OTC 23597-MS

Numerical Simulation of Floating Offshore Wind Turbines Including Aero-Elasticity and Active Blade Pitch Control

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This paper was prepared for presentation at the Offshore Technology Conference held in Houston, Texas, USA, 5–8 May 2014.

Abstract

A new numerical methodology is presented for simulation of dynamic behavior of floating offshore wind turbines. Wind forces are computed in the time domain through application of blade element momentum theory using the instantaneous wind velocities, blade pitch angles, and resulting rotor speed. Equations of motion are developed and solved in Euler-space, such that no small-angle assumptions are required in the solution; vessel motions are included in wind and wave force calculations. Aero-elastic effects are quantified using the industry-standard subroutine AeroDyn, with blade pitch-angles computed by the "DISCON" subroutine, both open-source and publicly available from the National Renewable Energy Lab (NREL). Effectiveness is demonstrated through a series of examples, first a case for small-angle motion is compared with results from an industry standard simulation tool for the spar-based NREL OC3-Hywind with constant wind speed and no waves; next, the same environmental conditions are applied to a smaller spar-based floater for which standard simulation tools would not be applicable. Finally, a case is presented including irregular winds and waves.

Introduction and Background

The economic potential of offshore deep water wind turbines has not yet been fully recognized in part due to the high cost of floaters that are sufficiently stiff in pitch and roll to offer dynamic behavior similar to that of bottom-founded nearly-rigid structures. Potential savings could be realized with the design of smaller floating structures that relax the design requirement for very high stiffness to the point that a new class of less costly floaters are developed that are highly compliant in the pitch and roll directions. Floating offshore wind turbines may still be slightly more costly, but offer other advantages: they can be located farther offshore, reducing visual pollution and having the wind turbine in a location where wind speeds are known to be consistent and stronger. These new highly compliant structures are expected to cost less but allow large angular pitch motion in the direction of wind thrust force where standard simulation tools are not valid in the cases the small angle assumption is violated. An Euler-angle-based method is chosen to efficiently simulate and assess innovative floater designs that allow for large angular motions.

The work presented here combines an existing Euler-based simulator with industry standard aero-elastic and active blade pitch control routines for simulating floating wind turbine motion and rotor speed. The Euler-based simulator was developed by Sweetman and Wang (2011) by solving the EOM's about the center of mass of the entire floating turbine system. The aero-elastic routine, AeroDyn, is an industry standard tool based on blade element momentum theory. The control routine, "DISCON," is a PI active blade pitch control routine written by Jonkman (2009) for NREL's conceptual OC-3 Hywind 5-MW floating turbine. Two key features were developed for successful integration of the existing Euler-based simulator with the aero-elastic and active blade pitch control routines: the creation of interfacing files for integration between the simulator with the aerodynamic and control routines, and then solving of the rotor speed equation of motion (EOM).

MATLAB executable (MEX) files are dynamically linked subroutines that allow the MATLAB interpreter to treat FORTRAN subroutines as built-in functions (Mathworks, 2013). MEX files can be used for interfacing complex FORTRAN computational routines that would otherwise be time consuming to rewrite as MATLAB functions. MATLAB's Application Program Interface (API) libraries contain the subroutines and functions required for interfacing with FORTAN. Input is passed through the MEX gateway routine using pointers and the necessary API functions to write the data into the correct FORTRAN variable. The FORTRAN computational routine is then called and output from the routine is transferred back to the MATLAB environment following the same method as the input.

The AeroDyn aeroelastic simulation tool and the DISCON active blade pitch control module, are established FORTRAN routines. The use of these industry standard routines for the aero-elastic forcing computation was important to prove the effectiveness of Euler-based simulator, in part because future revision of these industry standard computational routines would require future revision of the MATLAB rewrites. Rewriting both routines as MATLAB functions was not considered a viable option because of both the complexity of the rewrites and future maintenance issues. MEX files were created to interface both routines with the MATLAB developed Euler-based simulator. Once the MEX files are created, they have the convenience of acting as built in MATLAB functions allowing easy integration of the FORTRAN routines into the MATLAB environment, and can be reused on future revisions of the FORTRAN and/or MATLAB. Programmers can use similar techniques presented below to solve other legacy software issues.

Development of an EOM for the rotor is the only significant change to the original Euler-based simulator beyond developing the interface MEX functions. The loads received from AeroDyn are used in determining aerodynamic moment acting on the rotor. The motions of the floater are included in the wind forcing calculation, making the interaction fully aero-elastic. The turbine's energy output can then be calculated from the rotor speed and generator efficiency. The new methodology is directly applicable to evaluate highly compliant designs subject to irregular winds and waves to determine overall behavior and amount of energy captured.

Coordinate System.

