Numerical modelling and validation of a semisubmersible floating offshore wind turbine under wind and wave misalignment

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Abstract. Coupled aero-hydro-servo-elastic simulation tools play an important role in the design of offshore floating wind turbines. For rational design of the system, accuracy of the numerical tool is important in predicting the system responses. While the load cases where the wind and wave are aligned are sometimes the largest contributor to the design, evaluation of the load cases where the wind and wave are a misaligned condition are also required in the design codes. In this study, first a series of water tank tests is performed for a 1/50 scale semisubmersible floater and results for irregular wave tests with aligned and misaligned wind were analysed. Then, an in-house numerical tool, NK-UTWind is used to model the full scale system. Results showed that measured motions in surge, heave, and pitch are similar for the aligned and misaligned cases, and these were well reproduced by the calculation. Measured sway and roll motion in the misaligned case were characterized by the components in wave frequencies, which calculation expressed well for the roll motion while underestimated several peaks for the sway motion. The characteristics of frequency distribution of measured tower-base shear force in the x direction and moment around the y axis forces were similar for both aligned and misaligned cases, which agreed approximately well with the calculation. The peak frequencies of the measured tower-base shear force in the y direction were similar for aligned and misaligned cases, and the measured tower-base moment around the x axis force included additional components in wave frequencies for the misaligned case. Calculations reproduced the natural frequency component for the tower-base moment around the x axis in both cases, while the accuracy was low for shear force in y direction.

1. Introduction
Coupled aero-hydro-servo-elastic simulation tools play an important role in the design of offshore floating wind turbines. For rational design of the system, accuracy of the numerical tool is important in predicting the responses under various combinations of wind and wave conditions. The load cases where the wind and wave are aligned are usually the largest contributor to the design, and various efforts have been made for the validation of the aero-hydro-servo-elastic analysis tools for these cases, such as Coulling et al. (2013)\(^1\), and Robertson et al. (2017)\(^2\). Evaluation of the load cases where the wind and wave also in a misaligned condition, meanwhile, are also required in the design codes such as IEC61400-3\(^3\). While these load cases can also contribute to the fatigue design, literature regarding the performance of the coupled analysis tool on the misaligned cases is limited.

The aim of this study is to validate the performance of a numerical code for the response of a semisubmersible floater under misaligned wind and waves. First, a series of water tank tests is
performed for a 1/50 scale semisubmersible floater. Results for irregular wave tests with aligned and misaligned wind were analysed. Then, an in-house numerical tool, NK-UTWind is used to model the full scale system. Calculated results are validated for aligned and misaligned cases, and the behaviour of the system and the performance of the numerical tool are discussed.

2. Water tank test

The water tank tests were conducted using a 1/50 scale semisubmersible floater with 2MW wind turbine at Ocean Engineering Basin of National Maritime Research Institute, Japan, in July 2011. The outline of the 1/50 scale model is shown in Figure 1. All the values in this paper are presented at full-scale. Both the floater and the tower are modelled as rigid bodies. The system is designed to have natural frequencies in the range of linear wave frequencies generated by the wave generator. The wind turbine blade model was designed using the cross-section NACA63(3)-418, and a wind tunnel test was conducted for the whole rotor to evaluate the thrust force. To simplify the effect from the moorings, a taut mooring was chosen for the system. Four springs were used for the modelling. The outline of the mooring system is shown in Figure 2 as well as the measurement arrangements. The tower-base loads and wind turbine thrust forces were measured using load cells. The translational components of the floater motion were measured using motion capture systems, and the rotational components were measured using a gyro sensor attached near the centre of the gravity of the floater. All data was recorded at 50Hz in model scale. Details of the properties of the model converted into full scale are shown in Table 1.

