

INVESTIGATION OF COUPLING METHODS FOR FLOATING OFFSHORE WIND TURBINES AND THEIR APPLICATION FOR AN INNOVATIVE FLOATING PLATFORM

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**by
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ABSTRACT

INVESTIGATION OF COUPLING METHODS FOR FLOATING OFFSHORE WIND TURBINES AND THEIR APPLICATION FOR AN INNOVATIVE FLOATING PLATFORM

The search for more sustainable energy sources to replace fossil fuels has encouraged the development of several energy sectors, including floating offshore wind energy. Growth in this area focuses on research in platforms for aero-hydro-servo-elastic codes such as OpenFAST and aero-hydro coupling methods. In this thesis, the innovative floating platform, which was previously designed for 300 kW and 5 MW capacities, has been modified in terms of dimensions and features to be suitable for analysis with the 5 MW NREL reference wind turbine. The study examined coupling methods for spar, semi-submersible, common in the literature, and innovative platforms. This involved determining natural periods and damping ratios to see the system responses and behaviors of turbines and platforms, free decay tests, and various loads, including steady and turbulent wind conditions in regular, irregular wave conditions. The analysis provided several conclusions, including the verification of coupling methods, comparative evaluations of different platforms, and investigations into the behaviors of the innovative platform under flexible and rigid configurations. In this context, open-source programs like Capytaine and NEMOH and the commercial program AQWA produce results similar to WAMIT's OpenFAST outputs. The F2A coupled method also shows strong correlation and consistency with these results. Furthermore, while the innovative platform with mooring lines achieves higher values than other platforms, its pitch angle is significantly lower, which is crucial for system stability, fatigue, and extreme loads. This reduces loading on components such as the tower blade and yaw bearing.

ÖZET

YÜZER AÇIK DENİZ RÜZGAR TÜRBİNLERİ İÇİN AKUPLE YÖNTEMLERİNİN ARAŞTIRILMASI VE YENİLİKÇİ BİR YÜZER PLATFORMA UYGULANMASI

Fosil yakıtların yerini alacak daha çevreci enerji kaynaklarına olan ilgi arttıkça, çeşitli enerji alanları da devreye girmektedir. Bunlardan biri ve giderek artan potansiyeli ile dikkat çeken deniz üstü yüzer rüzgâr enerjisi, önemli araştırma konularından biri olarak platformun OpenFAST gibi aero-hidro-servo-elastik programlara entegrasyonu veya benzer aero-hidro kuvvetlerinin bir arada verilmesi yöntemlerinin incelenmesini kapsamaktadır. Bu tez kapsamında daha önceden 300 kW ve 5 MW değerleri için tasarlanmış olan yenilikçi yüzer platformun 5 MW'lık NREL referans rüzgâr türbini için ölçüleri ve özellikleri analizlerde kullanıma uygun şekilde düzenlenmiştir. Literatürde yaygın olarak kullanılan spar, semi-submersible platformlara ek olarak yenilikçi platform için akuple yöntemleri incelenmiştir. Türbinlerin ve platformların sistem tepkilerini ve davranışlarını görmek için doğal periyotları ve sönüm oranlarını bulma, serbest salınım testleri, düzenli, düzensiz dalga koşullarında, sabit ve türbülanslı rüzgâr koşulları dahil çeşitli koşullarda analizler yapılmıştır. Bunun sonucunda, akuple yöntemlerinin doğrulanması, platformların birbirleriyle karşılaştırılması, yenilikçi platformun esnek ve rijit yapısındaki farklı davranışlar incelenmiştir. Bu bağlamda, OpenFAST'a girdi olarak hidrodinamik katsayı sağlayan açık kaynaklı Capytaine ve NEMOH gibi programların yanı sıra AQWA gibi ticari programların, WAMIT gibi yaygın olarak kullanılan ticari programın OpenFAST çıktılarıyla benzer sonuçlar verdiği görülmüştür. Ayrıca, F2A akuple yönteminin de bu sonuçlarla oldukça tutarlı olduğu gözlemlenmiştir. Ayrıca, platformlar karşılaştırıldığında, bağlama halatlarındaki kuvvetlerin özgün platformda diğer platformlara göre daha yüksek olmasına rağmen, özellikle sistemin kararlılığı açısından önemli bir kriter olan platformun yunuslama açısının önemli ölçüde daha düşük olması sebebiyle, kule, kanat ve sapma yatağı gibi bileşenler üzerinde diğer platformlara kıyasla daha az yük oluştuğu hesaplanmıştır.

