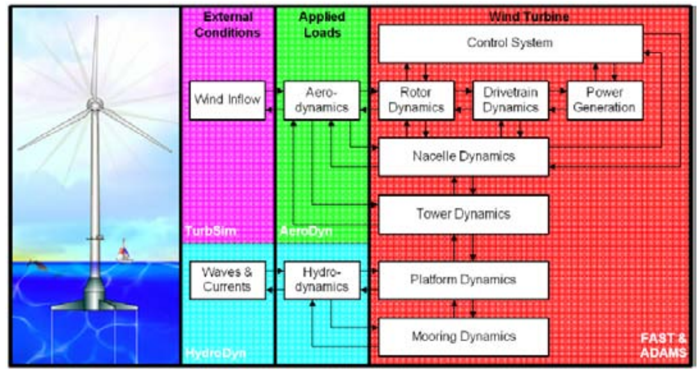

Figure 1: Interface between modules in the FAST code for FOWTs (Jonkman, 2007)

The FAST with AeroDyn and HydroDyn code has been used in a number of research contexts to model coupled wind turbine and floating platform dynamics. The configuration described above is that used by Jonkman (2009). The various modules of the FAST code, however, have also been coupled with a number of other dynamic analysis programs to model the dynamics and response of floating wind turbines. Two examples of this are presented below.

FAST with Charm3D Coupling The FAST with AeroDyn code is coupled with the floater-mooring dynamic analysis program Charm3D by Shim (2008). Charm3D is an FEM program for the dynamic analysis of moored floating offshore structures. It was developed jointly by Texas A&M University and Offshore Dynamics Inc., with partial funding from the Charm3D joint industry project. The coupling of this program to FAST with AeroDyn enables the mooring line and rigid-body dynamics of a floating wind turbine system to be integrated with the wind turbine dynamics in a coupled time-domain simulation.

In Charm3D, the first- and second-order hydrodynamic coefficients of the floating platform are calculated in the frequency domain using a panel-based 3D diffraction and radiation program (in this case WAMIT). In the time-domain analysis, various nonlinearities are taken into account, including the drag force on the mooring lines, the large (translational) motion of the platform, the free-surface effects, and the geometric nonlinearity of the mooring system. The mooring-line dynamics are solved simultaneously at each time step by a coordinate-based FEM program. The coupling between FAST and Charm3D is available in two forms. In the first method, the floating-body motions computed by Charm3D are provided as inputs to FAST with AeroDyn, and the resulting dynamic loads from the wind turbine computed by FAST with AeroDyn are returned to Charm3D as external forces. In the second method, the motions of the tower base computed through the wind turbine dynamics by FAST with AeroDyn are provided as input to Charm3D, which solves for the hydrodynamic and mooring-system loads that are returned as external loads to FAST with AeroDyn.

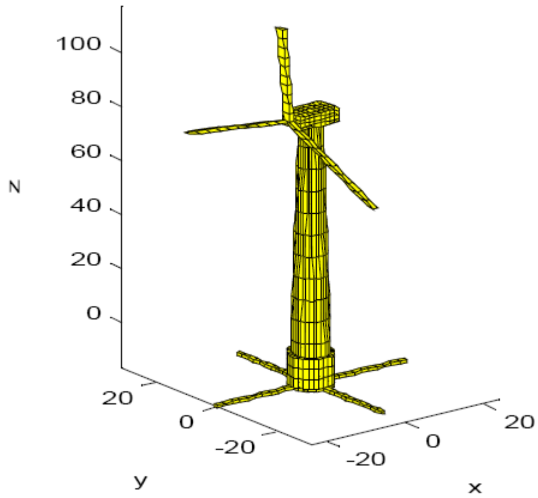

Figure 2: Model of TLP in Charm3D coupled code [13]

FAST with TimeFloat Coupling The TimeFloat software also has been coupled to FAST with AeroDyn to model the dynamic response of the WindFloat floating foundation concept for large offshore wind turbines (Roddier et al., 2009). TimeFloat is a time-domain software tool developed by Marine Innovation & Technology for the analysis of floating structures. The coupling of TimeFloat to FAST with AeroDyn enables the aerodynamic, hydrodynamic and mooring-system forces acting on the structure to be computed simultaneously, including the nonlinear quasi-static mooring forces and the nonlinear viscous forces generated by the water-entrapment plates. As described above, the wave-interaction effects are processed in the frequency-domain software WAMIT and the resulting added-mass, damping, and mean-drift coefficients and wave-exciting forces are passed to the TimeFloat code. The hydrodynamic forces then are calculated by TimeFloat and include memory effects, wave-excitation forces (using force components computed by WAMIT), viscous forces resulting from drag effects, drift forces, and mooring-line forces. The hydrodynamic forces are provided as an input to FAST with AeroDyn, which then solves the turbine and tower equations of motion and passes the platform motion back to TimeFloat.

