Aerodynamic Simulation of the MARINTEK 
Braceless Semisubmersible Wave Tank Tests

Gordon Stewart and Michael Muskulus
Department of Civil and Transport Engineering, NTNU, Høgskoleringen 7A, 7491 Trondheim, 
Norway
E-mail: gordon.stewart@ntnu.no

Abstract. Model scale experiments of floating offshore wind turbines are important for 
both platform design for the industry as well as numerical model validation for the research 
community. An important consideration in the wave tank testing of offshore wind turbines 
are scaling effects, especially the tension between accurate scaling of both hydrodynamic and 
aerodynamic forces. The recent MARINTEK braceless semisubmersible wave tank experiment 
utilizes a novel aerodynamic force actuator to decouple the scaling of the aerodynamic forces. 
This actuator consists of an array of motors that pull on cables to provide aerodynamic forces 
that are calculated by a blade-element momentum code in real time as the experiment is 
conducted. This type of system has the advantage of supplying realistically scaled aerodynamic 
forces that include dynamic forces from platform motion, but does not provide the insights into 
the accuracy of the aerodynamic models that an actual model-scale rotor could provide. The 
modeling of this system presents an interesting challenge, as there are two ways to simulate the 
aerodynamics; either by using the turbulent wind fields as inputs to the aerodynamic model 
of the design code, or by surpassing the aerodynamic model and using the forces applied to 
the experimental turbine as direct inputs to the simulation. This paper investigates the best 
practices of modeling this type of novel aerodynamic actuator using a modified wind turbine 
simulation tool, and demonstrates that bypassing the dynamic aerodynamics solver of design 
 codes can lead to erroneous results.

1. Introduction
The offshore wind energy resource worldwide is one of the largest renewable energy sources in 
terms of total potential energy. However, much of this resource is located over deep water, 
so floating offshore wind turbines are being developed that have the potential to economically 
capture this energy. Floating wind turbines have added benefits, as the ability of being towed out 
to the energy production site allows for assembly in port, and the potential to be located farther 
from shore to reduce visibility impacts. However, for useful design work to be possible, accurate 
computer modeling tools are essential. As full-scale prototypes are scarce, expensive, and often 
proprietary, many research institutions are conducting small-scale experiments in wave tanks 
to provide data both for platform design and modeling tool validation. One difficulty of small-

scale experiments of floating wind turbines is the scaling of forces between the hydrodynamics 
and the aerodynamics. A variety of methods have been used to modify the rotor to scale the 
aerodynamic forces correctly, including using a simple actuator disk [1], or modifying the chord 
and other blade properties of the rotor [2, 3, 4]. Recently, there have been experiments conducted 
that utilize an actuator in place of a rotor to provide realistic forces calculated in real time by
Figure 1. Image of the MARINTEK braceless semisubmersible (photo courtesy of MARINTEK.

aerodynamic codes during an experiment. These devices may take the form of a ducted fan that can be controlled to provide thrust forces [5, 4], or what is used in the recent series of experiments at MARINTEK, a frame with wires tensioned by small motors that provide the aerodynamic forces [6, 7]. A picture of the experimental setup can be seen in figure 1. The advantage of this type of actuator is that unlike a ducted fan, which can only provide force in the thrust direction, the tensioned frame can provide forces in five directions; all three rotational directions, surge, and sway; the MARINTEK actuator does not provide forces in the vertical heave direction, as aerodynamic forces in this direction were found to be insignificant.

