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WINDFLOAT: A FLOATING FOUNDATION FOR OFFSHORE WIND TURBINES PART II: HYDRODYNAMICS ANALYSIS

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ABSTRACT

WindFloat is a floating foundation for very large offshore wind turbines. This paper describes the hydrodynamic analysis of the hull, as well as ongoing work consisting of coupling hull hydrodynamics with wind-turbine aerodynamic forces. Three main approaches are presented in this paper:

- The numerical hydrodynamic model of the platform and its mooring system;
- Wave tank testing of a scale model of the platform with simplified aerodynamic simulation of the wind turbine;
- FAST, an aerodynamic software package for wind turbine analysis with the ability to be coupled to the hydrodynamic model

These conference proceedings include two other papers presenting the design basis and main systems of this floating foundation [1], as well as structural analysis of the hull and mast [2].

INTRODUCTION

The challenges associated with design and operations of floating wind turbines are significant. A floater supporting a large payload (wind turbine and nacelle) with large aerodynamic loads high above the water surface challenges basic naval architecture principles due to the raised center of gravity and large overturning moment. The static and dynamic stability criteria are difficult to achieve especially in the context of offshore wind energy production where economics requires the hull weight to be minimal.

The following fundamental aspects must be addressed to design such system: (1) the influence of the turbine on the floater, and (2) the influence of the floater motions on the turbine performance. A large body of work has been published on the hydrodynamics of floating platforms; see Chakrabarti [3] and Faltinsen [4] for comprehensive overviews. Hydrodynamics of a minimal floating platform with similar substructure is discussed by Cermelli and Roddier [5]. Wind loads on floating structures discussed in the above references are normally computed using a simple relation between the apparent wind speed and loading based on empirical drag coefficients or results from wind-tunnel tests. In the case of a floating offshore wind turbine, wind load components generated by the turbine and their effects on platform motion are significant and may lead to coupling effects, which cannot be accounted for using conventional methods.

The following methodology is followed in this paper, with increasing level of refinement of the coupling effects between the wind turbine and platform motion. In the first step, consisting of global sizing of the floater, coupling between the turbine and floater is accounted for using the following approximation: the wind thrust is determined by assuming that the base of the turbine is fixed and it is applied as force and overturning moment at the base of the mast. This approach is further described in Zambrano et al [6].

The second step involves time-domain simulations of the hydrodynamic response of the platform using TimeFloat software. The software was modified to compute wind turbine loads based on an equivalent drag model, which provides suitable wind thrust at the hub, and also generates aerodynamic damping. Gyroscopic effects due to the gyration of the rotor coupled with platform rotations are also included. This model is relatively simple to implement numerically, and could also be adapted to an experimental set-up in order to verify the platform motion predictions during wave tank testing of a small-scale model. Results obtained at the UC Berkeley ship-model testing facility are presented. This model does not account for the various control systems installed on large wind turbines, which have the ability to pitch the rotor blades resulting in variable thrust, in order to keep the rotor speed constant despite variable wind velocities.

In the third and most advanced step, the aerodynamic calculation software FAST developed at the National Renewable Energy Laboratory (NREL) was coupled with the hull hydrodynamic software TimeFloat to compute the platform motion and wind turbine loads including the effects of blade pitch control, and the effect of platform motion on the resulting aerodynamic forces. This offers the ability to compute simultaneously the effects of the mooring system, water-entrapment plates, as well as all wind-induced loads on the turbine. The methodology is similar to Jonkman [7], but coupling with TimeFloat allows accurate modeling of the nonlinear mooring forces, as well as nonlinear viscous forces generated by the water-entrapment plates.

To address the influence of the floater motion on turbine performance, a study was performed in which floater motions determined using the approach presented in this paper, were applied at the base of the mast and turbine performance was evaluated. The MSC Adams aerodynamic software allows for motion time-series input, similar to earthquake loading. The resulting forces in the various components of the turbine were compared with the case of a fixed base. Results of this study will be published shortly.

WINDFLOAT DESCRIPTION

The WindFloat platform, shown in Figure 1, is a floating support for a large wind turbine. It is comprised of the following elements:

- Three columns, which provide buoyancy to support the turbine and stability from the waterplane inertia.
- Horizontal plates at the bottom of the columns, which (1) increase the added mass, hence shift the natural period away from the wave energy, and (2), increase the viscous damping in roll, pitch and heave.
- Permanent water ballast, inside the bottom of the columns, to lower the platform to its target operational draft, once installed.
- An active water ballast system, which moves water from column to column, to compensate for the mean wind loading on the turbine. This moveable ballast compensate for significant changes in wind speed and directions. It aims at keeping the mast vertical to improve the turbine performance.
- Six mooring lines, made of conventional components (drag-embeddment anchors, chains, shackles, fairleads, and chainjacks).
- An offshore Wind Turbine, with as little requalification as possible from existing fixed offshore turbines.