Figure 3: WindFloat semi-submersible modelled in TimeFloat [14]

ADAMS by MSC ADAMS (Automatic Dynamic Analysis of Mechanical Systems) is a commercially available general-purpose MBS code developed by MSC Software Corporation. The code is not wind turbine-specific and also is used by the automotive, aerospace, and robotics industries. ADAMS models of wind turbines can be generated using the FAST tool's FAST-to-ADAMS pre-processor functionality.

Structural dynamics. The ADAMS code uses an MBS representation to allow for numerous structural configurations and DOF. The wind turbine blades and tower are modelled as flexible members consisting of a series of rigid bodies with lumped mass and inertia connected by flexible joints with linear stiffness and damping. The drivetrain can either be modelled similarly, either as a series of lumped masses or through a simple hinge/spring/damper element. The ADAMS code also can be used to model additional features, including torsional DOF in the blades and tower, flap/twist coupling in the blades, mass offsets in the blades and tower, and pitch actuator dynamics.

Aerodynamics. The AeroDyn aerodynamic subroutine package is used to calculate aerodynamic forces in ADAMS, as described above in the section relating to the FAST code.

Hydrodynamics. The hydrodynamic forces can be calculated in ADAMS by interfacing with the hydrodynamic subroutine package HydroDyn, as described above in the section relating to the FAST code. Alternatively, an equivalent subroutine can be used for calculating loads on the floating platform—see, for instance, Withee (2004).

Mooring lines. The ADAMS code also can be extended in a similar manner as the FAST code to enable the modelling of mooring lines. This can be done by solving the mooring line tensions quasi-statically in a separate module and interfacing with the main code at each time step. Alternatively, a look-up table specifying the relationship between restoring force and platform displacement may be defined at the mooring-line interface point.

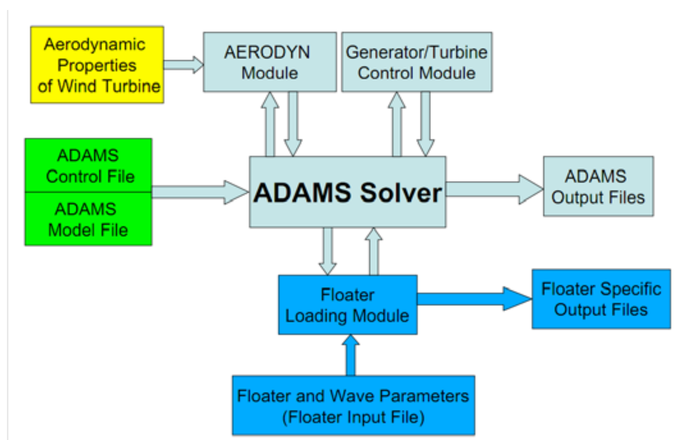

Figure 4: FOWT simulation routine in MSC ADAMS by Withee (2004)

Bladed by GL Garrad Hassan GH Bladed is an integrated software tool for calculating wind turbine performance and dynamic response (GL Garrad Hassan, 2010). It originally was developed by GL Garrad Hassan for the modelling of onshore fixed-bottom wind turbines. It has been extended, however, to include hydrodynamic loading for the modelling of offshore wind turbines. In the last year, the core structural dynamics of the code has been re-written to incorporate MBS.