The calculation of the aerodynamic forces is done in real time during the experiment, using both a given turbulent or steady simulated wind input and the location and velocity of the platform. This creates both correctly scaled wind-induced aerodynamic forces as well as forces due to platform motion and rotor interaction, including aerodynamic damping forces [7]. The MARINTEK experiment uses the aerodynamic solver from the National Renewable Energy Laboratory’s (NREL) design code suite, called AeroDyn, with some modifications for the integration into the experiment. In this way, all of the forces that are applied to the nacelle are known. To model this system in simulation, there are two options for the aerodynamics. Since the actual aerodynamic forces are known, the force time series could be directly applied to the simulation, bypassing the built-in aerodynamic solver of the code, or the wind speed time series from the experiment could be used as the simulation input, and the internal aerodynamic solver would calculate forces based on this wind input and the dynamics of the simulation. The first method has the potential to be inaccurate because the dynamic feedback forces from platform motion on the aerodynamic are uncoupled from the actual platform motion in the simulation, as those forces are calculated from the motion of the experiment. This paper will investigate the consequences of bypassing the aerodynamic calculation in this manner.
2. Methods
As the data from the MARINTEK experiment has not been released at the writing of this paper, simulation will be used to replicate the experiment and actuator for this work. The National Renewable Energy Laboratory’s wind turbine design software FAST will be used with the spar buoy model from the Offshore Code Comparison Collaboration project (OC3) [8]. FAST is a medium-fidelity simulation software that uses blade-element momentum theory for the aerodynamics, and includes hydrodynamic, structural, and control modules. The spar buoy model features a controller with modified pitch control gains to reduce the effect of surge instabilities.

To replicate the novel aerodynamic actuator used in the experiment, an addition to the FAST software had to be written that allows the aerodynamics calculation to be bypassed, by applying the sum of all aerodynamic and inertial forces from the blades directly onto the hub. In this way, a reference simulation could be run with the standard version of FAST, and the aerodynamics loads from this baseline simulation could be applied to a second simulation. Parameters and inputs to this second simulation could be modified to replicate experimental uncertainty. In this way, the baseline simulation represents the experiment, and the simulation that uses the predefined aerodynamic loads represents the simulation of the experiment. To model the uncertainty in the platform modeling of an experiment, the hydrodynamic drag coefficient was modified. The drag coefficient of the platform is chosen as an example of a hydrodynamic parameter that could be different between the simulation model and the experiment, any of the potential flow parameters could have been modified with a similar conclusion. A series of simulations are then run, using identical wind and wave inputs, but bypassing the aerodynamic calculation for one set of simulations.

3. Results and Discussion
A range of wind speed and wave heights are simulated, similar to the operational design load cases in the IEC standard. The wind and wave inputs used in the simulations can be seen in table 1. These significant wave height and peak spectral period values were taken from a study of the NOAA floating data buoys, and correspond to the expected value for the specified wind speed at a representative site from the east coast of the United States [9].

| Mean Wind Speed (m/s) | 4  | 6  | 8  | 10 | 12 | 14 | 16 | 18 | 20 | 22 | 24 |
|-----------------------|----|----|----|----|----|----|----|----|----|----|----|
| Significant Wave Height (m) | 1.1 | 1.2 | 1.3 | 1.5 | 1.8 | 2.2 | 2.6 | 3.1 | 3.6 | 4.0 | 4.5 |
| Peak Spectral Period (s) | 8.5 | 8.3 | 8.0 | 7.7 | 7.4 | 7.5 | 7.6 | 8.0 | 8.5 | 9.0 | 9.4 |

A baseline simulation of the OC3 spar buoy was run for each of these wind speeds, using the corresponding wave parameters. Next, these 11 simulations were repeated with the same wind and wave inputs (keeping the random seeds, and thus the turbulence and random waves the same), but with the platform hydrodynamic drag reduced from 0.6 to 0.5. Finally, a third set of simulations was run using the lower $C_d$ value, but bypassing the aerodynamic calculation and using the aerodynamic forces directly from the baseline simulation with the higher $C_d$ value. Figures 2 through 3 compare timeseries from various outputs for one windspeed (10 m/s). First, in figures 2 and 3, the platform surge displacement (translational movement of the platform in the direction of the wind) is plotted.

In figure 2, the plots show the surge output for the two simulations that used the baseline aerodynamic calculation but two different $C_d$ values. These outputs are very close to each other,
but slightly more variance can be seen in the output from the lower $C_d$ simulation due to the lower damping. Figure 3, which compares the baseline simulation with the simulation with both the predefined aerodynamic forces and the lower $C_d$, shows much more deviation of the two outputs. As the platform surges, the apparent wind speed seen by the rotor is increased or decreased by the surge velocity, which changes the rotor thrust magnitude, which in turn feeds back to the surge velocity. By predefining the aerodynamic load, this feedback is not preserved, and the small difference in the surge displacement early in the simulation lead to large differences later in the simulation.