![Figure 1. Outline of the scale model](image1)

![Figure 2. Outline of the mooring system](image2)

| Table 1. Model properties in full scale |
|---|---|
| Floater properties | Wind turbine Properties |
| Platform draft | 16 m | Hub height | 66 m |
| Platform mass | 4,992,000 kg | Rotor radius | 82.5 m |
| Platform KG | 8.44 m | Nacelle mass | 137,500 kg |
| Platform Kyy | 24.5 m | Blade mass | 11,875 kg |
| Platform GM | 3.7 m | Tower mass | 112,500 kg |
| Mooring spring coefficient | 28,825 N/m |

Various combinations of wind and waves were tested. In this study, results for irregular waves with the wind turbines in steady rotation are focused on. Two cases for aligned and misaligned conditions were chosen. Detailed test conditions of the selected cases are shown in Table 2. Here \( U \) is the mean wind speed, and \( I_u \) is the turbulence intensity. Despite intending for the wind to be steady in the experiment, some turbulence is generated due to the inherent nature of the wind generator. The wave conditions, wind conditions and wind turbine rotational conditions are basically the same for the two cases. For the misaligned case, the direction of the wind and the nacelle yaw are set in 30 degree
misalignment to the wave direction. Definition of global coordinates and arrangement of the wind generator and the scale model for the misaligned case are shown in Figure 3.

![Figure 3. Definition of global coordinates and arrangement of the wind generator and the scale model in 30 degree wind and wave misalignment](image)

**Table 2. Test conditions chosen for validation**

| Load cases | Wave condition | Wind condition | RPM | Duration |
|------------|----------------|----------------|-----|----------|
| Aligned    | JONSWAP, $\gamma = 3.3$ | $U=13.05\text{m/s, } I_u=5.9\%$ | 22.0 | 6120 sec |
|            | $H_s=6\text{ m, } T_s=13.01\text{s}$ | Wind direction=0 deg | | |
|            | Wave direction=0 deg | | | |
| Misaligned | JONSWAP, $\gamma = 3.3$ | $U=13.05\text{m/s, } I_u=5.9\%$ | 22.0 | 5800 sec |
|            | $H_s=6\text{ m, } T_s=13.01\text{s}$ | Wind direction=30 deg | | |
|            | Wave direction=0 deg | | | |

3. Numerical modelling

NK-UTWind is an in-house code of coupled analysis for floating offshore wind turbine developed by ClassNK and University of Tokyo. The code solves the equation of motion shown in Eq. (1) for the wind turbine support structure modelled with FEM beams.

$$M\ddot{x} + C\dot{x} + Kx = F^{\text{hydro}} + F^{\text{lines}} + F^{\text{buoyancy}} + F^{\text{aero}}$$

Here $M$ is the mass matrix, $K$ is the stiffness matrix, and $C$ is the Rayleigh damping matrix introduced for numerical stabilization but also is sometimes used to introduce the linear damping caused by the wave radiation. $F^{\text{hydro}}$ is the hydrodynamics for the platform and is evaluated with Morison equation represented as Eq. (2).

$$F^{\text{hydro}} = \rho \frac{\pi D^2}{4} u + C_m \rho \frac{\pi D^2}{4} (\ddot{u} - \ddot{x}) + C_D \frac{1}{2} \rho D |\ddot{u} - \ddot{x}| (\ddot{u} - \ddot{x})$$

where $\rho$ is water density, $D$ is the radius of the cross-section, $C_m$ is the added mass coefficient, $u$ is the velocity of the water particle, and $C_D$ is the drag coefficient.

$F^{\text{lines}}$ is the forces from the mooring lines. In this study it is a linear spring model. $F^{\text{buoyancy}}$ is the restoring force. $F^{\text{aero}}$ is the force from the wind turbines, which is evaluated in FAST. The forces from the wind turbine calculated with FAST are passed to NK-UTWind as tower top loads.