The same coordinate systems are applied that were previously developed by Sweetman and Wang. Each of the six rotating bodies has a body fixed coordinate system with the origin located at their respective instantaneous center of mass. These are selected to be the principal axes of inertia to simplify calculation of the angular momentum of the rigid bodies by decoupling the inertia matrix. The MEX file for interfacing uses the blade local coordinate system for passing to AeroDyn for computation of the aero-elastic effects. Also used in derivation of the EOM's are two global coordinate systems plus one system-fixed coordinate system.

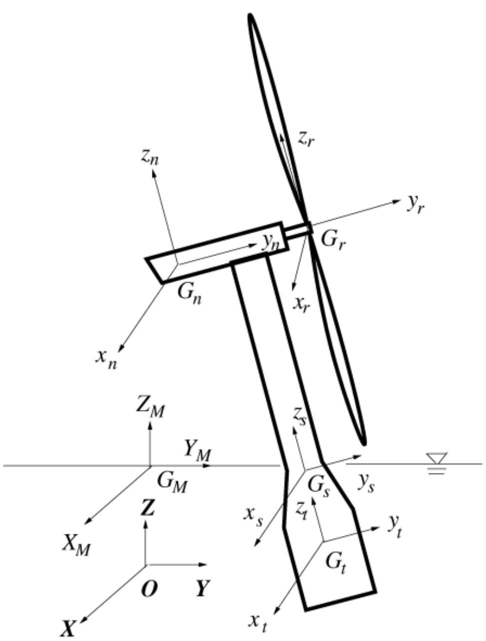

Figure 1 - Coordinate systems

Figure 1 shows both the earth-fixed global coordinate systems (X, Y, Z) and (X_m, Y_m, Z_m) located at the CM of the undisplaced system and still water level respectively. The (x_t, y_t, z_t), (x_n, y_n, z_n), (x_r, y_r, z_r), and (x_{b1}, y_{b1}, z_{b1}) are the body fixed coordinate systems that originate at the CM of the tower, nacelle, rotor, and first blade. The system-fixed coordinate system (x_s, y_s, z_s) is parallel to the (x_t, y_t, z_t) and originates at the CM of the entire system, the instantaneous change of which depends on the location of the CM of each body relative to the joints and motion among the bodies. The CM of the entire system is not constrained to any fixed location and may or may not be on a body in the system.

The (X, Y, Z) and (x_s, y_s, z_s) coordinate systems are used for application of both Newton's Second Law and the theorem of angular momentum on the entire system. The (X_m, Y_m, Z_m) is not used computationally, but it is included to enable direct comparison with FAST. Rotational motion is defined using the 1-2-3 Euler angle sequence, which is necessary for large-angle motion, but cause the order in which the angles of rotation are applied to be important. The coordinates (X_4, X_5, X_6) denote these angles, which are three rotational DOF's of the tower and describe the position of the rotating tower. The transformation matrix from (x_s, y_s, z_s) to (X, Y, Z) has been shown (Sweetman and Wang, 2011):

$$T_{s\to I} = \begin{bmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{bmatrix} \quad (1)$$

in which:

$$t_{11} = \cos X_5 \cos X_6$$
$$t_{12} = -\cos X_5 \sin X_6$$
$$t_{13} = \sin X_5$$
$$t_{21} = \cos X_4 \sin X_6 + \cos X_6 \sin X_4 \sin X_5$$
$$t_{22} = \cos X_4 \cos X_6 - \sin X_4 \sin X_5 \sin X_6$$
$$t_{23} = -\cos X_5 \sin X_4$$
$$t_{31} = \sin X_4 \sin X_6 - \cos X_4 \cos X_6 \sin X_5$$
$$t_{32} = \cos X_6 \sin X_4 + \cos X_4 \sin X_5 \sin X_6$$
$$t_{33} = \cos X_4 \cos X_5$$

Equation 1 results from defining the (x_s, y_s, z_s) system parallel to the (x_t, y_t, z_t) instead of the global (X, Y, Z). The resulting complexity is more than offset by avoiding the tedious calculation of the time derivative of this transformation matrix.

The Interface.

The gateways written for the AeroDyn and "DISCON" MEX functions take advantage of MATLAB's structured array capabilities by combining all turbine and blade markers into two unique arrays to ease data transfer. This is accomplished by using the MATLAB API functions "mxGetField" and "mxGetPr" combined with FORTRAN looping commands to pick apart the MATLAB structure array and store their memory location into pointers. The pointer location is then used in tandem with the API routine "mxCopyPtrtoReal8" to write the data into its corresponding FORTRAN variable. A flow chart of the process is shown in Figure 2.

