# Uncertainty Analysis of OC5-DeepCwind Floating Semisubmersible Offshore Wind Test Campaign

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# Uncertainty Analysis of OC5-DeepCwind Floating Semisubmersible Offshore Wind Test Campaign

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## ABSTRACT

This paper examines how to assess the uncertainty levels for test measurements of the Offshore Code Comparison, Continued, with Correlation (OC5)-DeepCwind floating offshore wind system, examined within the OC5 project. The goal of the OC5 project was to validate the accuracy of ultimate and fatigue load estimates from a numerical model of the floating semisubmersible using data measured during scaled tank testing of the system under wind and wave loading. The examination of uncertainty was done after the test, and it was found that the limited amount of data available did not allow for an acceptable uncertainty assessment. Therefore, this paper instead *qualitatively* examines the sources of uncertainty associated with this test to start a discussion of how to assess uncertainty for these types of experiments and to summarize what should be done during future testing to acquire the information needed for a proper uncertainty assessment. Foremost, future validation campaigns should initiate numerical modeling before testing to guide the test campaign, which should include a rigorous assessment of uncertainty, and perform validation during testing to ensure that the tests address all of the validation needs.

KEY WORDS: Semisubmersible; floating offshore wind; model validation; uncertainty analysis; OC5

## INTRODUCTION

Several companies are undertaking scaled model testing of floating wind turbines. There are two main objectives for this testing: to understand the global behavior of the system and assess whether simulation models can be used to predict their behavior. For the latter of these two objectives especially, it is important to understand the uncertainty associated with the test results to be able to fully assess the capability of the simulation tools to accurately represent the behavior of the system. However, to date, there has not been a concerted effort by those performing offshore wind tank tests to assess the uncertainty in the test campaigns.

Floating wind turbines are complex structures that include many different degrees of freedom, variables, and excitation from both wind and waves, making the assessment of uncertainty in a test campaign difficult. In addition, it is important to consider many different conditions, requiring a large number of experiments to be run, including numerous repeat experiments. The variables can be strongly or weakly coupled, meaning that error sources can strongly influence each other. On the hydrodynamic side, offshore wind tests are similar to those done for seakeeping of offshore structures. Uncertainty quantification in the seakeeping field is also not well developed, and is only recently getting attention (see Kim and Hermansky, 2014, for a review). Uncertainty quantification, however, is essential and needs be pursued. This paper takes some first steps at defining the methods that need to be followed to perform an uncertainty assessment for a floating wind test campaign in a wave tank environment, and will draw from many of the methods and suggestions from the work being done in seakeeping tests.

Several standards and guidelines are available that describe methods for assessing uncertainty in test campaigns. The International Standards Organization (ISO, 1993) and American Society of Mechanical Engineers (ASME, 2013) have developed standards that can be applied to any type of test. The International Towing Tank Conference (ITTC) has developed procedures and guidelines that provide more focused recommendations for assessing uncertainty in experimental hydrodynamics (ITTC 2008a), seakeeping experiments (ITTC 2008b), and for offshore wind turbines (ITTC, 2014).

Those who have started to address uncertainty for seakeeping tests have based their work largely on the recommendations presented in (Yum, 1993). This publication is in Korean, but Kim (2014) provides a good summary of the methods presented by Yum, as well as a review of the work being done by others in this area. Seakeeping tests are largely focused on estimating uncertainty for the motion response of the system (e.g., Irvine et al., 2008), the resistance/loads (e.g., Longo and Stern, 2005), or both (e.g., Hidaris et al., 2014 and Qui et al., 2014). Qui, et al. provides a good summary of potential uncertainties for a floating semisubmersible, focusing on both the motion of the system and the tension in the mooring lines. Soares (1991) has shown there is large scatter in the measured loads for ships, especially as the wave height increases. These references are useful in seeing the procedures applied for determining the uncertainty associated with wave excitation and model response, as well as giving some example uncertainty values for different model test campaigns.

Of course, the inclusion of a wind turbine and wind excitation for offshore wind model tests creates a greater level of complexity and uncertainty. Experimental testing of turbines in a wind tunnel can have a variety of goals, including assessment of the airflow across the blades, aerodynamic performance, loads, or wake development and propagation. In the context of this paper, we are focused on the thrust and torque loads that the turbine will experience during operation, and how they will affect the loads measured in the tower. The complex geometry of the turbine blades and the sensitivity of the turbine loading to that geometry will create the potential for significant uncertainty in the measured loads from the definition of the turbine model, as well as the turbine orientation during testing. In addition, floating wind device testing is done in a wave basin where there is much less control over the wind conditions, creating even more uncertainty. Combining these uncertainties with those for floating system motion due to waves leads to a very complicated system with strong interdependency between uncertainty sources.