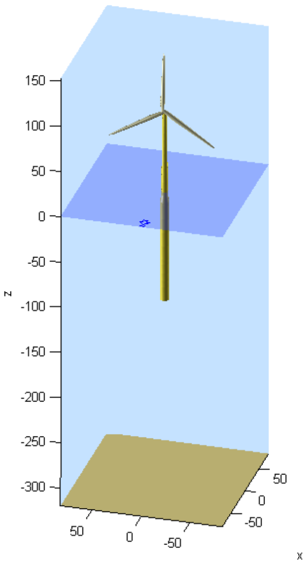

Figure 5: Spar-buoy platform modelled in GH Bladed

Structural dynamics. The Bladed code uses a combined modal and MBS representation to model the structural dynamics of a wind turbine. The wind turbine structure can be composed of any number of separate bodies. Flexible components such as the blades and tower are modelled using a modal representation. Individual modal properties for each component are computed independently using an FEM representation of the body as a Timoshenko beam. The mode shapes and frequencies are dependent on the mass and stiffness distribution and the position of the neutral axis of the body, as well as other parameters specific to the body in question. The modes are coupled using the appropriate equations of motion in the dynamic-response analysis. To model the tower, a multi-member model consisting of an arbitrary space-frame structure of interconnecting beam elements with user-specified mass and stiffness properties can be used. Craig-Bampton (C-B) style modes are used for the support structure. The resulting mode shapes are three-dimensional with six DOF at each node. The use of MBS dynamics enables more accurate modelling of floating structures. The turbine and support structure are not constrained by a direct connection to the ground. Instead, the structure is connected to a reference frame by a free joint and constrained by mooring-line forces. This enables all six support-structure DOF to be modelled with large rotations and displacements.

Aerodynamics. The aerodynamic forces on the rotor are calculated in Bladed using BEM theory with corrections, including tip and hub loss models based on Prandtl. A dynamic-wake model is included to account for the effect of blade loading on wake vorticity. The model included in Bladed is based on Pitt and Peters, and has received substantial validation from data on helicopters. Dynamic stall also is accounted for using the Beddoes-Leishman model.

Hydrodynamics. The applied hydrodynamic forces on the wind turbine support structure are calculated in Bladed using Morison's equation. For linear sea states, the wave-particle kinematics is calculated using Airy wave theory with free-surface corrections using Wheeler stretching. If linear waves are used, then an irregular sea state can be defined using either a JONSWAP spectrum or a user-defined wave-energy spectrum. For linear irregular sea states, the effects of wave diffraction can be accounted for by using a time-domain MacCamy-Fuchs approximation. In this approach, the wave-energy spectrum is altered to give the same resulting hydrodynamic load on the structure as the standard MacCamy-Fuchs method, in which the Cd and Cm coefficients are modified in the frequency domain. For nonlinear waves, the wave-particle kinematics is calculated using stream-function theory. The order of the solution is chosen based on the input values of wave height, wave period, and water depth.

Mooring lines. Mooring-line forces are applied in the Bladed code using the foundation module, which includes the capability to model non-linear relationships between the displacement of the platform and the restoring force from the mooring line. These relationships are calculated separately by the user, and implemented via a stiffness matrix at the fairlead position.

SIMO/RIFLEX by MARINTEK SIMO (Simulation of Marine Operations) is a general-purpose time-domain program developed by MARINTEK for the modelling and simulation of offshore structures. The code has been extended by Fylling et al. (2009) to enable modelling of floating wind turbines. This is done by the addition of an external module for the simulation of rotor aerodynamic forces. SIMO also has been coupled with the nonlinear FEM code RIFLEX by Nielsen et al. (2006). RIFLEX is a tailor-made code for the static and dynamic analysis of slender marine bodies such as risers and mooring lines, also developed by MARINTEK.

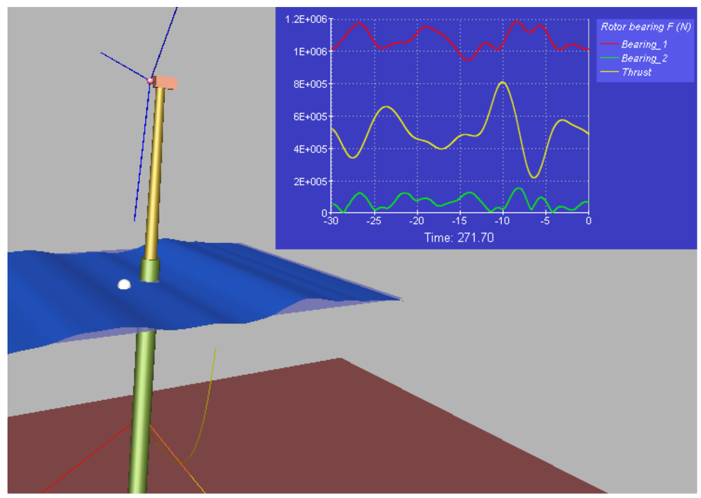

Figure 6: Rigid-body model of FOWT using 4-body configuration in SIMO (Fylling et al., 2009)

Structural dynamics. The SIMO code uses interconnected MBS to model structural dynamics. To model a floating offshore wind turbine, multiple bodies can be defined and coupled together. In Fylling et al. (2009), the turbine and support structure are defined using a few rigid bodies (two-body and four-body configurations are investigated). In this case, the rotor loads are transferred to the support structure using three flexible coupling elements consisting of two radial bearings and one axial bearing. In Nielsen et al. (2006), the coupling with RIFLEX enables a FEM formulation of the structure, allowing for unlimited displacements and rotations in 3D space. The rotor still is modelled as a rigid body but the tower is made up of flexible beam elements, each with 12 DOF, which means that the elastic behaviour of the tower can be investigated.