Figure 1: WindFloat perspective view

The WindFloat, in its existing configuration has dimensions listed in Table 1. We note that this is not the final design, and that each specific wind farm, being subjected to different winds and waves environments, will have variations from this configuration. It is also noted that the present design has the capability to support wind-turbines up to 10MW rated power.

Table 1: WindFloat Main Dimensions

USER-INPUT HULL DIMENSIONS				
column diameter	35	ft	10.7	m
length of heave plate edge	45	ft	13.7	m
column center to center	185	ft	56.4	m
pontoon diameter	6	ft	1.8	m
operating draft	75	ft	22.9	m
airgap	35	ft	10.7	m
bracing diameter	4	ft	1.2	m
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STABILITY

To assess the stability characteristics of the platform, the restoring moment is computed in intact and damaged conditions at different wind headings. The downflooding angle – heeling angle for which the vents above the top of columns are underwater – is also calculated.

The restoring moment curves obtained are compared to the curves of wind overturning moment, to determine the heeling angle at equilibrium. Combined with a factor of safety, the comparison provides an estimation of the stability of the platform. A rough assessment of the wind overturning moment under steady wind was carried out in this analysis, based on a range of thrust coefficients for a 10MW wind turbine. A worst case scenario (failure mode) is considered with a combination of wind overturning moment and a faulty active ballast system. Wind headings every 30 degrees are considered for this analysis.

Damage cases are also taken into account by assuming that a section of one column is flooded. The damage remains limited due to compartmentation of the columns.

In all considered configurations, the angle of static equilibrium is smaller than the downflooding angle with a comfortable safety margin and the platform remains stable in damaged conditions.

Table 2: Summary of Stability Characteristics

	Heeling Angle in Calm Sea (deg)	Down flooding Angle (deg)	Metacentric Height (ft)
Intact Case at 0 degree Wind Heading	0	20.5	53
Intact Case at 30 degree Wind Heading	0	22.5	53
Damaged Case at 0 degree Wind Heading	4.5	18	38

HYDRODYNAMIC MODEL

The time-domain software TimeFloat was developed by the authors for coupled analysis of floating structures. It uses WAMIT as a pre-processor to compute wave interaction effects, and computes the time-domain response of one or more floaters subjected to waves, wind, current and connected with moorings, tendons, hawsers, fenders, or any other mechanical connections. It takes into account the viscous forces due to shedding around the hull and wave drift forces. The solution is fully-coupled, as the influence of vessel motion on tether forces is taken into account at each time-step, and conversely, the influence of tethers on vessel motion is also included at each time-step. A summary of the algorithm is presented next.

In the frequency-domain, the equation of motion of a floater is:

$$(m + a(\omega))\,\ddot{x} + b(\omega)\,\dot{x} + c\,x = F(\omega) \qquad (1)$$

where a(ω) and b(ω) are frequency-dependent added-mass and radiation damping coefficients, and F(ω) is the sum of forces applied to the floater including the wave-exciting force.

In the time-domain, one can show that the equation of motion has the following general form:

$$(m + a')\,\ddot{x}(t) + \int_{-\infty}^{t} K(t-\tau)\,\dot{x}(\tau)\,d\tau + c\,x(t) = F(t) \qquad (2)$$

where a' is frequency independent and K is the retardation function.

$$\begin{cases} a' = a(\omega) + \dfrac{1}{\omega}\displaystyle\int_0^{\infty} K(\tau)\sin(\omega\tau)\,d\tau \\ K(\tau) = \dfrac{2}{\pi}\displaystyle\int_0^{\infty} b(\omega)\cos(\omega\tau)\,d\omega \end{cases} \qquad (3)$$

These integrals are calculated numerically.

TimeFloat uses an explicit scheme to solve up to 12-degree of freedom (DOF) equations of motion for a 2-body system. The WindFloat is the only vessel considered in this analysis, and the software only solves 6DOF equations. The general equation of motion is discretized in time, and the following linear vectorial equation is solved at each time-step:

$$([M]+[A'])\,a^k + [B']\,v^k + [C]\,x^k = F_{mem} + F_{diff} + F_{visc} + F_{drift} + F_{moor} + F_{wind} \qquad (4)$$

The left-hand side of the Newton's equation of motion (4) contains terms proportional to the 6-DOF acceleration (a^k), velocity (v^k), and motion of the floater (x^k), with the following notations:

[M] is the mass matrix,

[A'] is the 6x6 infinite-frequency added-mass matrix,

[B'] is the 6x6 matrix of retardation coefficients for t=0, which are integrals of the frequency-dependent radiation damping coefficients, due to outgoing waves generated by the moving floater. The damping coefficients are computed by WAMIT, and integrated at the beginning of the time-domain simulation to generate the retardation function matrix.