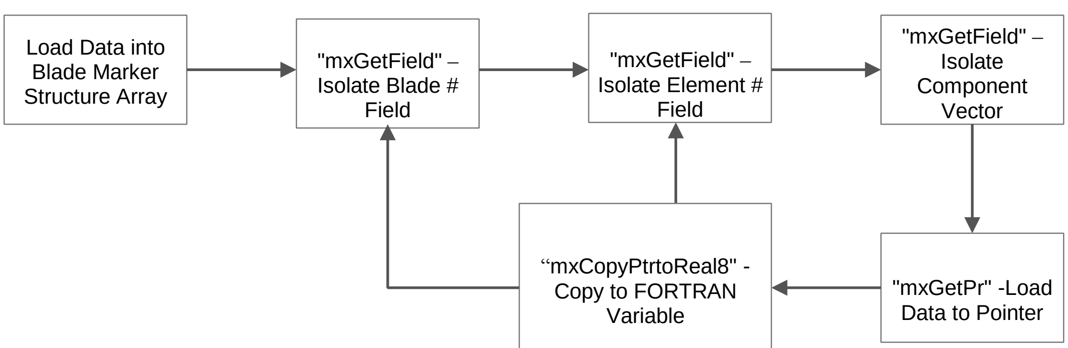

Figure 2- MEX function flow chart

Combining all turbine and blade markers into structure arrays reduces the length of input variables required for the function while providing the gateway routine a format that can easily be manipulated for data extraction. The output is handled in a similar fashion, with pointers to the output arrays in MATLAB environment and FORTRAN looping combined with API routines to write the data from the FORTRAN variable into MATLAB pointer.

Rotor Speed Equation of Motion.

The rotor speed is determined by solving a single one-dimensional equation of motion written about the hub's spin axis, and active control of the blade pitch angle is used to regulate this speed. The rotor speed, also called the low shaft speed, along with the gearbox ratiodefines the high shaft speed, or generator speed.

The resulting high shaft speed is used to determine the appropriate control strategy for the blade pitch angle. Blade pitch control operational regimes are classified as being in control region 1, 1.5, 2, 2.5, or 3. Region 1 is before cut-in wind speed, region 2 is the control region for optimizing power capture, and region 3 is the control region above rated wind speed. The 1.5 and 2.5 regions define linear transition between regions. The output commanded generator torque computed by the control system depends on the region in which the turbine is operating and acts opposite of the aerodynamic torque.

An ideal rigid rotor is assumed for determining the rotor speed. The drive shaft is also assumed rigid with no damping, and the gearbox is assumed to work at 100% efficiency. Euler's dynamic equation of motion is used to include motion of the nacelle in the computation of the spin velocity, in which the principal axes of the driveshaft rotate at the same angular velocity as the hub. (Hibbeler, 2012).

$$\sum M_y = I_y \dot{\omega}_y - (I_z - I_x)\omega_z \omega_x \qquad (2)$$

$\sum M_y$ is the total moment acting on the spin axis, $\dot{\omega}_y$ is the angular acceleration of the spin axis, ω_z and ω_x are angular velocities in the hubs x and y direction, and I_y, I_z, and I_x are the moments of inertia in their respective direction relative to the hub's coordinate system. The inertias are the sum of the rotor and generator inertias. The yaw and roll motion have been included in the EOM. The external moment is determined from the aerodynamic torque acting clockwise on the hub and the demanded generator torque acting counter-clockwise on the driveshaft. The aerodynamic torque is the computed moment from AeroDyn projected about the spin axis of the hub and the demanded generator torque is that computed by the pitch control routine. An advantage of using Euler's EOM is that the body fixed angles (ω's) are already associated with a set of sequenced Euler angles and therefore can be used directly without further concerns regarding large angle motions. A flow chart of the simulation is shown in Figure 3.

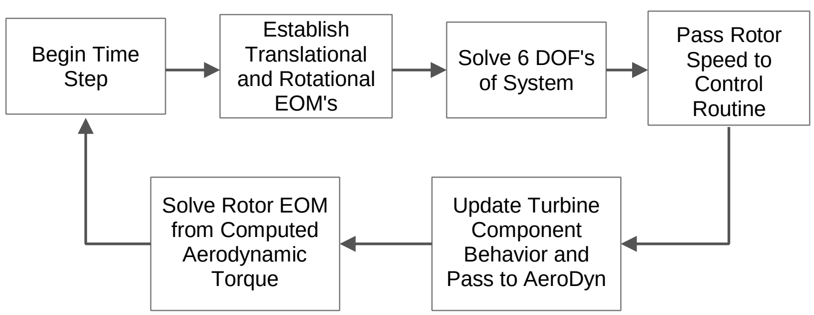

Figure 3 – Simulation flow chart

The rotor speed EOM is solved between the time steps of the system EOM's. The only assumption implicit to solving this EOM separate from the system's 6 DOF's is that the rotor acceleration is small between time steps. This assumption is reasonable since simulation time steps are normally in the range of 0.1-0.5 seconds. Known relationships between the blades and hub are used to project the aerodynamic moment onto the spin axis. The gyroscopic moments resulting from base excitation of the spin axis are already included in the system rotational EOM's through use of cascading transformation matrices between system components and ultimately transformed to the inertial coordinate system using equation 1. The rotor EOM is solved between every two timesteps to ensure the effects of the rotor speed are accurately included in the system simulation.