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CHAPTER 1

INTRODUCTION

To alleviate the negative impact of fossil resources on the environment and the effects of greenhouse gases, there has been a social demand for energy sources with lower emissions. Replacing fossil fuels with renewable energy sources is the most effective way to reduce carbon emissions and meet this demand.¹ Demand and investment amounts in renewable energy have increased in the last decade to achieve the Paris Climate Agreement and countries' carbon-neutral targets. Especially in recent years, with technological improvement effects, solar and wind have come to the fore against fossil fuels in this sense. For the last twenty years, these two energy sources have increased linearly, and their share in the total generated electrical energy has increased day by day on the levelized cost of energy (LCOE).

From a wind energy perspective, the increasing trend is towards offshore wind farms, as seen in Figure 1.1. Significantly, the growth in turbine sizes has begun to make this option economically available. The potential of offshore wind can be classified into two distinct types: shallow and deep waters. Fixed-based platforms are used particularly up to fifty meters of water depth, and as the depth increases, fixed platforms are replaced by floating platforms of various designs. Wind energy is used more widely in shallow waters today. However, once harvesting is significantly exploited, the potential for offshore deepwater wind will become more significant. Therefore, floating wind turbines must exploit this potential in deep waters.²

Although these turbines present many new technical challenges, they have higher potential than shallow water systems. This trend may have been caused by higher wind speeds in general, especially in deep waters further from the coast.³ Floating offshore wind turbine (FOWT) farms will increasingly be used by 2050, projected to account for 5% to 15% of the global offshore wind installed capacity.⁴ This anticipated expansion will bring many innovations, particularly in Floating offshore wind turbine FOWT research.

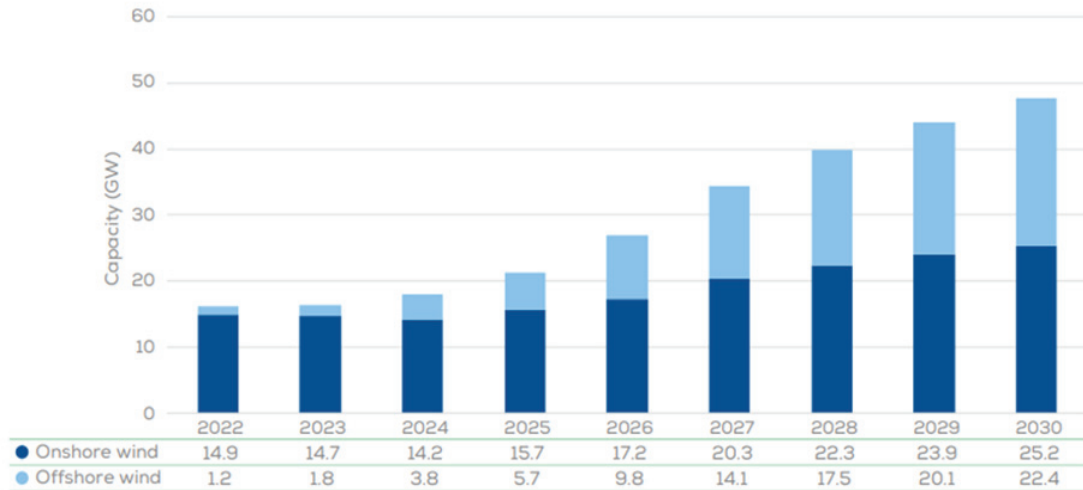


Figure 1.1. Harnessing wind energy in the EU according to the REPowerEU Scenario
(Source: Wind Europe 2022⁵)

According to the Global Wind Energy Council (GWEC)⁶, wind energy resources, which are 93 GW as of 2021, must double the current rate for countries to meet their net zero carbon targets. Limited land issues, particularly in some coastal cities (due to limitations on sites and transmission infrastructure), will mean that there will be a considerable increase in interest in offshore wind energy, which can be developed. Offshore wind energy, consisting of wind turbines installed in oceans, seas, and other waters, will be required to meet renewable energy targets. For this purpose, production and investments must gradually increase. In terms of advantages, FOWTs benefit from stronger and more consistent winds, less internal turbulence, easier transportation conditions, and the potential to enable the construction of larger turbines.⁷