[C] is the 6x6 hydrostatic stiffness matrix computed by WAMIT. Only the terms K(3,3), K(4,4), K(5,5), K(3,4), K(3,5) and K(4,5) are non-zero due to the port/starboard symmetry. Refer to WAMIT manual for details [8].

The right-hand side includes the various external forces. A brief description of the terms in this equation is given below.

F_{mem} represents the memory effect, i.e. the effects of wave components generated by past motion of the floater, described by the convolution of the retardation function with body velocity as shown in equation 3 above.
F_{diff} is the 6-DOF wave-exciting force determined by a Fourier series using WAMIT frequency-dependent wave-exciting force components and wave amplitude components representing the specified wave spectrum. A random phase and random frequency algorithm is used to generate irregular wave trains.

F_{visc} is the 6-DOF viscous force resulting from drag effects on the vessel columns and water-entrapment plates. These are computed using a modified Morison equation model based on the relative velocity of the wave/current kinematics and of special line members. Results of multiple model test campaigns have been used to calibrate the empirical viscous force model. The effect of ocean currents is captured with this viscous force model.

F_{drift} is the 6 DOF-drift force on the vessel computed based on WAMIT mean drift frequency-dependent coefficients obtained with the pressure integration or momentum approach, and the wave amplitude components. Newman's approximation is used. Alternatively, a full second-order diffraction model can be used, if WAMIT 2nd order module is run. Previous work has shown that the 2nd order potential solution was not required for the WindFloat.

F_{moor} is the 6-DOF force on the vessel resulting from all mooring lines. Mooring lines are modeled either with cable elements or non-linear springs. For cable elements, a finite-difference scheme is used to yield the dynamic mooring line configuration and mooring tensions at each time-step. The nonlinear finite-difference equations are solved using a Newton-Raphson algorithm as described by Chatjigeorgiou and Mavrakos [9].

F_{wind} is the 6 DOF wind turbine force on the vessel superstructure. The wind force model was modified to capture some of the aerodynamic coupling between the turbine and the WindFloat platform. It was assumed that the wind force applied on the rotor was proportional to the square of the relative velocity between the wind and the hub. It was determined that an equivalent disk in the rotor plane with 72.7m diameter would provide the maximum rated thrust of a 10MW turbine, assuming a 1.2 drag coefficient on the disk. The wind force is perpendicular to the disk and its direction varies in time with the platform rotations. The gyroscopic moment was estimated from:

$$\mathbf{M_{gyro}} = I\, \mathbf{\Omega} \times \mathbf{p} \tag{5}$$

where I is the moment of inertia of the spinning rotor, $\mathbf{p}$ is the rotational velocity vector of the rotor around its axis and $\mathbf{\Omega}$ is the rotational velocity vector of the platform around the pitch and roll axes. The gyroscopic moment $\mathbf{M_{gyro}}$ is added to the moment contribution of F_{wind}.
Newton's equation is applied in an inertial frame of reference which coincides with the vessel frame of reference at t=0. The origin of the vessel frame of reference is located at the mean water level directly under the center of gravity. The X-axis points toward the bow, i.e. the column supporting the wind turbine tower, the Y-axis toward port side, and the Z-axis upward.

TimeFloat is written in FORTRAN. Information is provided to the software through an input file in text format, with all vessel, mooring, and numerical parameters. Additional input consist of the WAMIT files and the wind and current coefficients files. After reading the input, TimeFloat solves an initial static phase, in which mean wind and current loads are applied as well as the mooring line pretension. This phase serves to reduce the transient phases, and quickly provides static information if needed. Then, the solution is advanced in time using a Runge-Kutta algorithm for the 6 DOF rigid body motion and velocities. At each of the 4 fractional steps used in this process, external forces are updated.

WAMIT6.3 software was used to compute added-mass and damping coefficients as well as wave-exciting forces and mean drift coefficients. Only the underwater part of the hull is modeled. The model includes the columns, water-entrapment plates and main tubulars connecting columns. The bracings are only modeled as line-members using Morison equation. Dipole elements are used to discretize the water-entrapment plate, since they are thin structural elements.

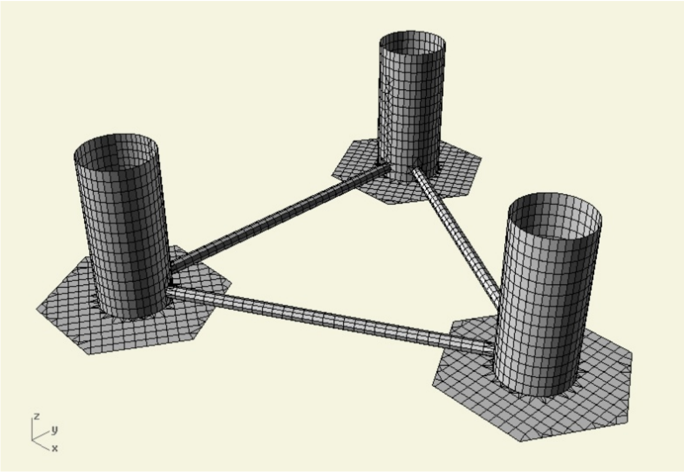


Figure 2: Wetted-hull of the WindFloat for the WAMIT model

DESIGN CASES

In the preliminary design phase, a selected number of design cases were defined based on a combination of offshore moorings design codes and offshore wind turbine design codes; i.e. API-RP2SK [10] and Germanischer Lloyd [11]. The design cases that were thought to be the most onerous for the platform motions were verified. These included the 100 year storm