AeroDyn and Blade Pitch Control

The external moments applied in equation 2 are determined from the aero-elastic and active blade pitch control routines. The aerodynamic moment is determined from the load received from AeroDyn acting on each blade element and the distance of the element from the spin axis. The effect of the blade pitch angle is included in the aero-elastic forces by means of the blade element orientation computed by DISCON and passed to AeroDyn.

AeroDyn.

AeroDyn is a dependent routine that requires markers from major turbine components to be passed to it from the calling dynamics simulator. The motions of the floater are included in the wind forcing calculation, making the interaction fully aero-elastic. Necessary information on the turbine geometry, blade-element and airfoil properties, and wind speed are obtained from standard AeroDyn data files. Operating conditions including velocity and location of the hub and other components are computed each time step and passed to AeroDyn. AeroDyn applies blade element momentum theory (BEM) for determining the aerodynamic lift, drag, and pitching moment of airfoil sections along the wind turbine blades (Moriary & Hansen, 2004). The BEM theory applied in AeroDyn is based on conservation of momentum analyzed at an element of the blade. In the theory, conservation of momentum is applied to a control volume and the differential thrust and torque are defined as a function of the flow conditions (Manwell, McGowan, & Rogers, 2009). Differential thrust and torque are computed as functions of the angle of the attack using lift and drag coefficients and equated with and then computed using conservation of momentum.

The markers passed to AeroDyn by the dynamics simulator follow the body fixed coordinate system as presented in NREL's AeroDyn user guide addendum and relative to the global XYZ (Jonkman & Jonkman, 2013). The body markers provide AeroDyn with the position, orientation, and translation and rotation velocities of the following turbine components: tower/floater, nacelle, rotor furl, hub, each blade root, and each blade element. The Euler-angle-based simulator passes body markers to AeroDyn at every time step. The marker components are determined after solving the system's EOM's and transferring the motion to each body through the cascading transformation matrices. Each body marker is then orientated with respect to the AeroDyn's pre-described global XYZ.

The MEX file created for the AeroDyn interface follows the flowchart in Figure 2 with two different structural arrays: "TurbineComponents" for the main bodies of the turbine, skipping the element number, and "InputMarkers" for the individual blade elements. The markers are written into the derived data type defined by AeroDyn. The output from AeroDyn is arranged into two matrices of dimension 3 x the number of blade elements for each blade, with one of the 3 x the number of blade elements matrix representing the moment about the blade pitch axis and the other matrix as the normal and tangential forces acting at each element perpendicular to the plane of rotation for each blade element.

Blade Pitch Control.

Computation of the thrust and torque in AeroDyn requires the instantaneous blade pitch angle. Blade pitch control is provided by the "DISCON" routine written for the conceptual OC3-Hywind by Jason Jonkman (Jonkman, Butterfield, Musial, & Scott, 2009). The OC3-Hywind is equipped with a 5 MW turbine that has a rated speed of 12.1 RPM. The pitch control routine uses gain scheduled proportional-integral (PI) control on the speed error between the filtered and rated generator speed. The gains were determined by designing the control system around a simple single DOF model of the angular rotation of the generator shaft (Jonkman et. al, 2009). The high shaft speed and current blade pitch angles are passed to the computational routine. The high shaft speed is the generator speed and determined by multiplying the rotor speed by the 97:1 gearbox ratio.

The desired pitch angle is determined from the current speed error between the desired rated speed and actual speed of the generator shaft. The gains are then applied and filtered through the max and min pitch angles and pitch angle speed so the demanded angle does not exceed the defined limits. For the "DISCON" routine, the blade pitch angle range is 0-90 degrees with a maximum pitch rate of 8 degrees per second (Jonkman et. al, 2009). The Euler-angle simulator uses collective pitch control, with the demanded blade pitch angle equal to the actual blade pitch angle and included in the transformation matrix from the hub to each respective blade. This transformation is used when defining the blade element orientation matrix passed to AeroDyn providing its inclusion in the aero-elastic calculations.

Euler-based Simulator

A floating offshore wind turbine can be modeled as a six-body system consisting of the tower and floater together as the base body, plus the nacelle, hub, and three blades, each treated as a rigid body. Conventional numerical tools for dynamic analysis of a multi-body system are the Newton-Euler equations, Euler-Lagrange equations, and Kane's method. The Newton-Euler equations are usually developed by separating the free body diagrams of each rigid body in the system. This method is useful for determining internal forcing but those forces are not necessary for simulation of general motion of a multi-body system. The Euler-Lagrange equations apply energy methods to develop the equations of motion (EOM) for generalized degrees of freedom. This method is efficient for solution of the motion but the derivation of partial derivative of energy about related degrees of freedom is laborious. NREL's computer-aided engineering tool, FAST, uses Kane's method for dynamic analysis. The coordinate system and solution method applied in FAST limit applicability to floater rotation of 20 degrees because of the solution method (Jonkman & Buhl, 2005).