Aerodynamics. The aerodynamic forces are calculated in a separate module and implemented in SIMO as a user-specified external force. BEM theory is used to calculate the forces on the rotor blades, with dynamic-inflow effects included. Individual blade-element forces then are summed and applied in SIMO as a six-component external load on a rotating body. The drag force on the tower and nacelle also is accounted for in the aerodynamic loading.

Hydrodynamics. The hydrodynamic forces are modelled using the standard SIMO code. Linear Airy wave theory is assumed for calculating wave kinematics. The calculation of hydrodynamic loads takes into account linear and quadratic potential forces including frequency-dependent excitation, added mass and damping contributions (calculated in the frequency domain using WAMIT), and slow drift. Viscous drag forces from Morison's equation, mooring-line forces, and body-to-body hydrodynamic coupling force models are also included.

Mooring lines. The mooring lines are modelled using the RIFLEX code. This enables the representation of mooring lines as finite elements, incorporating nonlinear material properties and dynamic properties. A separate mooring-system module is not required, as it is an integrated part of the RIFLEX code.

SIMO/RIFLEX with HAWC2 Coupling The SIMO/RIFLEX code also has been coupled with the HAWC2 code in Skaare et al. (2007) and Larsen and Hanson (2007). HAWC2 is an aeroelastic simulation tool developed by Risø National Laboratory for the dynamic analysis of fixed-bottom wind turbines (Larsen and Hansen, 2007). The coupling of these two codes enables detailed modelling of both the aerodynamic and hydrodynamic forces acting on a floating offshore wind turbine. The HAWC2 code also has been used to directly model a floating wind turbine in Karimirad et al. (2009), with the mooring-line analysis performed separately in SIMO/RIFLEX.

Structural dynamics. The HAWC2 code uses a combined linear FEM and nonlinear MBS representation to calculate the structural dynamics of a wind turbine. A number of separate bodies can be defined, consisting of an assembly of linear Timoshenko beam finite elements. The bodies are connected by algebraic constraint equations, which can take the form of flexible joints, bearings, or rigid connections. Internal forces are calculated from these algebraic constraints. To couple the two codes together, the position, velocity and acceleration vectors and rotation matrix at the interface point are passed to HAWC2 by SIMO/RIFLEX. The reaction force at the interface point is returned to SIMO/RIFLEX by HAWC2 at each time step.

Aerodynamics. The aerodynamic forces on the rotor are calculated in HAWC2 using BEM theory. The classic approach has been modified to include the effects of dynamic inflow, dynamic stall, skewed inflow, shear effects on induction, and effects from large deflections. The aerodynamic calculation points are positioned independently of the structural nodes to provide an optimal distribution of these points.

Hydrodynamics and mooring lines. In Skaare et al. (2007) and Larsen and Hanson (2007) the modelling of hydrodynamics and mooring lines is performed in SIMO/RIFLEX, as described above. In Karimirad et al. (2009) the hydrodynamic forces are calculated using Morison's equation based on the instantaneous position of the platform. The mooring lines are modelled in SIMO/RIFLEX using an FEM model and the resulting force-displacement relationship applied as an external force at the fairlead position.

3Dfloat by UMB The 3Dfloat code was developed by the Norwegian University of Life Sciences (UMB) for the modelling of floating offshore wind turbines with full coupling between structural dynamics, aerodynamics, hydrodynamics and control-system actions. The code has been used to analyze floating offshore wind turbine models and to compare conceptual designs by Nygaard et al. (2009).