In order to calibrate the added mass coefficient $C_m$ and drag coefficient $C_D$ in Morison equation as well as the Rayleigh damping term in the equation of motion, the natural periods, linear damping coefficients, and quadratic damping coefficients were estimated from the free decay tests. The linear damping coefficient $p$, and the quadratic damping coefficient $q$ are estimated with Eq. (3) and Eq. (4) using a least squares method, where $\Phi_i$ is the i-th peak amplitude in the measured free decay signal.

$$y = qx + p$$

$$x = \frac{1}{2} (\Phi_n + \Phi_{n+1})$$

$$y = \Phi_n - \Phi_{n+1} \frac{1}{2} (\Phi_n + \Phi_{n+1})$$

Calibrated coefficients and resulting natural periods and damping coefficients are shown in Table 3 and Figure 4 respectively. As shown in Table 3, all calibrated coefficients except for the footings
were in the range of theoretical values for cylinders. The Rayleigh damping is set as 2.5% in this study as a result of the calibration using the linear damping coefficients. Figure 4 shows that the calculated natural period and the damping coefficients are in approximately good agreement with the experiment. Some differences can be seen for linear damping in surge, heave, and yaw motions. One reason for this is the limitation of the ability of the Rayleigh damping matrix to tune the motions individually in each degree of freedom. Also, the quadratic damping in heave motion is not fully tuned to avoid using excessively high drag coefficients for the footings as it also affects the pitch motions.

The aerodynamic coefficients for the wind turbine blades were first determined according to the literature\textsuperscript{6} for NACA63(3)-418. However, the calculated thrust force largely overestimated the measurements, which is assumed to be caused by the large difference in the Reynolds number of the scaled experiment and the literature. Considering that it is the floater response that is in focus in this study, a modification coefficient was introduced to tune the mean thrust force. The coefficient is multiplied to the original lift and drag coefficients, and the value of the coefficient used is determined according to the load cases used in this study.

| Table 3. Calibrated added mass and drag coefficients |
|-----------------------------------------------|
| Centre Column (Horizontal) | Centre Column (Vertical) | Side Column (Horizontal) | Side Column (Vertical) | Brace (Horizontal) |
| $C_m$ | 0.9 | 1.0 | 0.75 | 0.57 | 0.9 |
| $C_D$ | 1.0 | 5.0 | 1.0 | 6.0 | 1.0 |

(a) Natural Period (s)  
(b) Linear Damping Coefficient  
(c) Quadratic Damping Coefficient

Figure 4. Comparison of calculated and measured (a) natural period, (b) linear damping coefficient and (c) quadratic damping coefficient

| Wave Amplitude (m) |
|---------------------|
| Time (s) |
| Obs. | Calc. |
| 0 | 1.5 |
| 10 | 2.0 |
| 20 | 2.5 |
| 30 | 3.0 |
| 40 | 3.5 |
| 50 | 4.0 |
| 60 | 4.5 |
| 70 | 5.0 |
| 80 | 5.5 |

| Wave Elevation (m) |
|---------------------|
| Frequency (Hz) |
| Obs. | Calc. |
| 0 | 0.05 |
| 0.1 | 0.15 |
| 0.2 | 0.25 |
| 0.3 | 0.35 |
| 0.4 | 0.45 |

| Wind Speed (m/s) |
|---------------------|
| Time (s) |
| Obs. | Calc. |
| 0 | 0.0 |
| 10 | 0.1 |
| 20 | 0.2 |
| 30 | 0.3 |
| 40 | 0.4 |
| 50 | 0.5 |
| 60 | 0.6 |
| 70 | 0.7 |
| 80 | 0.8 |

Figure 5. Comparison of calculated and measured (a) wave time series, (b) wave amplitude spectrum, (c) hub-height wind time series, and (d) hub-height wind amplitude spectrum
The input wave used in the numerical calculation was generated by applying the inverse FFT to the measured wave height. Linear airy waves are used for modelling of the wave kinematics. In generation of the input turbulent wind field, Kaimal model is used with the parameters defined for the model in the IEC61400-17. Amplitude spectra of the generated and measured wave and wind are shown in Figure 5 for the aligned case. It is seen that the high frequency amplitude is larger for the measured wind speed, and that the wind in water tank test was affected by the wave. Amplitude spectra of the calculated and measured wind turbine thrust forces are shown in Figure 6. It is seen that while the calculated thrust force are larger in the lower frequencies of the amplitude spectra, the measured thrust force are larger around 0.07 Hz to 0.12 Hz. This is partly due to the difference of the input wind spectrum as shown in Figure 5. Also, it is seen from the figure that measured thrust force contains the effect of tower shadow at 0.32 Hz, which were not expressed in the calculation. Total calculation time was set to 5500 sec for both cases, and first 500 sec was neglected to eliminate the initial transient response. Calculation time step was set at 0.01 sec. Welch's method was used to obtain the power spectrum density with Hann window. As the sampling frequency is different for measurement and calculation, the power spectrum density is then converted into amplitude spectra for the validations.

