Analysis of the influence of mooring dynamics and hydrodynamic models on the response of floating offshore wind turbines using FAST

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Introduction

In times of global warming, the need for renewable energy sources is growing rapidly. Wind turbines provide a clean, sophisticated possibility to harness the limitlessly available wind energy. Due to limited availability of installation area, public controversy and recent significant cost reductions, offshore wind is becoming increasingly popular. Wind conditions far off the coastline are superior to those in shallower waters. This makes floating offshore technology, which can be used for far deeper water depths than bottom-fixed systems, an attractive technology if the economical obstacles can be overcome [1].

The design and analysis of these floating systems is performed with aero-hydro-servo-elastic simulation tools, which combine aerodynamics, hydrodynamics, structure, and mooring dynamics in order to forecast the loads on the system. This thesis uses one of these codes, the Fatigue Aerodynamics Structures and Turbulence (FAST) code of the National Renewable Energy Laboratory (NREL) in order to review the capability of offshore codes to model platform responses under varying external conditions.

In an initial step, the capability of the latest FAST version to reproduce the results of the OC3 study is tested. The results can be seen in the appendix of the thesis.

Afterwards the importance of modelling the mooring lines as a dynamic system, compared to a quasi-static one, is examined. For this step the semisubmersible platform of the OC4 project is used. Several load cases with wind and wave excitation are performed with both modelling approaches and compared to the results of the initial study.

Then, the differences between two hydrodynamic models, Potential Flow theory and Morison's equation, are shown. The OC5 system is modeled for both approaches in FAST and several load cases are inspected regarding their hydrodynamic response. The outcome is compared with the experimental results from the initial OC5 project.

In the final step, the possibility of enlarging the application range of Morison's equation into scenarios where diffraction is the dominant force is examined. MacCamy's and Fuchs's diffraction theory is applied to create a new wave field as an input file into FAST. The resulting forces on a bottom-fixed cylinder are correlated with the forces created by regular airy waves.

OC4 Phase II: Semisubmersible Floating System

The Offshore Code Comparison Collaboration Continuation project (OC4) is a joint project of research institutes, universities, and companies with the goal to further increase the understanding about the design codes of floating offshore wind turbines. This paper uses the results from phase II of this project which benchmarks the participants' performance in predicting the loads and behavior of a semisubmersible platform in combination with the NREL 5MW turbine under various external conditions.