This paper examines the sources of uncertainty associated with the measured loads for a scaled, floating offshore wind test performed in a wave basin within the OC5 project (which is focused on validating offshore wind modeling tools by comparing simulated responses of select offshore wind systems to physical test data). The original goal of the investigation was to calculate the level of uncertainty in the measured loads so that they could be used to validate a model of the floating OC5-DeepCwind semisubmersible system. However, because of a lack of available information to do an accurate assessment, this paper instead will *qualitatively* examine the sources of uncertainty associated with this test to start a discussion of how to assess uncertainty for these types of experiments and to summarize what should be done during future testing to acquire the information needed for a proper uncertainty assessment. This paper does not focus on potential sources of uncertainty in the numerical models themselves, but focuses on the uncertainty in the tests. Numerical models may be used in a limited manner to help propagate uncertainty from input, or model, to output.

The remainder of this paper is organized as follows. The first section provides a general overview of uncertainty analysis, the second section looks at the potential sources of uncertainty in the OC5 test campaign, and the last section draws conclusions on what needs to be considered to perform an uncertainty analysis for future floating wind wave basin test campaigns.

## UNCERTAINTY OVERVIEW

Validation is the process of assessing the accuracy of a model in representing measured, real-world physical behavior. To compare measured data to simulated data from a numerical model, a set of metrics are needed that represent the important physical quantities of interest to be validated. The simulated value of the metric will never exactly match the measured one, so a range is needed on the measured value within which the simulated value would be considered acceptable. This data range is based on how certain the measured value is.

There are many sources of error that will contribute to the uncertainty of a measurement, and an estimate must be made based on the knowledge available for that test. Ideally, uncertainty levels are measured before, during, and after the test, to help guide the test methods. However, it is quite often the case that an uncertainty assessment is only performed after the test is done, and many times with very little information on the possible sources of error.

### Types of Uncertainty

Error is the difference between a measurement and the true value. Error, however, cannot be calculated because the true value is not known. Despite this, the uncertainty of the measurement can be evaluated. Uncertainty is an estimate of the limits of a response error with an associated level of confidence.

There are two different approaches to describing uncertainty: an International Organization for Standardization (ISO)-based approach (ISO, 1993) or an American Society of Mechanical Engineers (ASME)-based approach (ASME, 2013). ISO breaks uncertainty into two categories: Type A and Type B, based on how the uncertainty is evaluated. Type A uncertainty is random uncertainty that can be evaluated by statistical methods through repeated measurements. Type B uncertainty cannot be directly measured, but is assessed by experience or general knowledge. ASME also assigns uncertainty to two categories, but with different types: systematic and random. Systematic error results in an offset or bias in the solution. It should remain constant throughout a test, or be proportional to the test conditions. Random error, on the other hand, creates scatter in the results (also called the precision). Regardless of how the uncertainty is categorized, both the ISO and ASME methods result in the same summed value for overall uncertainty. This paper will follow the ASME approach, because that is the one being adopted within the U.S. Department of Energy's Atmosphere to Electrons project that is connected to this work.

Random and systematic error can come from a number of different sources. Attempting to identify all the elemental sources of error requires a thorough understanding of the test objectives and test process.

### Uncertainty Analysis Steps

The first step in an uncertainty analysis is defining the quantities of interest (QOI) to be evaluated. These are the measurements that are used to assess the success of a validation campaign, such as the measured shear force at the base of the wind turbine tower for floating offshore wind validation. A metric to evaluate this measurement may be desired, such as the maximum shear force, or the fatigue associated with that force. Uncertainty associated with the evaluation of the metric from the measurement will need to be considered as well.

Once the response QOI is identified, repeat tests are performed to determine the variability of the value to the same conditions (at least 10 repeat tests are recommended). This assessment may need to be done for multiple conditions to understand if the level of variability changes for different environmental or operational conditions. For instance, there may be more variation in measured loads for larger wave heights. Also, a wave-only test will have different uncertainty than one combined with wind, and this uncertainty level needs to be calculated separately if it is of interest. This process should assess the uncertainty associated with all random components of the experiment, including the excitation source, model, testing environment, and measurement sensors. There is no need to propagate random uncertainty from one source to another if a measurement of the QOI is available and repeat tests are performed. The random standard uncertainty, $s_{\bar{x}}$, is defined as the standard deviation , $s_x$, of the QOI ($x$) across the repeated tests, divided by the square root of the number of observations ($N$):

$$s_{\bar{x}} = \frac{s_x}{\sqrt{N}} \tag{1}$$

The next step is to determine any systematic biases in the experiment. This includes using expert judgment to determine potential biases in manufacturing specifications, unmeasured influences, and so on. Manufacturing literature should be consulted to determine bias limits of sensor hardware being used. Also, data from calibration and other reports that are traceable to National Metrology Institutes can be used. The systematic standard uncertainty, $b_R$, is the root-sum-square summation of all systematic uncertainty sources, $b_i$:

$$b_R = \left[ \sum_{i=1}^{N} (b_i)^2 \right]^{1/2} \tag{2}$$

If the uncertainty of a specific QOI cannot be assessed directly, it can be determined by combining and propagating each of the elemental uncertainties that contribute to it:

$$s_{\overline{X},R}^2 = \sum_{i=1}^{N} \theta_i^2 s_{\overline{X},i}^2 \tag{3}$$

$$b_R^2 = \sum_{i=1}^{N} \theta_i^2 b_i^2 + 2\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \theta_i \theta_j b_{ij} \tag{4}$$

where $s_{\overline{x},R}$ is the total random uncertainty from multiple sources and $\theta_i = \partial x / \partial X_i$ are the sensitivity coefficients of individual variables, $X_i$. Typically, the sensitivity coefficients are calculated analytically, but if that is not possible, numerical models of the system can be used to estimate them.