Figures 4 and 5 repeat the comparisons made in figures 2 and 3, but look at the platform pitch angle (rotational displacement in the wind direction) instead. Similar trends to the surge displacement figures can be seen in the platform pitch, with a large divergence for the simulation
with the predefined aerodynamic loads. Interestingly, the phasing of the predefined rotor thrust has resulted in a platform pitch that has a mean pitch angle that actually leans into the wind (which can be seen as a negative mean pitch angle in figure 5), which is a good indicator of the potential instability and erroneous results that using this method of aerodynamic simulation can produce.

Figures 6 and 7 show comparisons of the tower base bending moment. As this output is correlated with platform pitch (due to inertial loading), the trends in bending moment resemble the platform pitch results. The mean bending moment in figure 7 has also become negative for the predefined aerodynamics simulation, similar to figure 5.

To look at trends for the entire operational wind envelope for this platform, figures 8 through 11 show the standard deviation of various outputs plotted as a function of wind speed. Note that the wave height and peak spectral period also vary as wind speed varies (see table 1). In figures 8 and 9 the standard deviation of the surge displacement is compared for the baseline aerodynamic calculation for the two $C_d$ values (figure 8), and for the predefined aerodynamics (figure 9). The difference from the baseline in the standard deviation of surge is larger for the predefined loads, especially for the higher wind speeds (and thus higher wave hights).

In figures 10 and 11, the standard deviation of fore-aft tower base bending moment as a function of wind speed is compared. Here there is a negligible difference for the baseline case when varying the $C_d$ (figure 10), but the standard deviation of the bending moment increases by as much as 25% when using predefined aerodynamic loads (figure 11).

4. Conclusions and Future Work
The simulations presented in this paper show that using a predefined aerodynamic force time series can lead to large differences in both loads and platform motions when comparing simulations to experiments. These errors are due to the lack of realistic feedback between the platform motion and the aerodynamics captured in the simulations with predefined aerodynamic loads. However, as the data from the experiment are not available at the time of this writing, more investigation is needed using the data to confirm this conclusion. It is likely that this method is reasonable to use for simpler cases, such as regular waves with steady wind, as the phasing of the aerodynamic forces can be carefully matched with the wave loading. An upcoming
paper will use the experimental data to test the conclusion of the simulation work presented in this paper, as well as allowing the method of aerodynamic modeling that uses only the wind time series as an input to be tested.

Acknowledgements
The research leading to these results has received funding from the IRPWind program, part of the European Union’s Seventh Framework Program (FP7/2007-2013) under grant agreement no. 609795.

References
[1] Roddier D, Cermelli C, Aubault A and Weinstein A 2010 Journal of Renewable and Sustainable Energy 2
[2] Martin H R 2011 Development of a scale model wind turbine for testing of offshore floating wind turbine systems Ph.D. thesis Maine Maritime Academy

[3] Coulling A J, Goupee A J, Robertson A N, Jonkman J M and Dagher H J 2013 Journal of Renewable and Sustainable Energy 5

[4] Sandner F, Amann F, Azcona J, Munduate X, Bottasso C L, Campagnolo F and Robertson A 2015 EERA Deepwind

[5] Azcona J, Bouchotrouch F, González M, Garciandiá J, Munduate X, Kelberlau F and Nygaard T A 2014 Journal of Physics: Conference Series 524

[6] Kvittem M I, Bachynski E E and Moan T 2012 Energy Procedia 24 351–362

[7] Tande J O G, Kvamsdal T, Muskulus M, Bachynski E E, Chabaud V and Sauder T 2015 Energy Procedia 80 2 – 12

[8] Jonkman J and Musial W 2010 Offshore Code Comparison Collaboration (OC3) for IEA Task 23 Offshore Wind Technology and Deployment Tech. Rep. December National Renewable Energy Laboratory

[9] Stewart G M, Robertson A, Jonkman J and Lackner M A 2016 Wind Energy 19 1151–1159