The Euler-based method was developed by Sweetman and Wang (2011), writing the EOM's by applying the conservation of momentum to the floating wind turbine system. The core of the method is to calculate the angular momentum of each rigid body and sum them in a unified translating-rotating coordinate system to obtain the total angular momentum of the system, the derivative of which is equal to the sum of externally applied moments. Cascading transformation matrices are used to transfer the angular momentum of each rigid body onto the system's center of mass. The method makes use of the known geometrical relationships between the rotating contiguous bodies are used in deriving the rotational EOM's, the solutions of which are Euler angles. The rotational EOM's are combined with the translational EOM's controlled from Newton's second law to define the six degrees of freedom (DOF) for the entire system. The center of mass (CM) of the system is determined at every time step using the defined geometrical configuration of the system. A main advantage of the method is that the general motion of the floating wind turbine is determined using only six EOM's written about the CM of the entire system, easing computational demand. Writing the EOM's about the center of mass also decouples the translational and rotational forcing, which facilitates numerical integration of the EOM's.

Computation of non-linear mooring forcing requires the instantaneous position of each body at every time step. The velocities of each body must be determined to accurately compute hydrodynamic and aero-elastic forcing. In the numerical simulation, the motions and external forcing, non-linear due to their coupling, are transformed between various coordinate systems at each time step using the Euler angle cascading matrices. Thus, the fully nonlinear coupling between large-amplitude motion and external excitation is preserved.

Rotational Equations of Motion.

Conservation of angular momentum is applied in determining the rotational EOM's of the system. The sum of the externally applied moments applied about the CM of a system of bodies in the translating-rotating system, (x_s, y_s, z_s) equals the change of amplitude of the angular momentum within the coordinate system plus the change of direction of the momentum with respect to the global XYZ. The rotational EOM's can be shown to be (Wang & Sweetman, 2012):

$$\sum \underset{M}{\rightarrow} = \left(\underset{H_{G_s}^s}{\dot{\longrightarrow}}\right)_{x_s y_s z_s} + \underset{\omega_s}{\rightarrow} \text{ X } \underset{H_{G_s}^s}{\longrightarrow} \tag{3}$$

where $H_{G_s}^s$ is the angular momentum of the system and ω_s is the angular velocity of (x_s, y_s, z_s) with respect to the global XYZ. The externally applied moments include restoring, hydrodynamic, and aerodynamic forces. The angular momentum of the system is obtained by superimposing the moments of the six bodies and then decomposing the sum onto the (x_s, y_s, z_s) system. The angular momentum of each body is computed in the body's coordinate system about its principal axes of inertia and then transformed to the unified (x_s, y_s, z_s) system. It is then transferred to the origin of the (x_s, y_s, z_s) system.

Translational Equations of Motion.

Newton's second Law is applied to the floating turbine system to increase computational efficiency by avoiding the calculation of internal forces between rigid bodies:

$$\sum \underset{F}{\rightarrow} = m_s \underset{a_{G_s}}{\longrightarrow} \tag{4}$$

where the force vector $\sum \underset{F}{\rightarrow}$ represents the externally applied forces projected into the inertial C_I system, m_s is the mass of the entire system, and $\underset{a_{G_s}}{\longrightarrow}$ is the linear acceleration of the CM of the system. The solution of the translational EOM's is the motion of the CM of the system (G_s) referenced in the XYZ coordinate system. Direct solution of the equation decouples translations from rotations and frees G_s from being constrained to any rigid body. The external forces are composed of aero-elastic, hydrodynamic, restoring (mooring and hydrostatic), and gravity. The external forces must be decomposed into the XYZ system for application of equation 4.

Examples

Three cases are presented for showcasing the successful integration of an Euler-based simulator with AeroDyn and "DISCON" controls. In the first case, NREL's OC3-Hywind floating wind turbine is modeled in both FAST and the Euler-based simulator and subjected to a constant wind speed of 11.4 m/s with no waves. The option for still water is chosen so the wind forcing effect can be isolated for observation. The wind speed of 11.4 m/s is chosen because that is the rated wind speed for the 5-MW wind turbine. Next, a truncated version of the OC3-Hywind is modeled in the Euler-based simulator for critical comparison of power output with the original OC3-Hywind presented in the first case. Both the OC3-Hywind and truncated model are equipped with the NREL 5 MW turbine whose properties are outlined in NREL's 2009 publication (Jonkman, et al 2009). The tapering section of the floater is modeled in both cases as defined by Jonkman (Jonkman, 2007). The OC3-Hywind is truncated from a length of 120 m to 75.4 m, saving about 2300 tons, or about 30 % in total weight. The same environmental conditions are applied to the case; 11.4 m/s constant wind and still water. A third case is presented for a realistic simulation of the truncated model subjected to irregular wind and waves.