Once all the random and systematic sources of error are identified, the associated uncertainties are combined to determine the total combined uncertainty, $u_C$:

$$u_C = \sqrt{(b_R)^2 + (s_{\overline{x},R})^2} \tag{5}$$

Finally, confidence intervals are typically assigned to this uncertainty to define the expanded uncertainty. When the expected distribution of the measured data is approximately normal and the effective degrees of freedom (DOF) are large, confidence intervals of 95% to 99% are typically used, which results in a coverage factor (*k*) of approximately 2 to be applied to the uncertainty bound (Kim and Hermansky, 2014). In the end, a representation of a quantity of interest, *x*, is given as:

$$X = x \pm U \tag{6}$$

where $X$ is the best available estimate of the measurement, $U$ is the expanded uncertainty ($U = k*u_C$), and $x$-$U$ and $x$+$U$ define the uncertainty bounds that would include a large portion of the possible occurrences of the QOI.

## Uncertainty Sources

### *Measurement uncertainty*

Measurement uncertainty comes from errors in the instruments used to measure a quantity, and can be either random or systematic. Calibration is performed to eliminate known systematic errors so that the measurement uncertainty is reduced to an acceptable level. For offshore wind basin testing, measurement uncertainty is associated with the instruments used to measure the environmental excitation, as well as the response (motion and loads). Manufacturer specifications can be used to assess the level of uncertainty in the sensors, which can originate from nonlinearity, hysteresis, nonrepeatability, zero offset drift, temperature coefficient, and resolution (Kim and Hermansky, 2014). In addition, error in the sensors can come from incorrect mounting, including a loose connection, incorrect positioning, or misalignment. As an example, if the manufacturer specifications state that a motion sensor has a dynamic accuracy of the roll/pitch angles of 2° root mean square, this can be interpreted as a 2° standard uncertainty (Kim and Hermansky, 2014). However, manufacturer specifications may only give error sources, which may then be propagated to obtain the standard uncertainty.

Fig. 1. Instrumented OC5-DeepCwind model in the MARIN offshore basin (Helder and Pietersma, 2013)

The data acquisition system and any data processing performed can also add additional uncertainty to the data. For the data acquisition, this can include the influence of temperature, humidity, and noise. Uncertainty sources in data processing originate from processes such as integration, differentiation, and filtering. Estimation of statistics, such as the significant wave height or ultimate and fatigue loads, are other examples.

For high-quality instrumentation, the random measurement uncertainty is usually quite small compared to any systematic uncertainty (ITTC, 2008).

### *Model uncertainty*

In addition to the uncertainty associated with the measurements, the test article itself may have some uncertainty, which can be created by imperfections or simplifications/idealizations in the physical model description. When considering the global motions and tower loads of a floating wind turbine (the focus of the OC5 project), some of the important model properties will be the system center of mass (CM), geometry at the waterplane, mass distribution, and stiffness of the tower (as well as the tower connection to the turbine and platform). The turbine itself will also be a source of considerable uncertainty, the most significant sources being the blade geometry, mass distribution, and stiffness.

Uncertainty may also arise from unmodeled interactions between the test instrumentation and system, or between the system and test facility. Unless there are known issues that must be directly assessed, model uncertainty is typically determined from past experience. Some example values for seakeeping tests are provided in ITTC (2008a).

***Environmental uncertainty***

Uncertainties associated with the wind and waves in a basin can come from multiple sources. First, there are the limitations of the generation equipment and basin to produce accurate and repeatable properties. Second, environmental uncertainty can come from natural randomness of wind and wave intensity over time. Or, it can be similar to model uncertainty in that the method used to measure the environmental conditions does not capture all of its characteristics, resulting in an idealized representation. For example, if measurements for the wind speed are only made at one point, that measurement would not capture the spatial variability of the wind. Even measurements made at multiple points across the rotor plane would not capture the three-dimensional variations that might exist, which can be influential for a floating wind system that has significant movement in all six DOFs. For waves, there could also be spatial variability in the tank, but there is also uncertainty related to the wave properties if only the elevation is measured and not the depth-dependent kinematics. Limited measurements could miss the influences of wave spreading, reflected waves, wind/wave interaction, variation of wind speed and turbulence spatially, and wind blockage effects. The random uncertainty of wind/waves can be evaluated from repeated observations.