(13.5m Hs), Extreme Coherent Gust (ECG), and Extreme Operating Gust (EOG). In addition, a number of operating cases were ran corresponding to the turbine maximum thrust wind speed (~12m/s) with associated waves (~2m Hs), and the maximum wind speed with turbine spinning (~25m/s) with associated waves (~4m Hs).

For detail design and certification, a much larger number of design cases will have to be considered, however the return period of the maximum events will likely be 50 year in accordance with wind turbine design codes, rather than the 100 year return period selected for this preliminary study.

Space does not allow for an extensive presentation of the hydrodynamic simulations, however some results of numerical predictions are provided later and compared with model test results for key parameters.

MODEL TESTS SETUP

A model test campaign was conducted at the UC Berkeley 200ft long (61m) ship model testing facility to test the validity of the numerical analysis tools. A 1/105 scale model of the platform was fabricated out of acrylic. Lead weights were placed inside the columns and on the water-entrapment plates to adjust the center of gravity to its target position; item (1) in Figure 3. The platform motion was measured using a digital video camera tracking the motion of LED's placed on the model (2). The system provides 3DOF measurements of the motion in the plane of the camera.

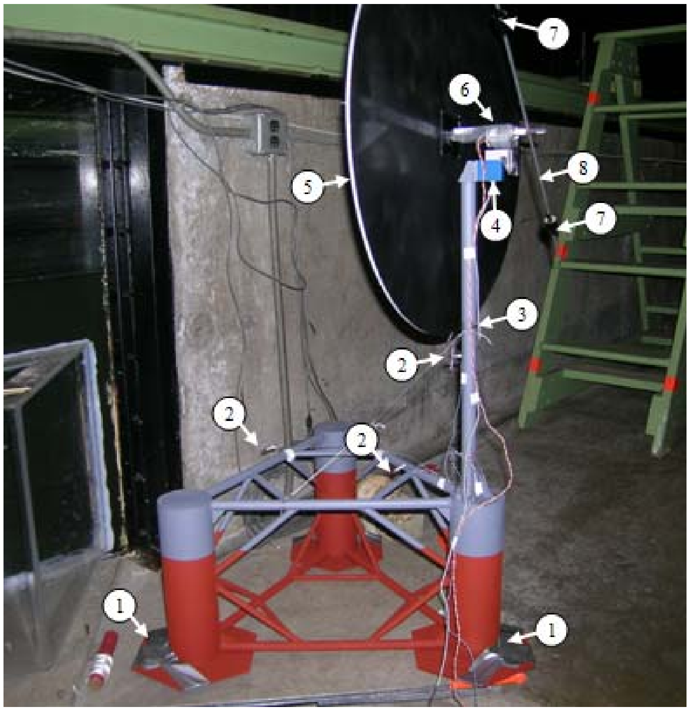


Figure 3: picture of the WindFloat model

The tower (3) was made of a thin (not-to-scale) 1" OD acrylic pipe, because the device used to model the wind turbine was relatively heavy and it was not possible to obtain the correct center of gravity with the lead weights if the tower was modeled with a 3" OD acrylic pipe, as originally planned. Stays made of thin string were connected to the tower to increase its stiffness.

The turbine model device was connected to the top of the tower onto a load cell (4) which measured the axial force perpendicular to the tower. A large disk (5) made of foam board was placed on the model to attract wind loads corresponding to the design wind force. No attempts were made to match the atmospheric turbulence. The wind maker naturally produces turbulence and the turbulent wind fluctuations are somewhat averaged by the large disk. In the end, the wind force was measured and the turbulence level will be compared to variations in the aerodynamic forces generated by a prototype wind turbine. The disk diameter is a third of the total area covered by the rotor. The drag coefficient on the disk is estimated to be 1.2.

An electrical motor (6) was placed at the top of the tower to model the gyroscopic effect. This well-known mechanical force arises when a rotor spinning around a certain axis undergoes a rotation around a different axis. For instance, platform pitch and yaw would lead to gyroscopic forces applied on the tower. These forces are a significant design issue for the blades and the shaft/bearings, but they may also have a contribution to the global response of the floater. The motor was adjusted to spin at the Froude-scaled turbine speed of 2Hz (approximately 12 rpm in prototype scale), and the inertia of the blades was modeled with two weights (7) positioned on an aluminum rod (8).