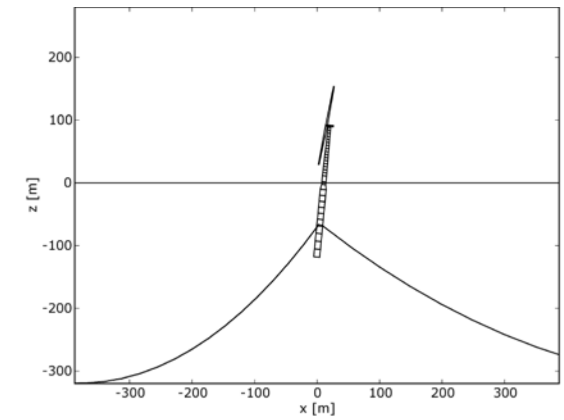

Figure 7: OC3-Hywind spar-buoy modelled in 3Dfloat (Nygaard et al., 2009)

Structural dynamics. The 3Dfloat code uses FEM for modelling the structural dynamics of a floating wind turbine. Euler-Bernoulli beams with 12 DOF are used, and geometric nonlinearities in the elements are taken into account by casting the model in a co-rotational framework. The rotor and drivetrain are modelled as rigid, with no interaction between the rotor and the tower. Flexibility is included in the tower. The global motion of the structure is taken into account by using structural modes.

Aerodynamics. Rotor aerodynamics is calculated in 3Dfloat using BEM theory. Extensions for dynamic inflow and large yaw errors also are included.

Hydrodynamics. The hydrodynamic forces are calculated in 3Dfloat using Morison's equation with wave particle kinematics derived using linear Airy wave theory. The hydrodynamic loads include terms for added mass of water from the acceleration of the structure, linear hydrostatic restoring, and nonlinear viscous drag.

Mooring lines. The mooring lines are modelled in 3Dfloat using beam finite elements with extensional stiffness included and bending stiffness neglected. The mooring lines also can be replaced by linear stiffness at the fairlead positions for the purposes of eigenfrequency analysis.

SIMPACK by SIMPACK AG SIMPACK is a commercially available general-purpose MBS code developed by SIMPACK AG. The code is used by the automotive, railway, aerospace, and robotics industries. A version of SIMPACK—SIMPACK Wind—offers extensions to the original code that allow integrated wind turbine simulation. The SIMPACK code has been used to model a floating wind turbine in Matha et al. (2011).

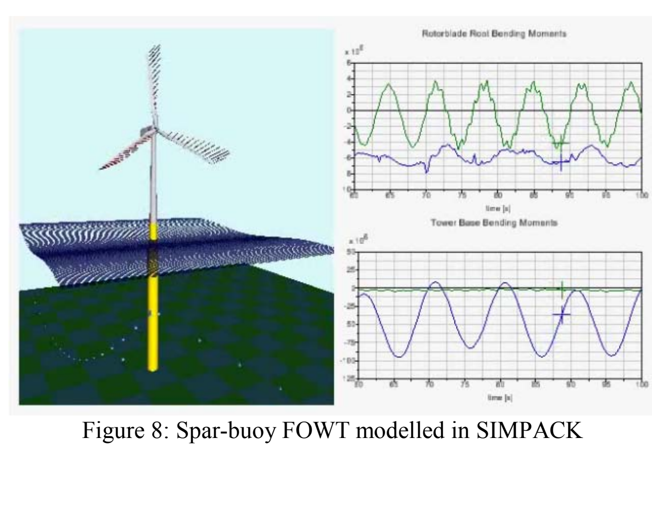

Figure 8: Spar-buoy FOWT modelled in SIMPACK

Structural dynamics. The SIMPACK code uses an MBS representation to allow a large number of structural configurations and DOF. In SIMPACK, the parts or bodies of the wind turbine structure are connected using complex joints with different types of force elements acting from the inertial system on the bodies (e.g., aerodynamics on the rotor, hydrodynamics on the support structure) and between bodies (e.g., spring-damper elements). The parts of the wind turbine where the relative deflection of the bodies is small in comparison to the rigid-body motion are considered rigid. The SIMPACK code is able to include flexible FEM bodies of arbitrary geometry with the C-B method into the MBS model to account for larger deflections. This option is used for modelling of the wind turbine blades and tower. An FEM blade model, consisting of Euler-Bernoulli or Timoshenko beam elements, is reduced by the C-B method and is capable of considering bending in flap- and edgewise direction, torsional and tensional rigidity, and the relevant coupling effects. The relevant geometric stiffening effects are included for the reduction, representing a nonlinear model for medium displacements. The blade model also can be split into separate C-B reduced flexible bodies that are connected with zero DOF, representing a nonlinear blade model for large displacements. The validation for the nonlinear behaviour is based on a comparison with the FEM code Abaqus, and is described in more detail in Matha et al. (2010) The flexible tower is modelled with the same approach. Single- and multi-torsional drivetrain models can be implemented to account for flexibility of the bedplate and other components. Drivetrain models for specific analysis, mainly for frequency domain analysis, also can include models for tooth contacts.