## UNCERTAINTY ASSESSMENT FOR OC5 FLOATING WIND TEST

Using the uncertainty concepts presented in the last section, this section will apply that knowledge to estimate the uncertainty associated with various components of the OC5-DeepCwind floating semisubmersible system test. This was a validation campaign performed under International Energy Agency Wind Task 30, with the goal of validating coupled modeling tools used for designing offshore wind systems (Robertson et al., 2017). This project exemplifies the work being done by different institutes in assessing the ability of modeling tools to accurately represent the physical behavior of floating wind systems, and the findings and recommendations from this example can hopefully be used to inform future test campaigns in this field.

### Test Overview

The OC5-DeepCwind system is a 1/50th-scale floating semisubmersible with a flexible tower and performance-scaled turbine (see Fig. 1). The associated test campaign involved a number of tests ranging from simple free-decay tests to complex operating conditions with irregular sea states and dynamic winds. Recorded data from the floating wind turbine model included rotor torque and position, tower-top and tower-base forces and moments, mooring line tensions, six DOF platform motions, and accelerations at key locations on the nacelle, tower, and platform.

The validation of the model within the OC5 project was focused on the ultimate and fatigue loads of the structure at three locations: the tower top, tower bottom, and upwind mooring line. The test cases considered in this validation exercise are summarized in Table 1 and consisted of wave-only and combined wind/wave test cases. (Numerical values are reported in this paper at full scale.) Unfortunately, there were no repeat tests done for this test campaign. Prior to validation, free-decay and additional wind-only and wave-only test cases were used to calibrate the model.

Table 1. Description of validation test (load) cases

| Load Case | Description | Rotor rpm | Blade Pitch (deg) | Wave Condition | Wind Condition (m/s) | Sim. Time (min) |
|---|---|---|---|---|---|---|
| 3.3 | Operational Wave | 0 | 90 | $H_s$ = 7.1 m,<br>$T_p$ = 12.1 s,<br>$\gamma$=2.2, | N/A | 176 |
| 3.4 | Design Wave | 0 | 90 | $H_s$ = 10.5 m,<br>$T_p$ = 14.3 s,<br>$\gamma$=3.0, | N/A | 180 |
| 3.5 | White Noise Wave | 0 | 90 | White noise:<br>$H_s$ = 10.5 m,<br>$T_{range}$ =6-26 s | N/A | 180 |
| 4.1 | Operational Wave, Steady Wind 1 | 12.1 | 1.2 | $H_s$ = 7.1 m,<br>$T_p$ = 12.1 s,<br>$\gamma$=2.2, | $V_{hub,x}$= 12.91 ,<br>$V_{hub,z}$= -0.343<br>$\sigma_x$ = 0.5456,<br>$\sigma_z$ = 0.2376 | 180 |
| 4.2 | Operational Wave, Steady Wind 2 | 12.1 | 15.0 | $H_s$ = 7.1 m,<br>$T_p$ = 12.1 s,<br>$\gamma$=2.2, | $V_{hub,x}$ = 21.19,<br>$V_{hub,z}$= -0.600<br>$\sigma_x$ = 0.9630,<br>$\sigma_z$= 0.4327 | 180 |
| 4.3 | Operational Wave, Dynamic Wind 1 | 12.1 | 1.2 | $H_s$ = 7.1 m,<br>$T_p$ = 12.1 s,<br>$\gamma$=2.2, | NPD spectrum,<br>$\mu$ = 13.05 | 180 |
| 4.4 | Design Wave, Steady Wind 1 | 12.1 | 1.2 | $H_s$ = 10.5 m,<br>$T_p$ = 14.3 s,<br>$\gamma$=3.0, | $V_{hub,x}$= 12.91 ,<br>$V_{hub,z}$= -0.343<br>$\sigma_x$ = 0.5456,<br>$\sigma_z$ = 0.2376 | 180 |
| 4.5 | White Noise Wave, Steady Wind 1 | 12.1 | 1.2 | White noise:<br>$H_s$ = 10.5 m,<br>$T_{range}$ = 6-26 s | $V_{hub,x}$= 12.91 ,<br>$V_{hub,z}$= -0.343<br>$\sigma_x$ = 0.5456,<br>$\sigma_z$ = 0.2376 | 180 |

### Uncertainty Assessment

Ideally, the random uncertainty of the QOIs would be assessed by calculating the standard deviation of the measured value across multiple repeat tests with the same conditions. And this assessment would be performed for different conditions, say a wind-only case, wave-only case, and combined wind/wave cases at different excitation levels. However, we do not have access to repeat tests for this test campaign. Therefore, the random uncertainties must instead be estimated from the elemental components that contribute to the load response (QOI), and combine and propagate them to determine the load response uncertainty. This estimation includes the random uncertainty associated with the excitation (wind/waves), the model properties, and the measurement sensors, and will be examined in the following subsections.