A summary of properties pertinent to the presented examples for the OC3-Hywind and truncated model are cataloged in Table 1:

Table 1: OC3 Hywind 5-MW Wind Turbine Properties

	OC3- Hywind	Truncated Model
Floater Length	120 m	75.4 m
Floater Mass	7,466,330 kg	5,150,000 kg
Pitch Inertia	4,229,230,000 kg-m^2	1,636,930,000 kg-m^2
Rotor Inertia	38,759,228 kg-m^2	38,759,228 kg-m^2
Generator Inertia	5,025,497 kg-m^2	5,025,497 kg-m^2
Initial CM (below SWL)	85.6 m	60.9 m
Elevation to Tower Top (above SWL)	87.6 m	87.6 m

Small Angle Case.

The initial conditions of six DOF's of platform motion are zero and the only external forces acting on the body are from the wind and restoring forces; hydrostatic and mooring. The mooring and hydrostatic forces are defined in FAST with the "UserSubs" routine and in the Euler-based simulator through a similar method. The initial rotor condition is set to the rated speed of 12.1 rpm and the initial blade pitch angles are zero. Figure 4 shows a comparison between the Euler-based simulator and FAST for the pitch and surge motions resulting from a constant wind of 11.4 m/s.

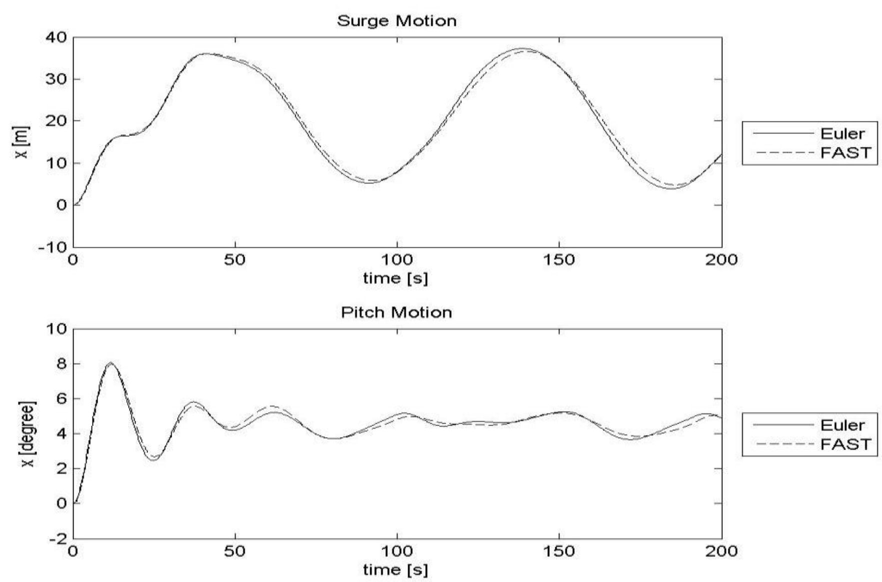

Figure 4 - Surge and pitch motion comparison

The results show acceptable agreement between FAST and the Euler-based simulator for the OC3-Hywind simulation. The mean pitch angle due to the wind force is about 5 degrees, within the range of the small angle assumption. Figure 5 shows the comparison of the blade pitch angle, rotor speed, and generator power.

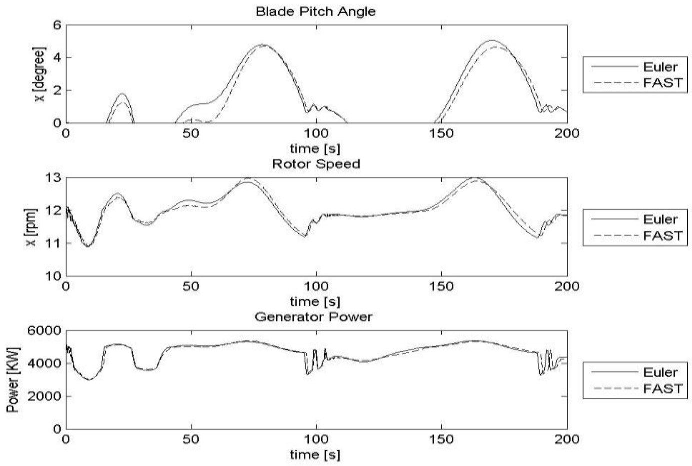

Figure 5 - Comparison of blade pitch angle, rotor speed, and generator power

There is a discrepancy with the blade pitch angle demanded by the controls near the 50 second mark. This large divergence results from a small discrepancy in the rotor speed: the Euler-based simulator computes a speed of 12.1 rpm, which is in control-region 3 of the controller and triggers active blade pitch control, FAST computes a spin rate just below 12.1 rpm, so active blade pitch control is not activated. Despite this difference, the Euler-based generator power and rotor speed have good agreement with FAST. The generator power in the Euler-based method is determined by multiplying the generator torque by the generator speed. The mean generator power is about 4.8 MW, close to the ideal 5 MW.