Aerodynamics. The AeroDyn aerodynamic subroutine package is used to calculate aerodynamic forces in SIMPACK, as described above in the section relating to the FAST code.

Hydrodynamics. The hydrodynamic forces in SIMPACK are calculated by interfacing with the hydrodynamic subroutine package HydroDyn, as described above in the section relating to the FAST code.

Mooring lines. SIMPACK can model mooring lines two ways. One method is to solve the mooring-line tensions quasi-statically in a separate module and interface with the main code at each time step. The other way is to use an integrated nonlinear MBS mooring-line model, in which each line is discretized into separate rigid or flexible bodies connected by spring-damper elements.

TESTING AND VALIDATION OF DESIGN TOOLS

The development of design tools capable of modelling floating platforms is an important step forward for the offshore wind turbine industry, but the results obtained from these codes must be shown to be accurate and reliable. Comprehensive testing and validation therefore is crucial for giving sufficient confidence to developers and investors. The best way to achieve such confidence is to take measurements from a real machine and compare the measured data with the results from numerical simulations. The floating wind turbine industry is relatively new, therefore very little measurement data is available to use to validate the codes. Therefore, a second method also is employed—that of comparing the results of different codes with each other.

Code-to-Measurement Comparisons A number of studies have been performed by Statoil for the development of the Hywind floating wind turbine concept, see Nielsen et al. (2006). The Hywind floating platform concept consists of a deep-water slender spar-buoy with three catenary mooring lines. The integrated SIMO/RIFLEX/HAWC2 design tool was used in Skaare et al. (2007) to model the structure. As part of the development of this concept, model-scale experiments were carried out at the Ocean Basin Laboratory at MARINTEK in Trondheim to validate the coupled wind and wave modelling of the Hywind concept. A model of the floating wind turbine was built at 1:47 scale, with Froude scaling applied. DC motors were used to control the rotational speed of the rotor and the blade pitch angle. A variety of sea states and wind velocities were tested, including the 100 year wave condition and wind speeds above and below rated wind speed. The JONSWAP wave spectrum was applied with turbulent wind for both the simulations and the model experiments. The measured hub wind speed from the model scale experiments was used as the basis for the turbulent wind field used in the simulations, with corrections for Reynolds number effects. The results of these tests showed very good agreement between the responses of the scale model and the predictions from the simulation code. The results also showed a significant increase in the damping of the tower motion when active blade-pitch damping was introduced.

Another floating wind turbine code which has been validated with the use of measurements is TimeFloat, a time-domain design tool for coupled analysis of floating structures (described above). The hydrodynamic calculations within this code were validated using wave-tank tests performed at the University of California-Berkeley ship-model testing facility (Roddier et al., 2009). A 1:105 scale model of the floating platform was fabricated. It included a foam disk at the tower top to represent wind forces and an electrical motor to model the gyroscopic effect of the rotor. A three-hour realization of the 100-year sea state was generated with and without steady wind, and the resulting platform motion measured using a digital video camera. The floating platform also was modelled in the TimeFloat software using a simplified model for aerodynamic forces acting on the rotor. The results from these numerical simulations then were compared with the measurements from the tank tests. The comparison of model test results and numerical simulations showed good agreement, with the TimeFloat software generally underpredicting platform motion slightly. This is most likely due to imperfections in the model and experiment data.

Other measurement campaigns are being planned. The University of Maine DeepCwind Consortium in the U.S. has been awarded a $7.1-million grant to develop floating offshore wind capacity. One of the stated aims of this project is to validate the coupled aero-hydro-elastic models developed by NREL. The research program will include tank testing, deployment of prototypes, and field validation.

The EOLIA project, led by Acciona, also has included some code-to-measurement tests. The objective of the project is to develop solutions for the design and implementation of deepwater offshore wind farms. As part of the project, the capabilities of FAST with AeroDyn and HydroDyn have been extended and applied to the analysis of three floating concepts (spar buoy, TLP, and semi-submersible), alongside comparisons with the SIMO/RIFLEX code. To verify the models, tank tests also have been performed at 1:40 scale for each of the concepts. No public results from this project are currently known to the authors.

The HiPRwind project is an EU research project awarded in the 2010 Seventh Framework Programme. The project aims to develop and test new solutions for offshore wind farms at a large scale. One of the main aims of the HiPRwind project is to install a 1:10-scale model of a future commercial 10-MW floating wind turbine installation. The model will be deployed in real sea conditions, and will be used to monitor and assess the important operational parameters. The resulting measurement data will be an important contribution toward overcoming the gap between small-scale tank testing and full-scale offshore deployment.