The model was kept in position in the tank using four soft springs – two of them connected to column 1 which holds the turbine, and one on each of the other columns. The mooring lines were connected at the edges of a 7 x 7 ft square frame placed on the tank floor. This provided a top angle for the mooring lines of approximately 45 deg. This equivalent mooring model provided horizontal stiffness similar to that of the prototype six line catenary mooring system, yielding a 65 second resonant period in surge. However, the prototype mooring design has not been finalized, and the focus of these tests was placed on platform motion. No attempts were made to measure mooring tension or validate mooring dynamics.

A plunger type wave maker is located at one end of the tank and a parabolic wave absorption beach at the other end. A set of 5 large wind fans was assembled to generate the required wind loading on the turbine model, as shown in Figure 4. The effect of the active ballast system was modeled by shifting lead ballast on the model to compensate for the mean wind overturning moment.

A 3-hour long realization of the 100 year waves was generated. The associated wind is 25m/s, which is the maximum wind speed at which the wind turbine is allowed to rotate. Such wave events may occur at the site with wind speed under the cut-off speed due to swells. Most likely, the rotor was parked if such wave conditions arise; however, this conservative design case was generated to establish upper bounds of platform motion. The 100 year wave run was repeated without wind. Additionally, regular waves were run with and without wind to determine Response Amplitude Operators (RAO's).

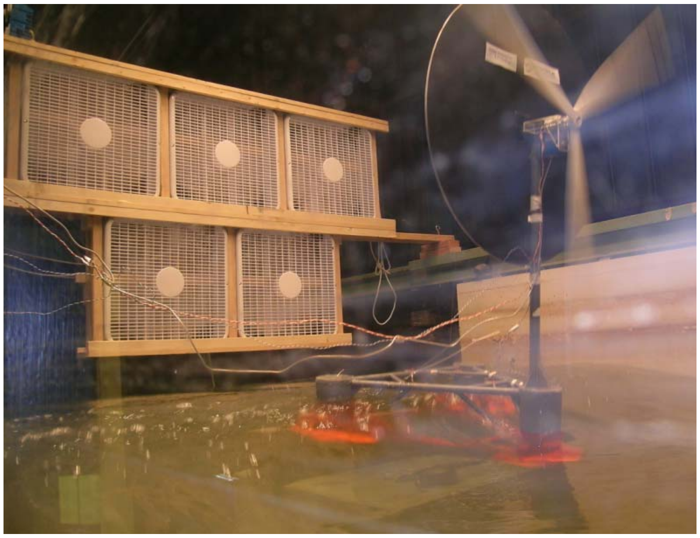


Figure 4: WindFloat model in the 100 year storm

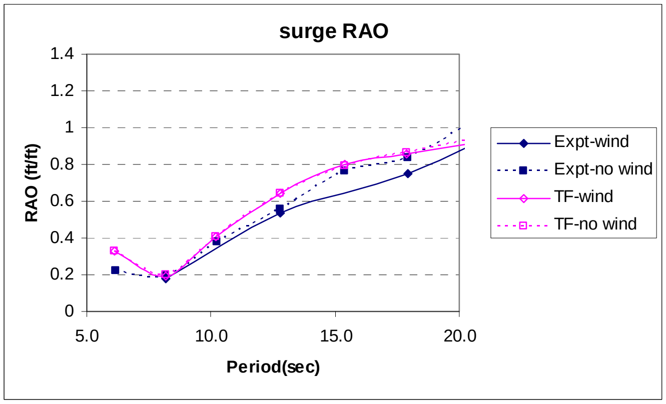
RESULTS

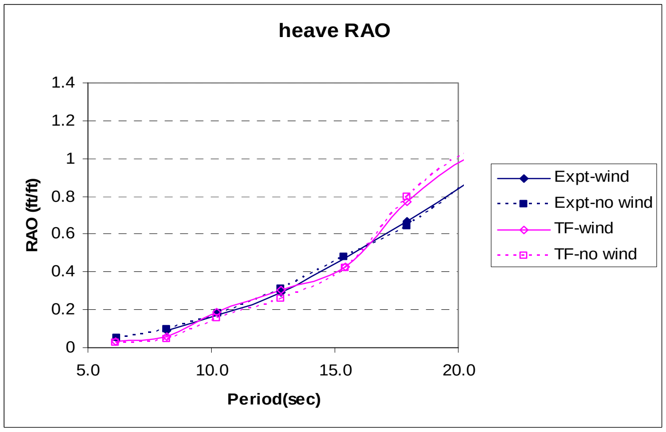
Results of the 100 year storm simulation are summarized in Table 3. Time-series of platform surge, heave and pitch were processed to yield rms, maximum and minimum values. These show a satisfactory agreement between the model test results and numerical simulations performed with TimeFloat. The pitch rms is slightly underpredicted by the software (1.15 deg versus 1.27 deg measured), and the minimum and maximum pitch angles are off by one degree due to some differences in the predicted versus measured wind overturning moment; the platform response is however deemed extremely well behaved, with maximum pitch angle of 5 degrees in a 13.5m Hs sea-state. The maximum crest to trough pitch is 7 degrees with a 21.3 m maximum wave height (crest to trough). Similar responses and trends were observed for all tested platform headings (0 and 90 deg) and for runs with and without wind. The maximum yaw angle measured in the 90 deg runs was under 10 degrees.