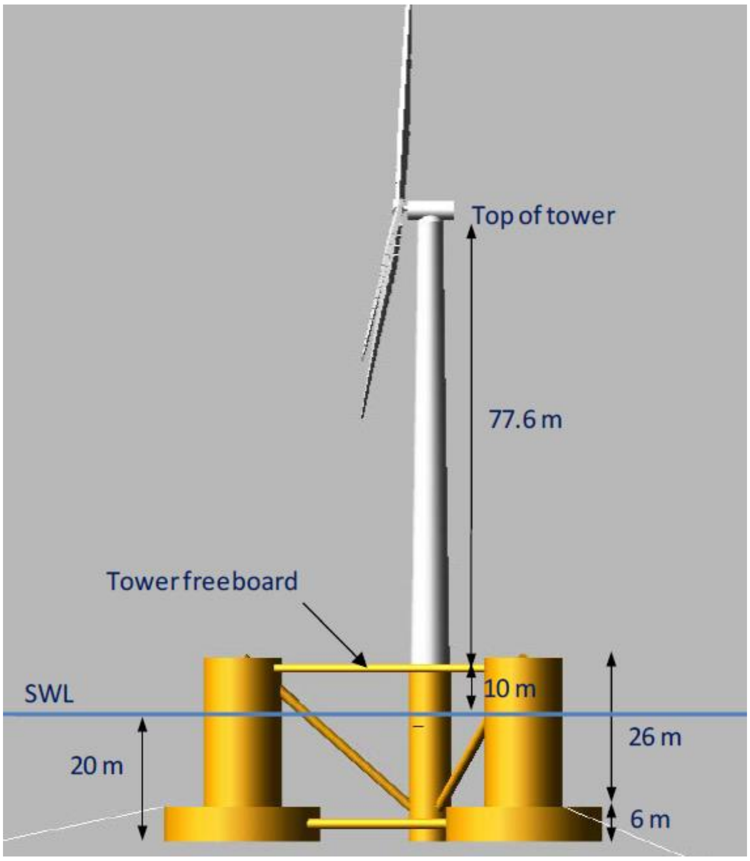

Figure 1: OC4 semisubmersible with NREL 5MW turbine

The models are first calibrated with static equilibrium and free decay tests and then tested with wind-only, wave-only and full system load cases. This paper performs the tests with the latest version of FAST

(8.16) and examines in particular the difference between quasi-static and dynamic mooring models. For this purpose, all load cases are conducted with both the MAP++ (quasi-static) and MoorDyn (dynamic) module of FAST. The dynamic approach considers effects like line inertia, drag and, vortex shedding which are not negligible especially for increasing water depths. Nevertheless, both codes agree on the results for most of the OC4 load cases, which are performed for a water depth of 200m. The difference only becomes visible if the Response Amplitude Operators of the mooring line tensions are regarded. There the quasi-static models fail to capture high mooring loads in the upper frequency range.

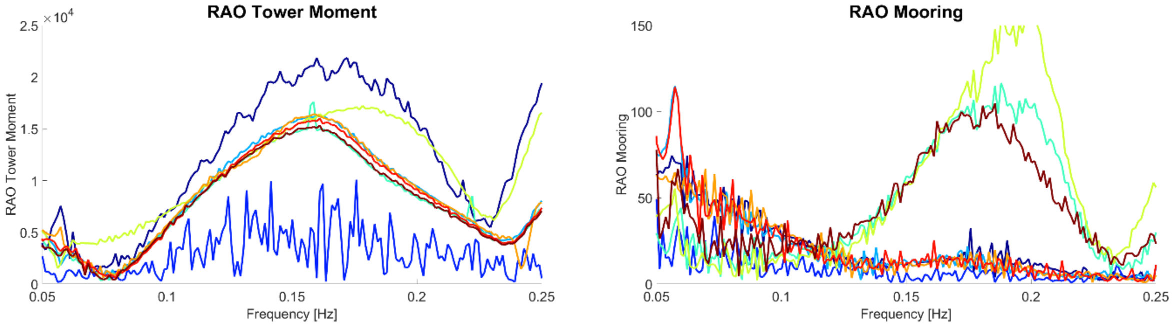

Figure 2: Figure 19: Response Amplitude Operators for the tower and mooring system

Figure 2 shows a grouping between the codes utilizing dynamic and those using quasi-static moorings. These high frequency fatigue loads have a big influence on the lifetime and highlight the importance of using dynamic modelling approaches for mooring systems, especially in load cases with strong wind and wave influence.

Further findings of the OC4 study include that codes with Morison's equation only need to consider the instantaneous platform position to capture drift forces, and need to implement dynamic pressure terms (Froude-Krylov-Forces) for shallow-draft platforms to correctly capture the heave movement. Potential Flow-based models deliver better results if the viscous loads are modeled by adding the specific drag term from Morison's equation.

OC5 Phase IIb – Semisubmersible Platform

Next, the differences of modelling the hydrodynamics with either Morison's equation or a Potential Flow solution is examined. To see which model predicts the loads better, the semisubmersible platform of the OC5 project is chosen. The OC5 project features experiments with a 1:50 scaled turbine in a wave tank and therefore offers experimental results for comparison. A FAST input model for both hydrodynamic models is created. Due to limited information about the ballasting of the platform, the ballast is considered part of the rigid platform.

Static equilibrium and free decay tests are performed to finetune the models and match the experimental behaviour. In both cases it is necessary to add a pretension in surge direction to match the experimental surge displacement. In the free decay test an increased pitch natural frequency is observed. This is caused by the diminished platform inertia due to the omission of the ballasting. The results of the static equilibrium tests are shown in figure 3. As can be seen, the results are in the range of the ones achieved by the participants of the project and also sufficiently close to the experimental observations.