Other current and future FOWT research projects include the EU DeepWind project, the Spanish Azimut project, the ZEFIR Test Station project off the coast of Spain, and the FOWT prototypes being jointly developed and tested by Sasebo Heavy Industries and Kyoto University, Currently there is no detailed information about code-to-measurement campaigns planned for these projects.

Code-to-Code Comparisons In addition to validating codes using measurements, an important way to verify the predictive accuracy of numerical simulation tools is through code-to-code comparisons. Most of the codes used for the analysis of floating wind turbines have been validated in this manner. One example is the FAST code, the aero-elastic features of which have been verified through comparisons with ADAMS, described in Buhl (2001). Another example is the SIMO/RIFLEX code used to model the Hywind floating wind turbine concept, which was validated in part through comparisons with HywindSim, a relatively simple MATLAB/Simulink code developed for the purposes of such comparison in Nielsen et al. (2006). Numerous code-to-code comparison methods were used to verify the hydrodynamic calculation module HydroDyn used in the FAST code. These methods included comparisons between the WAMIT frequency-to-time conversion and HydroDyn calculations; comparisons between the mooring-line force-displacement relationship calculated by the quasi-static method and that calculated by another code; and comparisons between time-domain results and frequency-domain results. The methods are described in full in Jonkman (2009). The GH Bladed code has recently undergone development from a pure modal representation of structural dynamics to a MBS representation, as described above. The new code structure is released in Bladed v4.0. Several levels of testing and validation were carried out for the new code structure, including code-to-code comparisons and code-to-measurement campaigns. Full details are given in Witcher et al. (2010).

The most extensive code-to-code comparison work in the offshore wind industry has been performed as part of the Offshore Code Comparison Collaboration (OC3) project within the International Energy Agency (IEA) Wind Task 23 (Jonkman et al., December 2010). In this project, a number of participants used different aero-elastic codes to model the coupled dynamic response of the same wind turbine and support structure, with the same environmental conditions. The results were compared to verify the accuracy and correctness of the modelling capabilities of the participant codes, and to improve the predictions.

Offshore Code Comparison Collaboration Phase IV In Phase IV of the OC3 project a floating offshore wind turbine was modelled (Jonkman et al., April 2010). The turbine model used was the publicly available 5-MW baseline wind turbine developed by NREL, and the floating platform was a modification of the Hywind spar-buoy developed by Statoil of Norway. The turbulent wind fields and irregular wave kinematics were generated independently and were provided to all participants to ensure tight control of all the inputs. A stepwise verification procedure then was used, and the complexity of both the model and the test cases was increased with each step.

Figure 9: Illustration of NREL 5-MW wind turbine on OC3-Hywind spar (Jonkman et al., April 2010)

A number of floating design tools were involved in Phase IV of the project, including FAST, ADAMS, Bladed, HAWC2, 3Dfloat, SIMO, SESAM and DeepC. The SESAM and DeepC tools were not included in the discussion above because currently they cannot model the coupled dynamics of the turbine with floating platform. A variety of different load cases were performed. These included a full-system eigenanalysis; a static equilibrium test; free-decay tests for each of the six rigid-body degrees of freedom of the platform; time series response tests with regular waves and irregular waves modelled with a rigid rotor and no wind; time-series response tests with regular waves and irregular waves modelled with a flexible rotor and steady and turbulent wind; and "effective RAOs" calculated with regular waves at varying frequencies. Not all of the codes were able to contribute results to every test case performed due to various limitations on their modelling capabilities. The test cases provided a number of interesting results, some of which are outlined below.

Structural dynamics. The participating codes all employ different methods for modelling structural dynamics, which was illustrated in a number of differences in the results. The rotor-nacelle assembly was modelled rigidly in 3Dfloat and both the rotor-nacelle assembly and tower were modelled rigidly in SIMO, SESAM, and DeepC. This meant that these codes could not model structural deflections in these components. The FAST code predicted a higher natural frequency for the second blade asymmetric flapwise yaw frequency than that provided by the other codes. This is because FAST does not account for a torsional mode in the tower, whereas other codes that include tower flexibility do account for this mode. The ADAMS code predicted less energy from the irregular wave simulations in the power spectra for tower-top shear and rotor torque at the second tower and blade bending natural frequencies than produced by FAST and Bladed. This might be because of an effect typical of ADAMS simulations, in which numerical damping increases with frequency.