Table 3: Numerical and model test results in the 100 year storm with 0 deg wave heading and 25m/s steady wind

Heading	0	Wind	85ft/s	steady
		Surge (ft)	*Heave (ft)*	*Pitch (deg)*
RMS	Model Tests	10.56	6.88	1.27
	TimeFloat	9.18	6.40	1.15
MAX	Model Tests	48.46	18.97	4.87
	TimeFloat	43.51	16.18	5.77
MIN	Model Tests	-22.16	-22.05	-3.87
	TimeFloat	-17.28	-22.61	-2.67

Response Amplitude Operators were computed for wave periods between 6 and 18 seconds. Figure 5 shows the RAO's in surge, heave and pitch for 0 deg wave heading. The presence of wind does not affect surge or sway significantly, but its effects are slightly more pronounced on the pitch RAO's. Although wind speed is constant in all the regular wave runs, it does impact the regular wave response because the wave-induced motions generate a sinusoidal variation of the relative speed between the wind and the disk, which results in an additional periodic force component on the disk leading to a corresponding periodic pitch moment.





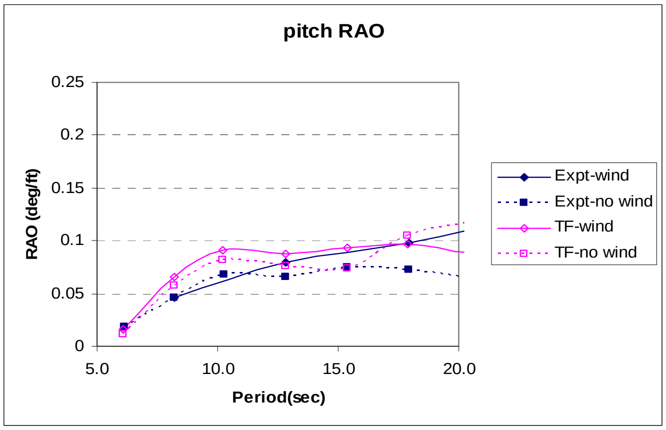


Figure 5: Response Amplitude Operator in Surge, Heave and Pitch at 0 deg with and without wind

Regular wave tests were repeated with 90 deg wave heading to investigate the platform yaw response; i.e. the model orientation was changed by rotating the anchoring frame 90 degrees. There is no yaw for 0 degree wave heading since the platform is port/starboard symmetric; the yaw RAO at 90 degrees is shown in Figure 6. Additional tests were carried out by adding two large triangular vertical plates on each column (named yaw plates) with the bottom edge extending outward to the edge of the heave plate and the side extending from the heave plate to 20 ft below Mean Water Level in prototype scale. The effects of "yaw plates" in reducing first-order yaw were minimal. The irregular wave test showed that the second-order yaw was also not significantly reduced. Overall, the experiment did not point to serious limitations of the numerical modeling ability.

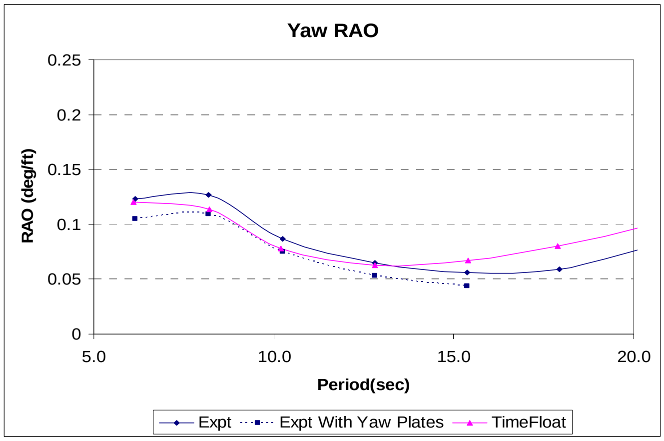


Figure 6: Response Amplitude Operator in yaw at 90 deg without wind

COUPLED AERO-HYDRODYNAMIC MODEL

The forces generated by the wind turbine are reasonably well computed by the modified TimeFloat software, and are correspondingly well modeled experimentally for a steady wind speed. However in reality, the wind speed is constantly changing due to naturally occurring turbulence in the atmosphere. Large wind turbines are equipped with sophisticated control systems generally designed to keep the rotor speed constant at all times using a variable torque generator and a blade pitching mechanism (changing the angle of attack of the blades by rotating them around their local axis). This technique, known as "blade pitching", can have significant effects on floating platforms as observed by Nielsen et al. [12] and by Jonkman [13]. The control system may induce negative damping, which results in resonant oscillations of the platform at its roll or pitch natural period.