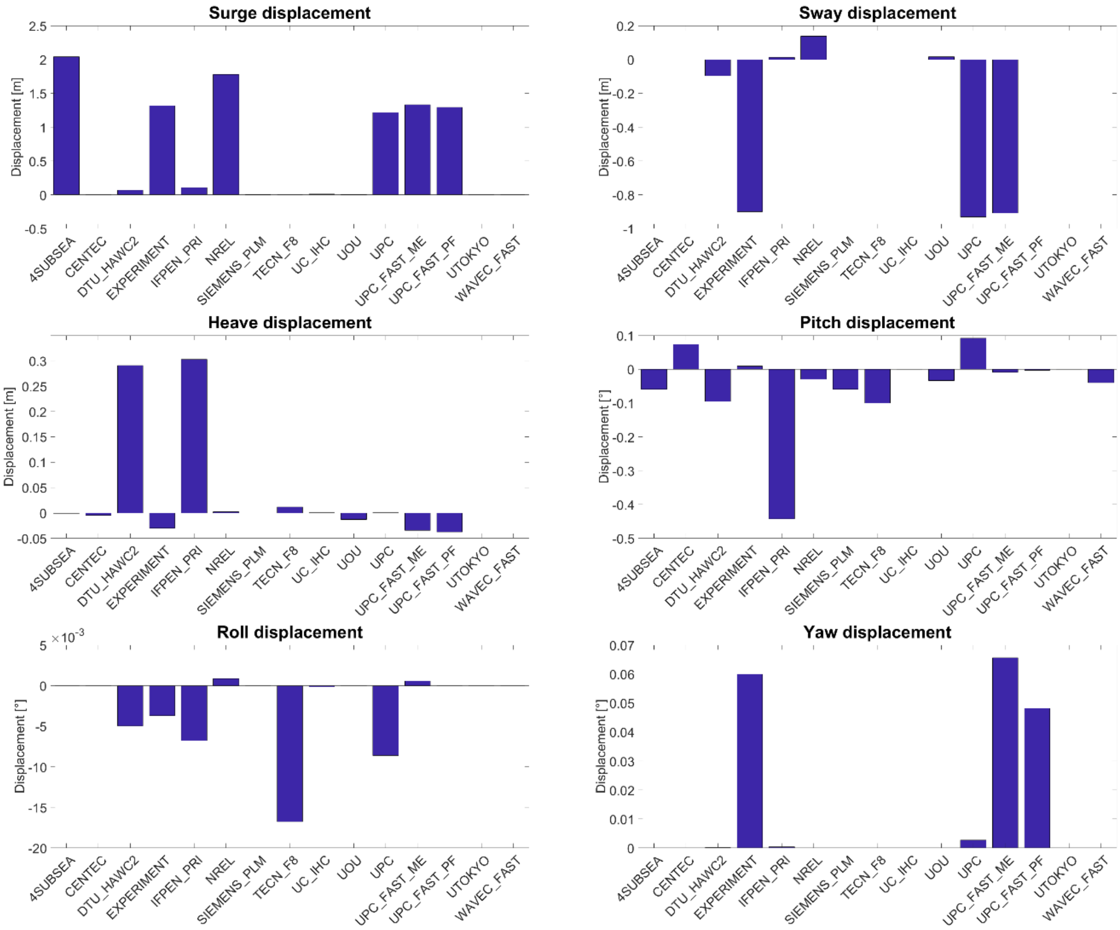

Figure 3: Static equilibrium test results for OC5

Afterwards two load cases with regular wave excitation are performed. Response Amplitude Operators are used to measure the behavior of the platform. Figure 4 display the RAOs for heave, pitch, and surge displacement as well as the tension in the three mooring lines for a wavefield with a height of 9.41 meters and a 14.3 seconds period.