Aerodynamics. Most of the participating codes use BEM theory for the calculation of aerodynamic loads with the exception of SESAM and DeepC, which did not model aerodynamics for the purposes of this project. The 3Dfloat, SIMO, SESAM, and DeepC codes modelled the rotor as rigid, which meant that the aero-elastic response was not rigorously modelled. One example of this was in the calculation of effective RAOs, for which the 3Dfloat code showed lower excitation in yaw, greater excitation in fairlead tensions, and greater excitation at the first tower bending frequency for all parameters. This was thought to be due to differences in aerodynamic damping due to the rigid rotor, although it also could have been related to the modelling of the rigid spar with beam elements of artificially high stiffness. The 3Dfloat code also gave a higher mean thrust in the simulations with regular wind and waves, which corresponded with higher platform surge and pitch displacements.

Hydrodynamics. The free-decay tests showed a few differences between codes in their prediction of the amount of hydrodynamic damping present in the various modes. The HAWC2 predicted too much heave and pitch damping and ADAMS predicted too little pitch damping relative to the other codes. The main difference in terms of hydrodynamic analysis was between codes that used linear potential flow methods and those that used the simple Morison's equation. The most interesting difference was found from the effective RAO calculations. The FAST code used by POSTECH was missing one hydrodynamic damping term, which led to the surge displacement and fairlead tension having a negative effective RAO. The physical meaning of this is that there was more system motion in still water than there was with waves. This occurred because there was a controller-induced instability of the platform surge mode at the surge natural frequency, and there was negligible hydrodynamic damping in the model. With waves included, the wave radiation damping at the wave excitation frequency damped out this instability, thus reducing platform motion considerably. This result indicates the importance of using potential flow-based solutions that include wave radiation damping for the analysis of floating support structures.

Mooring lines. Various methods are used in the different codes for modelling mooring lines. These included both user-defined force-displacement relationships and full dynamic models. The SESAM and DeepC codes used FEM for the mooring lines, and also predicted more energy content above 0.1 Hz for fairlead tension in the power spectra from irregular wave simulations both with and without wind (0.1 Hz corresponded to the peak spectral wave period of 10 s). This probably is due to undamped high-frequency motions in the FEM representations of the mooring lines. Other results confirmed that the mooring-line tensions were interacting with the floating platform as expected. In the simulations with regular wind and waves, for instance, the upstream fairlead tension was greater than the downstream fairlead tension, which is what you would expect given that the mooring-line tensions are counteracting the thrust from the rotor. The fairlead tensions also were higher overall in 3Dfloat, which had a greater mean thrust. The results from the effective RAO calculations showed that the behavior of the fairlead tension was similar to that of the surge displacement, which confirms that platform surge is the factor that most influences fairlead tensions in a spar buoy.

One of the most significant outcomes of the project is that it has helped to identify deficiencies and areas needing improvement in the participating codes. This led to significant improvements in the accuracy of modelling and response prediction. The outcome is extremely beneficial both for the developers of the floating design tools and for the industry in general. Complete results from the floating phase of the OC3 project can be found in Jonkman et al. (April 2010).

CONCLUSIONS

The development of floating wind turbine technology will enable the utilization of a vast amount of wind resource that is located in areas having deep water. Efficiently designing and analyzing floating support structures requires sophisticated design tools that can simulate floating offshore wind turbines in an integrated way. These codes must perform calculations in the time domain to ensure that nonlinear dynamics are captured. The current status of a number of floating wind turbine design tools is presented in this paper, together with a description of the analysis methods used by these tools.

To increase confidence in the predictions of the simulation codes, they must be comprehensively tested and validated. This is achieved through comparisons with measured data and also through code-to-code comparisons. There is very little measured data from floating wind turbines available to the industry. Further tank tests and measurement campaigns from full-scale installed prototypes therefore are needed to validate the design tools. Code-to-code comparisons have been performed both in the validation of individual codes and also as part of the OC3 project. This continues in the OC4 project, which started in 2010.

It is recognized that the floating wind turbine design tools currently available to the offshore market—although highly sophisticated—have several limitations. The major modelling challenges and development needs for floating wind turbine codes, together with descriptions of advanced modelling methods being developed to meet these needs, are presented in the companion paper by Matha et al., *Challenges in Simulation of Aerodynamics, Hydrodynamics and Mooring-Line Dynamics of Floating Offshore Wind Turbines* (2011).

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