In order to assess the effects of blade pitching on the floater, as well as to provide accurate computation of all loads induced by the wind turbine on a moving foundation, a software dedicated to wind turbine design, FAST, was interfaced with TimeFloat to provide a fully coupled aero-hydrodynamic time-domain numerical model of the WindFloat platform with a 5MW wind turbine.

FAST, which stands for "Fatigue, Aerodynamics, Structures, and Turbulence" is an aeroelastic design code for horizontal axis wind turbines developed by the National Renewable Energy Laboratory (NREL). FAST models the wind turbine as a combination of rigid and flexible bodies. The rigid bodies are the earth, nacelle, hub, and optional tip brakes. The flexible bodies include blades, tower, and drive shaft. The model connects these bodies with several DOFs, including tower bending, blade bending, nacelle yaw, rotor teeter, rotor speed, and drive shaft torsional flexibility. FAST uses Kane's method to set up equations of motion, which are solved by numerical integration. The AeroDyn subroutine package developed by Windward Engineering is used to generate aerodynamic forces along the blades.

The FAST and TimeFloat FORTRAN source codes were modified to change TimeFloat into a subroutine called by FAST. Hydrodynamic forces, including wave-exciting forces, viscous forces and mooring forces are computed by TimeFloat and passed to FAST, which solves the coupled turbine-tower problem, and passes platform motion back to TimeFloat.

The FAST model of a utility-scale multimegawatt turbine known as the "NREL offshore 5-MW baseline wind turbine" was developed by Jonkman et al. [14] using publicly available information from turbine manufacturers. This wind turbine is a conventional three-bladed upwind variable-speed variable blade-pitch-to-feather-controlled turbine. A conventional control system was used with a generator-torque controller whose goal is to maximize power capture below the rated operation point and a blade-pitch controller designed to regulate rotor speed above the rated operation point.

The coupled FAST-TimeFloat model was run using the validated WindFloat hydrodynamic model described in previous sections. Sample results are provided for a 4m significant sea-state with 12 seconds peak period and a 12m/s steady wind. Waves and wind are at 0 degree heading, along the symmetry axis of the WindFloat. A Jonswap wave spectrum is assumed with peakness factor γ=2.4. No atmospheric turbulence is assumed in this simulation.

Figure 7 shows sample time-series of the platform roll, pitch and yaw over a five minutes duration after the initial transients generated at the beginning of the numerical simulation have disappeared. A slight asymmetry is present due to the rotation of the rotor in one direction, generating a small mean roll (~1 deg) and yaw (~2 deg) component. A background platform pitch oscillation of approximately +/-2 degrees is caused by the blade pitch controller, which excites the platform at its pitch resonant period around 30 seconds. Superposed to the resonant pitch cycles are wave-induced pitch oscillations, which result in slight changes between resonant cycles, but are overall a small contribution to the platform pitch in this sea-state.

In Figure 8, time-series of the base of the tower are shown. Wave-induced surge is clearly visible in this 4m irregular wave sea-state. Mean surge is primarily driven by mean aerodynamic loads on the turbine. The platform pitch oscillation results in vertical movement of the tower base at the same period as the pitch cycles.