Large Angle Case.

A truncated version of the OC3-Hywind is modeled by reducing the spar length from 120 m to 75.4 m, and reducing the mass by 30% to 5,150,000 kg. Hydrostatic stability is preserved, but the restoring moments in the pitch and roll directions are reduced substantially. The time-series for the truncated model simulated with the Euler-based method is compared to the OC3-Hywind results simulated using the same method. The truncated model supports the same NREL 5 MW wind turbine as the OC3-Hywind.

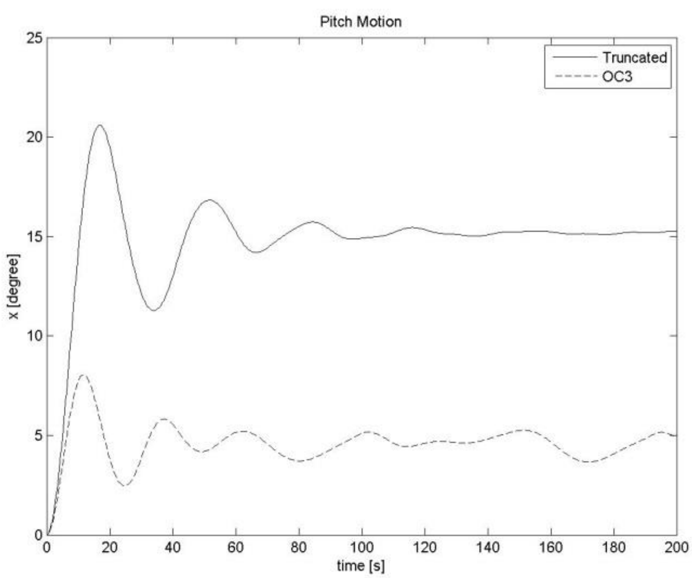

Figure 6 - Pitch comparison between the OC3 Hywind and truncated models

The mean pitch angle for the truncated model is about 10 degrees larger than the OC3, at about 15 degrees. The maximum pitch angle of 21 degrees occurred during start up. The increase in pitch motion is due to a reduction in the hydrostatic restoring caused by the truncation of the floater. A comparison of the rotor speed and generator power is shown in Figure 7.

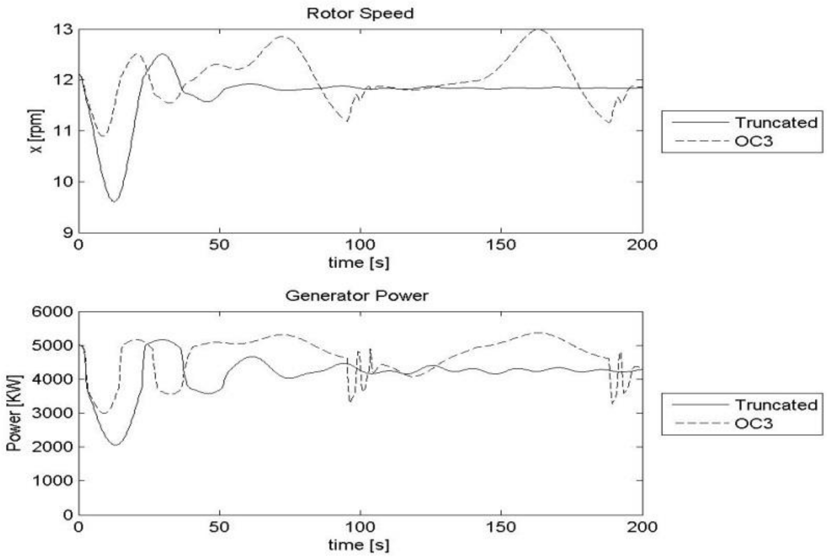

Figure 7 - Rotor speed and generator power comparison between the OC3 Hywind and truncated models

The blade pitch comparison was not included because the truncated model never exceeds the rated rotor speed of 12.1 rpm so increasing the blade angle was not required. The spin rate of the truncated model steadies at about 11.8 rpm so the energy captured is less than ideal. The larger mean-pitch angle reduces the rotor sweep area perpendicular to the wind causing the slower rotor speed. The generator power comparison is useful to assess the overall cost efficiency of highly compliant floaters. The truncated floater simulation shows mean generator power of about 4.1 MW compared to a mean of about 4.6 MW for the OC3-Hywind, indicating for a 10.9% reduction in electricity harvest in these conditions. It should be noted the controls used for truncated floater are optimized for the OC3-Hywind. There is potential for increased energy capturing efficiency by optimizing the generator controls for the truncated model, or for development of developing control strategies intended to help stabilize the floater pitch angle.

Irregular Wind and Waves.