Figure 6. Comparison of calculated and measured (a) time series and (b) amplitude spectrum of the thrust force

4. Results

4.1. Validation of the floater motions

Comparison of the calculated and measured floater motions for the aligned and misaligned wind and wave conditions are shown in Figure 7 and Figure 8 respectively. Figure 7 (a) and Figure 8 (a) show that measured surge motion has similar distribution for both aligned and misaligned cases. The
frequency amplitudes were characterized by the surge natural frequency and the input wave frequency, which were expressed well with the calculation. Figure 7 (b) and Figure 8 (b) show that measured sway motion contains components of 0.13 Hz and 0.18 Hz apart from the natural frequency for both aligned and misaligned cases, while wave frequencies were added for the misaligned case. These were not expressed in the calculation. Considering that the 0.13 Hz component is only seen in the sway motions for both aligned and misaligned cases but not in the tower-base loads as shown in Figure 9 and 10, it may be caused by the vibration of the supporting frame of the motion capture system. Figure 7 (c) and Figure 8 (c) show that the measured amplitude spectra for the heave motion have similar distribution for both misaligned and aligned cases. Calculations underestimated the amplitudes for both cases, which may due to the underestimation in the damping coefficients as shown in Figure 4. Measured results in Figure 7 (d) and Figure 8 (d) show that only roll natural frequency is excited in the aligned case while both roll natural frequency and wave excitation frequencies are excited in the misaligned case. This is well captured by the calculation. Figure 7 (e) and Figure 8 (e) show that in the measured pitch response, both pitch natural frequency and wave excitation frequencies are excited and the amplitudes are similar for both aligned and misaligned cases. Calculated results agreed well with the measurement. Figure 7 (f) and Figure 8 (f) show that measured yaw responses are only excited at the yaw natural frequency for both aligned and misaligned cases. While these components are well expressed by the calculation in both cases, the excitation in the wave excitation frequency is seen in the calculated misaligned case. Coupling of the floater motions between each degree-of-freedom was not observed for both aligned and misaligned cases.

4.2. Validation of the loads
Comparison of the calculated and measured loads for aligned and misaligned wind and wave conditions are shown in Figure 9 and Figure 10 respectively. Figure 9 (a) and Figure 10 (a) show the results for $F_x$, the tower base shear force in x direction. Measured amplitude spectra were similar for both aligned and misaligned cases. Calculated results showed approximately good agreement with the measurement except for the peaks around 0.08 Hz, which are the peaks that were underestimated in the calculation of the thrust force as shown in Figure 6. This underestimation results from the underestimation of the spectra of the measured wind speed by the Kaimal model in this region as shown in Figure 5 (d). Figure 9 (b) and Figure 10 (b) show the results for $F_y$, the tower base shear force in y direction. It is seen that the peak frequencies of measurements were similar for the aligned and misaligned cases. For the aligned case, the calculation underestimated components in natural frequency and was unable to reproduce the wave frequencies. For the misaligned case, the calculation...
matched well with the measurement in the natural frequency while some components in wave
frequencies was not captured. Figure 9 (c) and Figure 10 (c) show the results for $M_x$, the tower base
bending moment around x axis. Figures show that the measured moment is dominated by the
components of the roll natural frequency and 1P frequency for the aligned case while the components
of the wave frequencies are also excited for the misaligned case. Calculated results reproduced the
components in the roll natural frequency well for both cases, while some components in the wave
frequency range were under estimated in the misaligned case. Figure 9 (d) and Figure 10 (d) show the
results for $M_y$, the tower base moment around y axis. It is seen that the spectra of the measured loads
are similar in both peak frequencies and peak amplitudes for the aligned and misaligned cases. Calculated results reproduced the measurement well except for the frequency amplitude around 0.08