The systematic uncertainty of the load measurements cannot typically be directly assessed, but instead needs to be determined by also considering the systematic error of each of the elements that contributes to the system response, combining these uncertainties, and propagating them to the load measurement. An alternative approach is to eliminate the influence of systematic uncertainty by examining the change in a QOI between two conditions rather than looking at its absolute value. If there are influences that create a bias in the measurement that does not change with a change in condition, this bias would be eliminated by comparing the QOI of two different states. The following subsections will review potential sources of systematic uncertainties. However, uncertainty levels will be difficult to assess, and so the recommendation is to try to understand or eliminate these influences as much as possible in future test campaigns.

***Measurement uncertainty***

The Maritime Research Institute Netherlands (MARIN) provided an estimate of the uncertainties associated with the measurement equipment used during the test, which can be found in the Appendix. The information is presented as a single value and is assumed to be the precision of the instrumentation, which would be represented as random uncertainty. No systematic uncertainties are therefore reported. However, calibration of the instruments should eliminate the majority of any measurement bias, with the remaining levels being of little significance.

The processing of the measurements is another source of error, including the derivation of statistical properties from the data. It is known that the assessment of extreme values (such as the ultimate load) in particular may have strong uncertainty (Qui et al., 2014).

***Environmental uncertainty***

The MARIN wave tank has focused on wave tests for tens of years and developed rigorous methods for achieving repeatable and spatially consistent wave fields. The addition of wind device testing is fairly new, however, and the conditions of the tank are not ideal for achieving a smooth, consistent wind field. The excellent efforts to achieve a quality wind field at MARIN have resulted in a fairly consistent wind speed and turbulence spatially, including a fairly low turbulence intensity and negligible swirl. However, there is no outlet for the wind flow, resulting in the potential for blockage effects, as well as other influences from the large room in which the testing is performed.

Calibration tests were performed that provide measurements of the wave elevations at different locations in the tank (see Fig. 2) and wind speed and turbulence at different locations across the rotor plane (see Fig. 3). These tests are performed without the wind turbine present and provide the unadulterated excitation measurements that were used in the validation campaign run under OC5 (Wave CL and VWind CL).

Wave uncertainty

During testing, the wave elevation was measured at only two of the locations in the tank: the one coinciding with the location of the system in the tank, but offset to the side (Wave 180), and the other slightly downstream location (Wave 225). The Wave 180 measurement is fairly uncorrupted by the wind turbine, and provides an avenue to assess the random uncertainty of the wave excitation if the same wave spectrum is used in multiple tests. As can be seen in Table 1, the same operational wave spectrum was used for load cases 3.3, 4.1, 4.2, and 4.3 (as well as an additional test with different wind that was not used in the validation campaign, and the calibration wave test). Fig. 4 shows the measured wave power spectral density (PSD) for these six tests at the Wave 180 position, as well as a comparison to the measurement at the Wave CL position for the calibration case. The spectrums are fairly consistent, but the Wave CL measurement (black line) varies the most from the other measurements. This means that there is some level of inhomogeneity in the wave field spatially that should be assessed in future test campaigns.

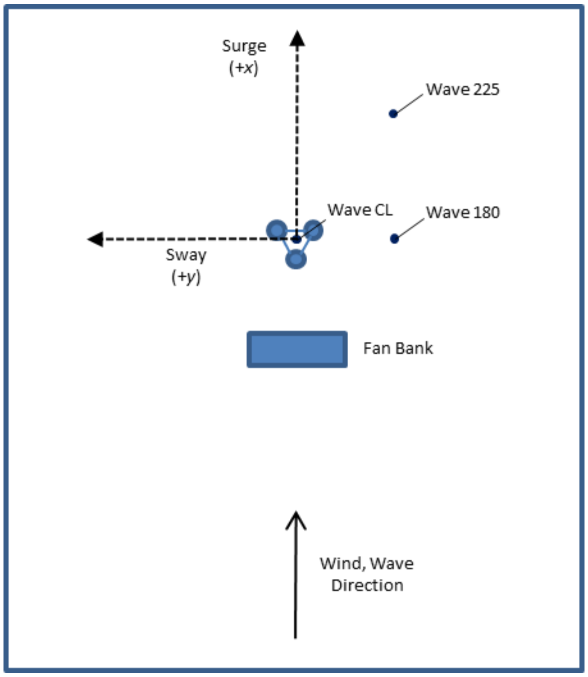

Fig. 2. Wave measurement locations

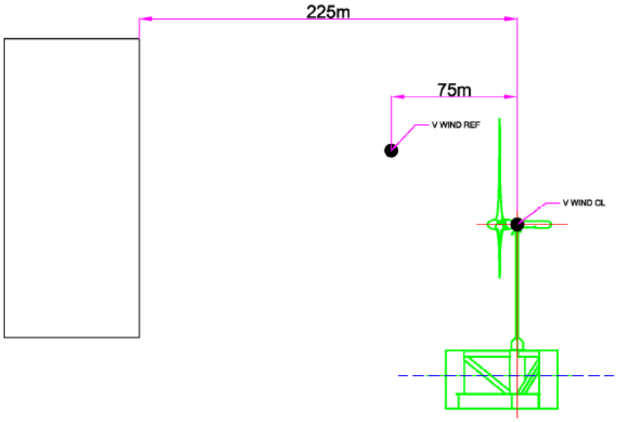

Fig. 3. Wind measurement locations (Helder and Pietersma, 2013)