The truncated spar is modeled with wave forcing to demonstrate a realistic simulation. The sea state is simulated from the JONSWAP spectrum with a significant wave height of 5 m and 10 second wave period and a uniformly distributed random phase distribution. Wave forces are computed using the Morison equation including the relative motion of the spar through the water. The wind environment is represented by a mean 13 m/s turbulent wind data file simulation using TURBSIM. The resulting global motions of the spar are shown in Figure 8.

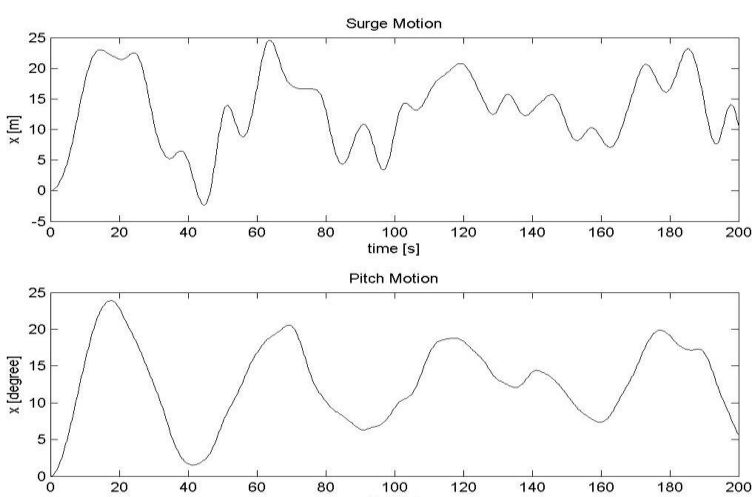

Figure 8 - Surge and pitch motion of the truncated spar in irregular wind and waves

The maximum pitch angle of 24 degrees occurs during start up and the mean pitch angle is about 15 degrees. The results are reasonable when compared to the same truncated spar in the previous case subjected to rated wind speed and no waves. Plots of the blade pitch angle, rotor speed, and generator power are shown in Figure 9.

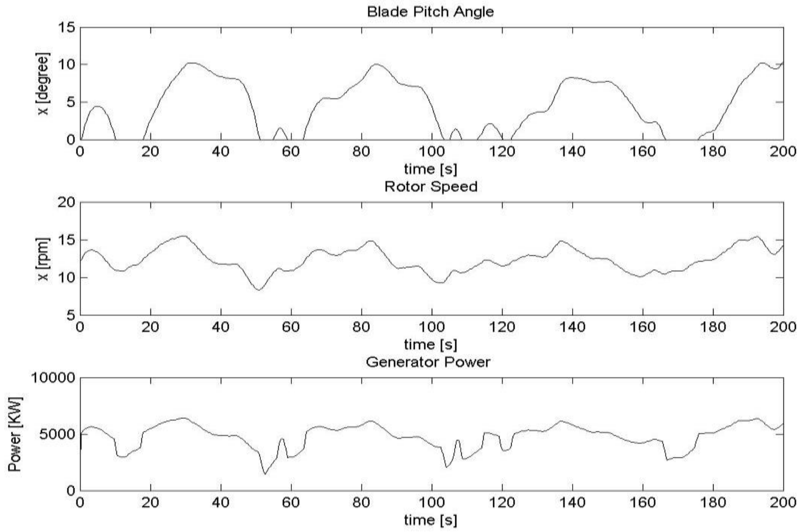

Figure 9 - Blade pitch angle, rotor speed, and generator power of the truncated spar in irregular wind and waves

The mean generator power acts at about the rated capacity of 5 MW, indicating the system including controls and rotor are performing well in the speciefied the environmental conditions.

Conclusion

An Euler-based simulator has been integrated with industry standard aero-elastic and active blade pitch control routines. MEX files were developed for the interfacing between the Euler-based simulator written in MATLAB and the supporting routines written in FORTRAN. An equation of motion to determine the rotor speed resulting from the aerodynamic torque was developed and implemented into the Euler-based simulator. The Euler-based simulator can be used for rotational displacements that exceed the small angle assumption common in industry standard tools. The integration was verified by comparison with the industry standard modeling tool, FAST. NREL's OC3-Hywind was modeled in both the Euler-based and FAST simulators for critical comparison. The same environmental conditions were applied: rated constant wind speed of 11.4 m/s and still water. A truncated spar with 30% less mass was modeled and its behavioral results were compared to the OC3-Hywind results given the same environmental conditions. The mean generator power for the truncated spar was 4.1 MW compared to 4.6 MW for the OC3-Hywind. A simulation with irregular waves and wind forcing for the truncated model was produced to demonstrate a realistic event. The resulting dynamics simulation tool can be used to perform detailed statistical optimization studies of the relative efficiency of future highly compliant designs. Future work includes further benchmarking against industry-standard tools and optimization of the blade-pitch controller.

Acknowledgements

This work was supported by the National Science Foundation, Energy for Sustainability, within the Division of Chemical, Bioengineering, Environmental, and Transport Systems, agreement number CBET-1133682. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the view of the National Science Foundation.

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