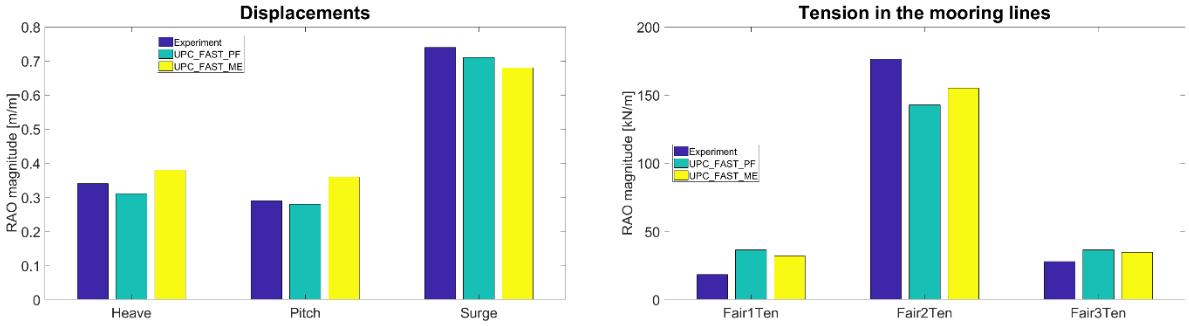

Figure 4: Response Amplitude Operators of the OC5 system for regular waves

The heave and pitch movement are overestimated by Morison's equation while both models predict too little surge displacement. Presumably the missing inertia and not-perfectly finetuned hydrodynamic coefficients are responsible for this phenomenon. It also leads to a shift in the mooring tension from line two towards lines one and three.

Finally, the load on the tower during irregular waves with a JONSWAP spectrum of 7.1 meters height, 12.1 seconds period and a peak shape parameter of 2.2 is examined. While the Potential Flow code underpredicts ultimate and fatigue loads on the base of the tower, the Morison's equation version shows exactly the opposing results. This behaviour was also observed by the participants of the OC5 study. The reason for this becomes visible by regarding the Power Spectral Density of the load signal. As seen in figure 5, the Potential Flow model shows excitations close to the experimental measurements but heavily underpredicts the excitation at the natural pitch frequency of the platform around 0.03 Hz. Thus, the total predicted load is significantly lower than expected. The same behaviour is seen for the Morison's equation model, but it also displays an overestimation of the tower excitation at the tower natural bending frequency of 0.3 Hz. The reason for this overprediction might be based on the omission of diffraction influences in Morison's equation. As a measure to increase the performance of Morison's equation codes, MacCamy's and Fuchs's diffraction theory is proposed.