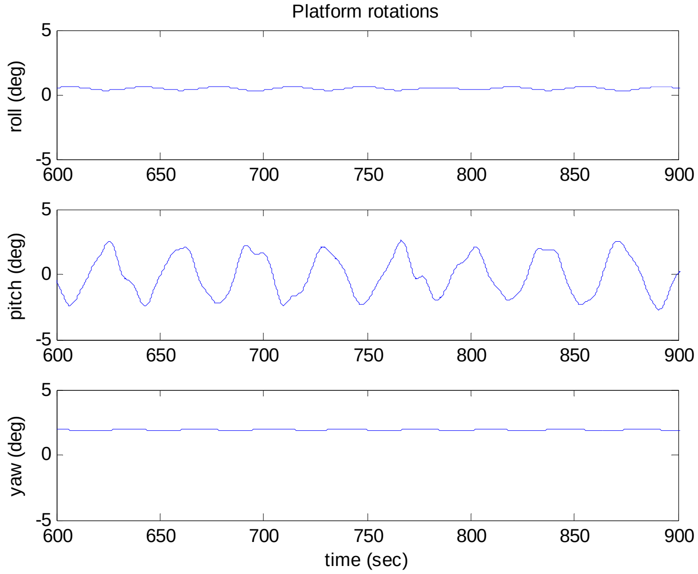


Figure 7: WindFloat rotations in 4 m seas with 12m/s wind

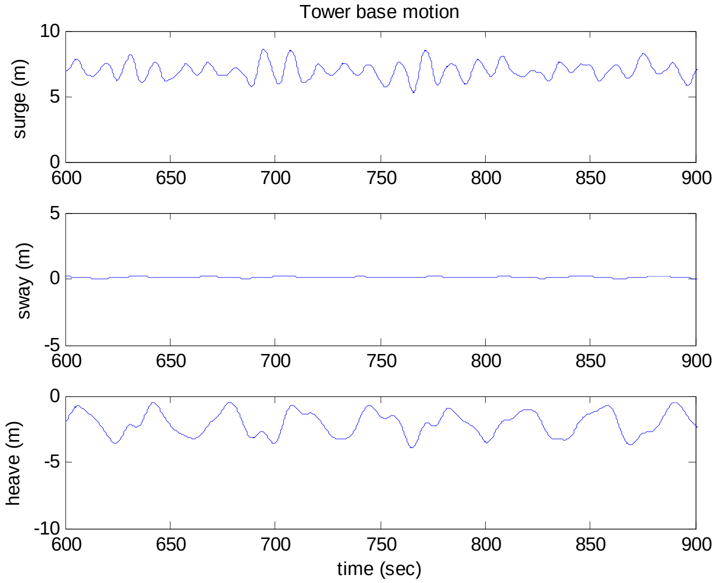


Figure 8: Tower base motion in 4 m seas with 12m/s wind

Figure 9 presents the blade pitch angle time-series (at the bottom) and power out-take (at the top). The blade pitch controller locks into the platform pitch resonance with 30 seconds cycling of the blades. A drop in produced power occurs for approximately two seconds at each cycle when the relative speed between the nacelle and incoming wind drops below the threshold for maximum power output. This does not have a large impact on mean produced power, which is 4.95MW on average, but would require filtering. Further investigations of the control system will be required to eliminate this resonant response in order to maximize power production, and minimize fatigue loading of all components and systems.

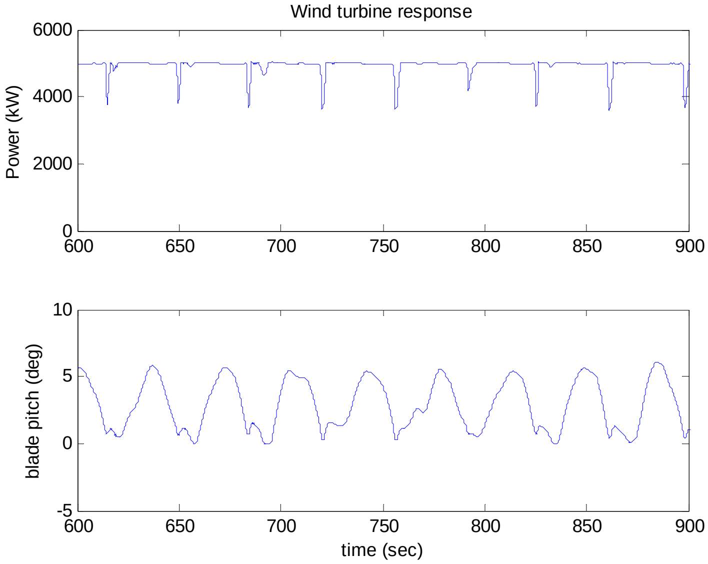


Figure 9: Power outtake and blade pitch in 4 m seas with 12m/s wind

CONCLUSION

This paper discusses the hydrodynamic analysis of the WindFloat, a floating platform for support of large offshore wind turbines. Numerical analysis was first carried out with simplified models of the wind turbine forces. This work was done with a fully coupled time-domain algorithm, which accounts for diffraction-radiation effects, as well as viscous forces and the influence of the mooring. Model tests were performed to validate the predictive ability of the numerical hydrodynamic algorithm. This experimental work consisted of generating wave loads in a wave tank facility, as well as wind loads using fans and a drag disk placed on the model, as well as a rotor to model gyroscopic effects.

A coupled aeroelastic-hydrodynamic model was then implemented to provide better resolution of wind turbine loads and take into account the effects of the turbine control system. For this work, the validated hydrodynamic model discussed above was interfaced with FAST software developed by the NREL for design of wind turbines. It was shown that interactions between the wind turbine control system and the platform generate small rotational oscillations with long periods (~30 seconds), which, in some cases, could result in slightly reduced power output. Further work will be carried out to improve the turbine control system, and assess the effects of coupled aeroelastic-hydrodynamic loads on the WindFloat components.

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