The seven operational wave measurements shown in Fig. 4 were used to assess the random uncertainty in the wave measurements. Table 2 summarizes the uncertainty quantification of these seven tests, which have a standard uncertainty of the wave height of 0.033 m and wave period of 3.12E-4 s. The end goal—the uncertainty in the measured response loads—cannot be assessed from these tests because they each had a different wind condition. Instead, simulations using each of these seven measured waves (for a wave-only test) were used to assess the sensitivity of the load response of the wind turbine to the uncertainty in the waves. The resulting estimated random uncertainty of the ultimate loads is also given in Table 2. The uncertainty levels estimated here are small, and show that the wave randomness causes very little uncertainty in the load response. This outcome is expected for a wave basin with high-quality wave generation equipment and practices.

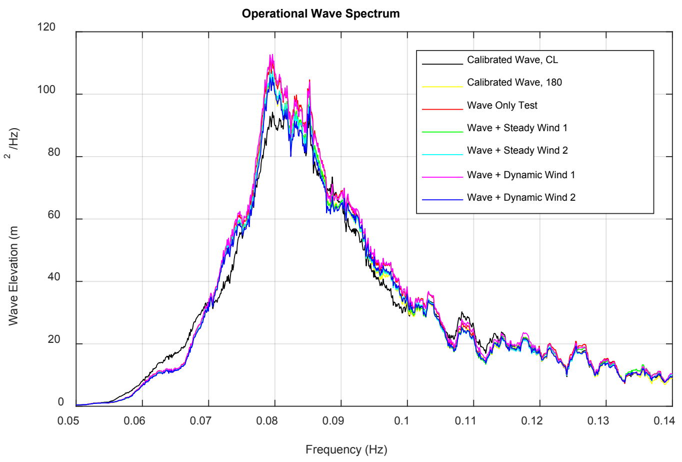

Fig. 4. Variation of wave spectrum for multiple tests using Operational Wave

Table 2: Random standard uncertainty estimates for ultimate loads using seven different operational wave measurements

| **Operational Wave Only (LC 3.3)** | *Mean* | $s_x$ | $s_{\bar{x}}$ |
|---|---|---|---|
| Maximum wave amplitude (m) | 4.93 | 0.0972 | 0.0367 |
| Maximum tower-base force (kN) | 666 | 12.8 | 4.82 |
| Maximum tower-top force (kN) | 525 | 4.54 | 1.72 |
| Maximum mooring 2 force (kN) | 1.15E+6 | 2.23E+3 | 841 |

### Wind uncertainty

For the wind, only one measurement was recorded during testing, at a location above hub height and just upwind of the turbine. Unfortunately, this wind measurement will be influenced by the wind turbine and cannot therefore be used to assess random uncertainty of the wind excitation as was done for the waves described earlier.

Sources of systematic uncertainty for the wind include the variability of the wind speed and turbulence spatially across the rotor, which is represented in terms of shear, veer, point-to-point coherence, and component-to-component correlation. In addition, there is uncertainty of the spatial variability of off-axis wind components. Random uncertainty could be related to the turbulence variation in time, as well as the influence of the room conditions during testing. Examination of the wind calibration cases show that between the two measurement locations, the wind speed on average varied about 10%, and the turbulence intensity varied by about 30% for steady wind cases and 7% for dynamic wind cases (see Table 3). This level of spatial variation is much larger than what is seen for the waves. Wendt et al. (2017) performed an analysis to understand the influence of different levels of turbulence, shear, coherence, and so on, on the variation in the measured loads in the system. This assessment was done in an attempt to calibrate numerical models to have a better match with the measured loads when wind is present. The analysis showed that these properties could significantly affect the load response in certain frequency regions.

For future test campaigns, it is important to get a better understanding of both random and systematic uncertainty through repeat measurements of the wind field at multiple positions simultaneously in the tank to understand spatial variation and repeatability.

Table 3: Difference between wind speed mean and turbulence at two measurement locations for calibrated wind tests

| | *Mean*<br>(% diff) | *TI*<br>(% diff) |
|---|---|---|
| Steady Wind 1 | 9.00 | 34.3 |
| Steady Wind 2 | 10.1 | 31.5 |
| Dynamic Wind 1 | 8.67 | 7.51 |
| Dynamic Wind 2 | 10.1 | 6.76 |

### ***Model uncertainty***

Uncertainties in the model will come from the geometry of the structure and moorings, mass distribution, inertia, and stiffness properties. Engineering practice will need to be used to estimate the level of potential bias in these properties. As an example, Qui et al., (2014) estimated a geometric manufacturing tolerance of 1.5 mm for a semisubmersible system, which was assumed to have minimal influence on the model behavior. Qui also estimated that mass deviations would result in less than a 0.5% change in displacement, a CG uncertainty of 2 mm, and moment inertia uncertainty of 3.5%.