![Figure 9](image1.png)

**Figure 9.** Comparison of the amplitude spectra of the calculated and measured floater loads for
(a) tower-base $F_x$, (b) tower-base $F_y$, (c) tower-base $M_x$, (d) tower-base $M_y$, (e) mooring 1 tension and (d) mooring 2 tension for the aligned case

![Figure 10](image2.png)

**Figure 10.** Comparison of the amplitude spectra of the calculated and measured floater loads for
(a) tower-base $F_x$, (b) tower-base $F_y$, (c) tower-base $M_x$, (d) tower-base $M_y$, (e) mooring 1 tension and (d) mooring 2 tension for the misaligned case
Hz for both aligned and misaligned cases. The components of the same frequency were underestimated in the evaluation of the thrust force. Figure 9 (e) and Figure 10 (e) show results for the tension of the No.1 mooring, of which anchor locates in the negative direction of x axis. Figures show that the spectra of the tension show the same behavior with surge displacement for both aligned and misaligned cases. The calculation matched well with the measurement. Figure 9 (f) and Figure 10 (f) show the results for the tension of the No.2 mooring, of which anchor locates in the negative direction of y axis. Figures show that sway natural frequency and the wave excitation frequencies are the two major components for the spectra of the measured tension for both aligned and misaligned cases. These peak frequencies were well reproduced by the calculation, but the calculated results overestimated the measurement in amplitudes for the misaligned case. The results for the loads were generally similar to those for the floater motions.

Statistics such as the maximum, standard deviation, and fatigue loads are calculated for the tower-base loads to examine the effect of misalignment of the wind and wave in the design phase. Comparison of the statistics between aligned and misaligned cases for measurement and calculation are shown in Figure 11. It is seen from the measured results in Figure 11 that the maximum and fatigue load of $F_x$ and $M_y$ were lower and $F_y$ and $M_x$ were higher for the misaligned case than those for the aligned case. Standard deviations of the tower-base loads were similar for aligned and misaligned cases. While these characteristics were qualitatively reproduced in the calculated results, the tower-base loads were underestimated in the maximum, standard deviation, and fatigue damage rates. Contribution of $F_y$ and $M_x$ to the fatigue damage were small compared to the component of the other directions for both aligned and misaligned cases. Both the maximum and fluctuating loads were underestimated by the calculation, which is mainly caused by the underestimation of the components in the range of 0.05 to 0.12 Hz as seen in Figure 9 and 10. These components correspond to those underestimated in the thrust force, which is resulting from the difference in the frequency characteristics of the measured and calculated wind turbulences.

Figure 11. Comparison of (a) (b) maximum and (c) (d) standard deviation of the tower-base loads for aligned and misaligned cases.
5. Conclusions
In this study, water tank test and numerical modelling were performed for a semi-submersible floating wind turbine for aligned and misaligned wind and wave conditions, and following conclusions were obtained.

a. For the misaligned case, coupling of the floater motions in each direction was not observed from both the measurement and the calculation, and the system response was characterised by the increased components of wave excitation region in sway, roll, and yaw direction. The fluctuating components were similar in surge, heave and pith direction for the aligned and misaligned cases, where the response mostly consists of components in the natural frequency in each degree of freedom and the wave frequencies.

b. When the wind and waves are in 30 degree misalignment, the measured mean tower-base loads in longitudinal direction are reduced compared to the aligned case, while the standard deviations are similar for both cases.

c. The floater motions and the loads were well reproduced by the calculation. The underestimation may be caused by the difference in the frequency characteristic of the measured and calculated wind turbulence.

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