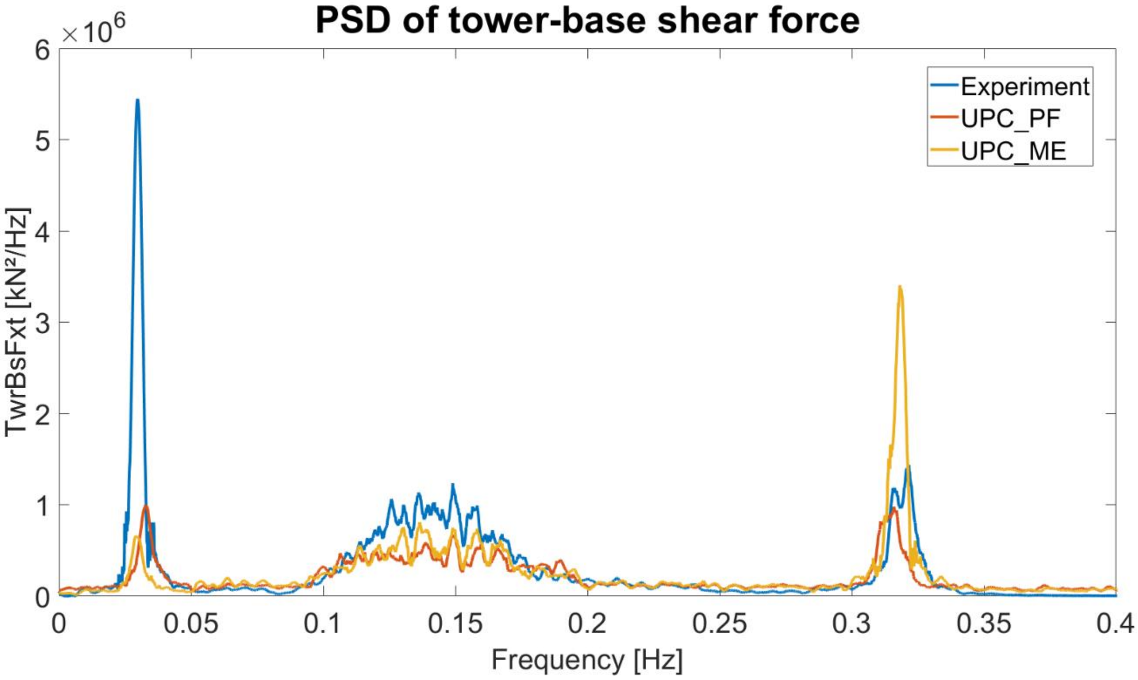

Figure 5: Figure 30: Power spectral density of the tower base loads

MacCamy's & Fuchs's diffraction theory

Morison's equation is only valid if the diameter of the regarded system is significantly smaller than the wavelength. If a ratio of $\frac{D}{\lambda}$ exceeds values of 0.2, diffraction becomes an increasingly dominant phenomenon. Diffraction loads are inflicted on the platform due to the reflection and subsequent scattering of the incoming wave on the structure. In an attempt to make Morison's equation able to deal with diffraction problems, MacCamy's & Fuchs's diffraction theory is used to create a new wave field as a FAST input file which already contains the contribution of the reflected wave. The wavefield is described by the following expression:

$$\eta(r,\beta,t) = \frac{H_I}{2}\Re\left\{\sum_{m=0}^{\infty} i^m \varepsilon_m \left[J_m(kr) - \frac{J_m'(ka)}{H_m^{(1)'}(ka)} H_m^{(1)}(kr)\right] \cos(m\beta)\, e^{-i\omega t}\right\} \tag{1}$$

Figure 6 shows a wave field based on MacCamy & Fuchs. The used input parameters are a wave height of four meters, a wave period of eight seconds and cylinder radius of ten meters. These parameters put the system well within conditions where inertia forces are the dominant effect. Therefore, MacCamy's and Fuchs's theory can be applied and a significant increase in wave height can be observed due to the influence of the diffracted wave pattern.

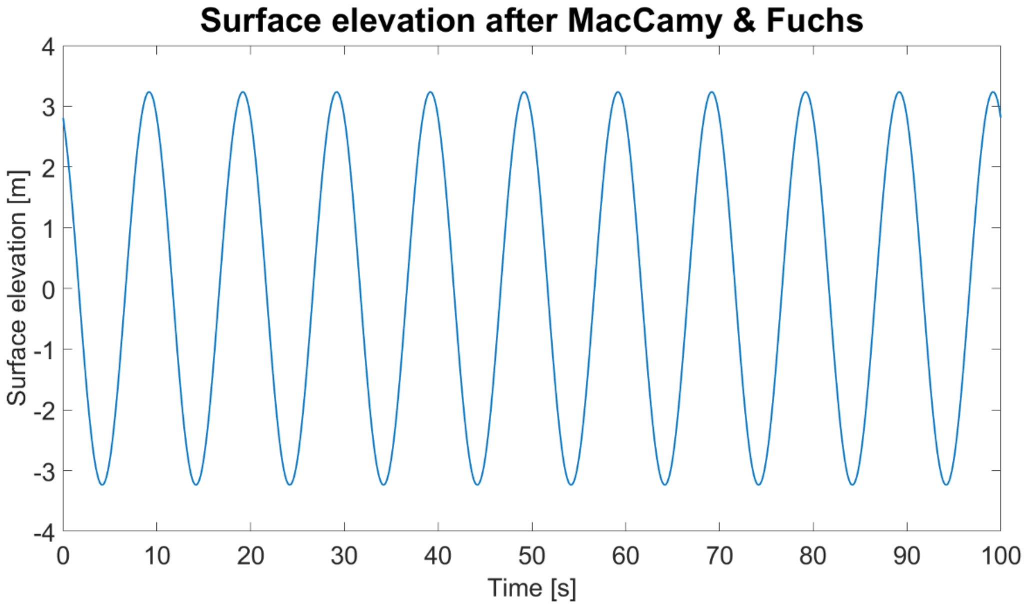

Figure 6: Wave field comparison

To see if the code, which is used to obtain the surface elevation in MATLAB, is correctly implemented, several steps are performed: First the velocity components of a regular airy wave of the same input parameters are calculated and put into the inertia term of Morison's equation:

$$F_{Inertia,Morison} = \frac{\pi}{4}\rho C_m D^2 \cdot \dot{u}(t) \tag{2}$$

Then the results are compared with the force on a bottom fixed cylinder predicted by MacCamy and Fuchs at different wavelengths. The results are presented in figure 7:

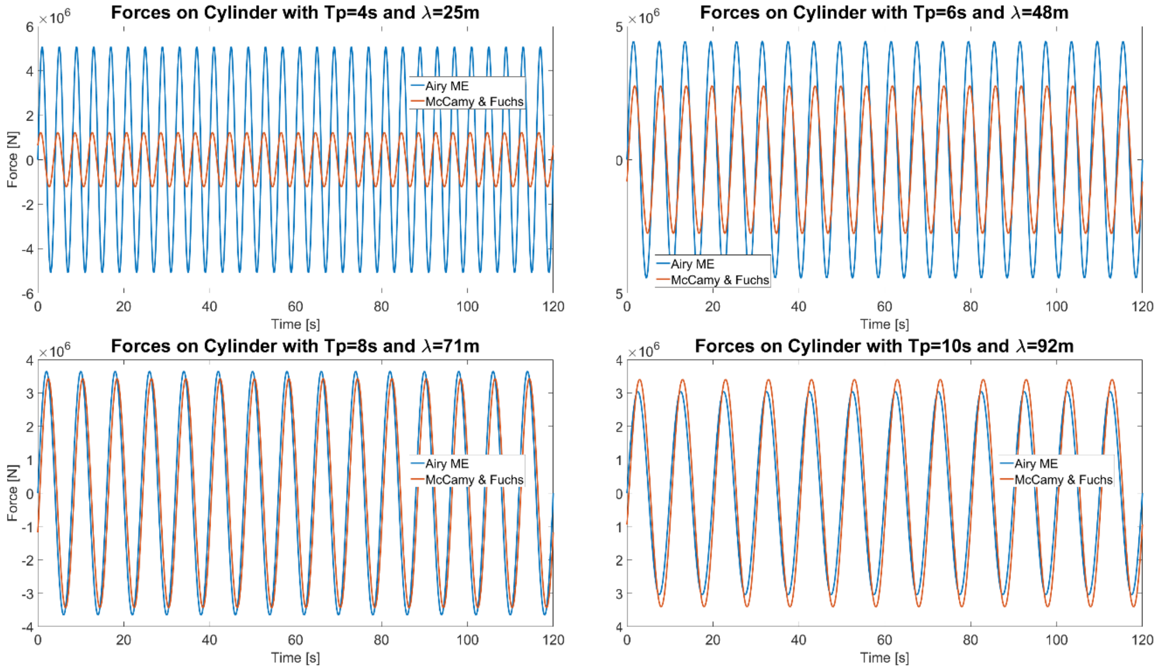

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Figure 7: Forces on a bottom-fixed cylinder

The first two graphs with wavelengths up to 48 meters are well within the diffraction-dominant domain. Therefore the application of MacCamy's and Fuchs's theory is valid. The results show a strong reduction of the predicted force on the cylinder if diffraction is taken into account.

This could help to solve the overprediction of incident forces shown by codes using only Morison's equation during the OC5 study. The RAO of the shear force at the tower base shows in high frequencies a significantly increased peak, which does not agree with the experimental results if Morison's equation is used. The implementation of MacCamy's and Fuchs's diffraction theory would have exceeded the scale of this paper and will be subject of future works.

References

[1] J. Cruz, M. Atcheson (Eds.), Floating offshore wind energy: The next generation of wind energy, Springer, [Cham], 2016.