A significant source of uncertainty for the OC5-DeepCwind model comes from the instrument cable used to send information from the measurement sensors to the data acquisition system. In Fig. 1, these cables can be seen attached to the tower and then hanging off of the tower around the midline of the structure. The weight of the cable section attached to the tower was measured and included in the system properties, and its influence on the system dynamics examined through a free-decay test with the cables present and without. This test showed a shift in the pitch natural period from 32.1 seconds to 34.3 seconds—indicating a change in stiffness properties, but with little effect on the damping of the system. Unfortunately, there was not enough surge motion in this test to assess the influence on the surge response. In a computer model of the semisubmersible system, the cable bundle can be modeled directly as an additional mooring line on the structure, or else its influence can be represented by an additional global pitch stiffness. A direct model of the cable bundle as a mooring line, however, is hampered by incomplete information regarding its properties, because only the weight of the portion attached to the tower was measured. Further, representing its influence as a pitch stiffness could be incomplete because the influence could be nonlinear and different test conditions could lead to dynamic excitation during testing, causing additional loads and frequency excitation in the system. Unfortunately, without direct access to the system, it is not possible to accurately model the influence of the cable or assess the level of uncertainty it instills in the system response. In future test campaigns, rigorous testing should be performed to understand the influence of the instrumentation. This assessment can be achieved by doing testing while removing as much instrumentation as possible, and comparing that to tests with all instrumentation included. It would also be beneficial to progress to smaller instrumentation or wireless sensors, if possible.

Examination of the DeepCwind test results showed that the initial position of the system varied between tests, and the cause of this variation is assumed to be hysteresis in the mooring lines. Uncertainty in the location of the structure, orientation of the moorings, and amount of mooring on the tank floor all contribute to uncertainty in the loading and behavior of the mooring lines, as well as the system loading and response. Additional uncertainty will come from the bottom friction of the mooring lines, length, diameter, weight distribution, stiffness distribution, damping, stress/strain characteristics, location of anchor points, fairlead position, spring stiffness at the anchor, influence of in-line force sensors, and pretension.

The turbine rotor is a fairly complex system, and there could be uncertainties in the geometry of the blades (airfoils) as a result of manufacturing tolerances and handling, the mass distribution, and pitch settings, which could all contribute to uncertainty in the response loads. As with the support structure, variations in the setup or orientation of the structure for a given test will add additional uncertainty. During the validation campaign of the OC5 system, examination of the loads at the top of the tower during wind-only testing showed the existence of harmonics of the blade-passing frequency at 1P, 2P, 3P, 4P, and so on, as well as large broadband frequency excitation (see Fig. 5). The 2P and 4P harmonic excitations are not typical in wind turbine response, and the cause of these and the large levels of response compared to the simulations should be investigated during a test campaign.

Additional model uncertainties could originate from simplification assumptions, including the assumption that the turbine blades, drivetrain/nacelle, and support platform are rigid structures, and that the tower connection at its base to the platform and at its top to the rotor-nacelle assembly (RNA) is an ideal clamped connection. The tower, in fact, was connected to the platform and RNA through load cells, which could add some compliance to the system. The simulation models used in the OC5 validation campaign in general have fairly simplistic representations of the structural properties, which may not capture the full representation of the system properties.

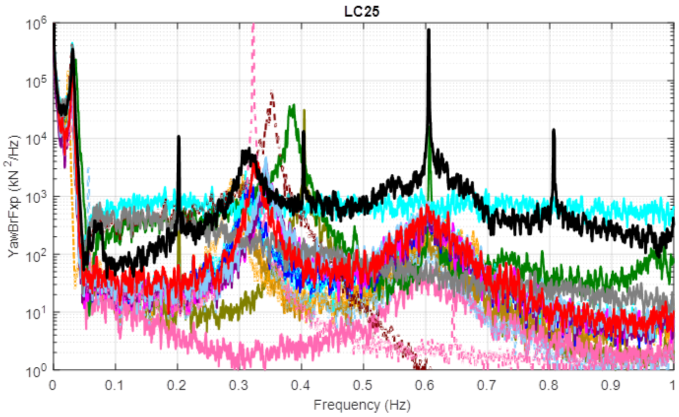

Fig. 5: Tower-top shear force during wind-only testing with an average wind speed of 13.05 m/s and rpm of 12.1 (black is the experimental measurement and colors are participant simulations)

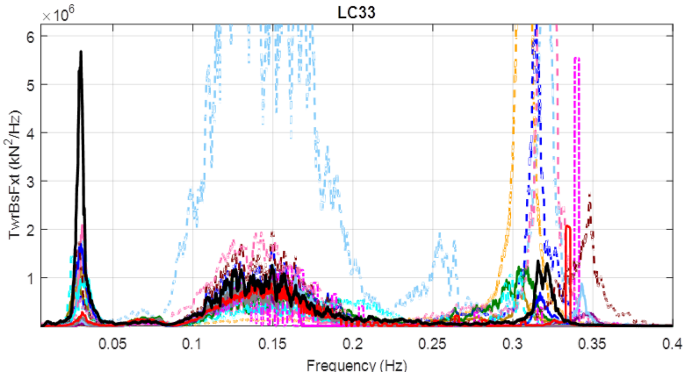

Fig. 6. PSD of tower-base shear force for operational wave excitation, with a significant wave height of 7.1 m and peak period of 12.1 s (black is the experimental measurement and colors are participant simulations)

Fig. 6 shows the PSD of the tower-base shear force during wave-only excitation. The black lines of the experiment show increased response relative to the simulations in the low- frequency regions at the pitch natural frequency (0.03 Hz). Could this potentially be because of an uncertainty in the model properties of the system, or is it a deficiency in the hydrodynamic models being employed in this validation campaign? Only by examining potential uncertainties in the model and instrumentation influences during the testing campaign can we begin to understand the source of the difference.

## CONCLUSIONS

The floating wind tests completed to date have been an excellent resource in understanding the behavior of these complex systems. The majority of testing has been done in wave basins, which this analysis shows are capable of achieving minimal uncertainty related to the wave environment. Wind is something new to these basins, though, and is not the ideal environment for achieving a smooth, consistent wind field. Adding the complexity of a wind turbine on a moving platform creates a lot of potential sources for uncertainty in a floating wind system test campaign.

To validate the tools used to model these systems, a systematic uncertainty analysis needs to be performed during the test campaign. Numerical modeling should be initiated before testing to plan and guide the tests. The validation procedure may illuminate issues not identified during testing, and so ideally, the validation should also be performed during the test campaign to allow for additional tests and analysis of the test structure and environment, if needed.

The most important component that needs to be considered in future test campaigns is repeat tests to assess the level of random uncertainty in the response measurements. Ideally, at least 10 repetitions of a given condition need to be performed. This approach would require a large amount of additional testing, and so perhaps this can be done for only a few of the different test conditions. Because the analysis done here shows low levels of uncertainty in the waves, it may be beneficial to focus only on the repetition of tests that include wind. Some ways to reduce the expense of the repeat tests might be to set up an automated process for the repetitions, or to shorten the testing time for the repetitions, provided that the time length enables appropriate resolution of low-frequency excitations. Through these repeat tests, the accumulated random uncertainty associated from the excitation, test subject, and response measurements are all assessed through the measurement of the response of interest (QOI).

To assess the systematic uncertainty in the test measurements, the uncertainty of all variables contributing to the QOI need to be determined and propagated. It might be useful to do testing with a structure of lower complexity to better focus on certain properties and their associated uncertainty. For instance, testing with just a mass at the top of the tower instead of a turbine can be used to better understand the structural response of the support system to waves without the complexity of the turbine and wind. And a rigid tower could be used to remove that DOF as well. Also, a stepped approach involving individual components of the support structure could be used to better understand and model the hydrodynamic properties of the semisubmersible system.

Because of the difficulty of achieving a good wind field in a wave tank as well as the difficulty in scaling the wind turbine properties, another option is to consider a hybrid testing approach in which the wind excitation is emulated by means of a pulley system at the tower top or using a fan. This approach will accomplish the basic needs of wind/wave coupling and will be useful as a first step in understanding the behavior of a floating wind system. Additionally, wind tunnel testing of the turbine alone can be used to better develop the aerodynamic properties of the turbine.

In summary, to enable a better understanding of floating wind systems and the ability of researchers to model them, it is important that we begin to address uncertainty in future test campaigns.

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## APPENDIX

Table 4: Reported uncertainty in measurement sensors for DeepCwind test campaign

| **Measured Quantity** | **Device Type** | **Sensor Manufacturer** | **Estimated Uncertainty Model (Full) Scale** |
|---|---|---|---|
| Wave at SET UP | Resistance type wave probes | Not provided | 1 mm (0.05 m) |
| Wind beside of CL (longitudinal/vertical) | Anemometer | Not provided | Not provided |
| Wind direction | Anemometer | Not provided | Not provided |
| Longitudinal motion | Krypton optical measuring system | In-house MARIN | 0.1 mm (5 mm) |
| Transverse/vertical motion | Krypton optical measuring system | In-house MARIN | 0.1 mm (5 mm) |
| Motion around longitudinal /transverse /vertical axis | Krypton optical measuring system | In-house MARIN | 0.1 deg |
| Longitudinal /transverse/ vertical acceleration (LOW/MID/TOP position) | Accelerometer | Not provided | Not provided |
| Longitudinal/ transverse/ vertical force | Six-component force frame | In-house MARIN | 0.1% full scale |
| Forces in moorings | Ring-shaped force transducers | In-house MARIN | 0.1% full scale |