Onshore wind turbines have already been significantly technically developed, and their space is limited, and their development has slowed down.⁸ Therefore, there is a huge potential demand for the application of offshore wind turbines. As an advantage, the sea surface has much lower roughness values than that of the ground, meaning that offshore wind turbine rotors will be exposed to more consistent wind speeds compared to onshore wind turbines. They also have stronger winds, indicating more significant energy recovery potential. Finally, offshore wind turbines do not deal with restrictions such as noise emissions like onshore wind turbines. FOWTs can make the most of wind resources and have the potential to reduce noise pollution.⁹ Especially recently, great strides have been made in offshore wind energy development, both in terms of engineering and investments. However, even more technological developments are needed. For example,

as of 2020, there is approximately 25 GW of offshore wind energy installed capacity in Europe alone.¹⁰ The target announced by the European Commission is to reach at least 60 GW by 2030 and up to 300 GW by 2050.¹¹ The global floating offshore wind (FOW) industry is targeting a substantial expansion to reach a capacity of 270 GW by 2050, driven by the development of floating platforms that harness large, untapped wind resources.¹² Floating offshore wind turbines (FOWT) offer the benefit of lower seabed impact than bottom-fixed turbines during both the construction and operation phases. They are projected to comprise between 5% and 15% of the global offshore wind capacity by 2050.⁴ Türkiye's current energy balance as of the end of March 2024: 29.4% hydraulic energy, 23.2% natural gas, 20.2% coal, 11.7% solar, 11.2% wind, 1.6% geothermal, and 2.5% consists of other sources. (Republic of Türkiye Ministry of Energy and Natural Resources, 2023).¹⁴ According to WindEurope's 2021 statistics, the installed capacity of land-based wind energy exceeds 10 GW, with the majority located in the Aegean Region. This area is expected to spread to the seas over time as of 2024, there are no offshore wind farms in Türkiye yet. However, there is offshore wind potential out of a total of 75 GW, of which 12 GW is suitable for fixed base foundations and 63 GW is for floating foundations. (Energy Sector Management Assistance Program, 2019).¹⁵ In Figure 1.2, in terms of water depth, floating wind turbines are likely to be cost-effective and technically feasible on the West coast of Türkiye.

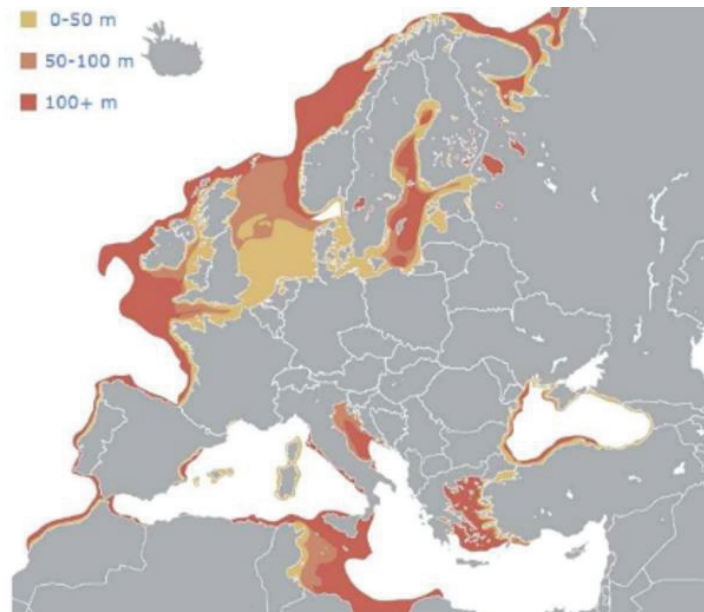


Figure 1.2. Water depth around Europe
(Source: DeepWind'2014¹³)

Floating offshore wind turbines have different platform types, which can be adapted to match specific site conditions. Spar, semi-submersible, barge, and Tension Leg Platform (TLP) type platforms can be considered. As shown in Figure 1.3, there are three main categories of wind turbine stabilization methods. In the ballast stabilized corner, turbines maintain their stability underwater using additional weights, such as the "Hywind" platform. In the buoyancy stabilized corner, turbines provide stabilization with their buoyancy on the water, and platforms such as Barge become stable with this method. Finally, in the Mooring stabilized corner, the platforms are stabilized by connecting them to the bottom of the water with iron or cable; TLP is an example in this category. In addition, there are hybrid platforms that provide both ballast and buoyancy stabilization, the most popular of which is the semi-submersible platform. This platform consists of partially submerged structures underwater and floating structures carrying wind turbines on top, and the submerged parts of the structures extend into the depths of the sea, providing both the weight and buoyancy capacity of the platform.

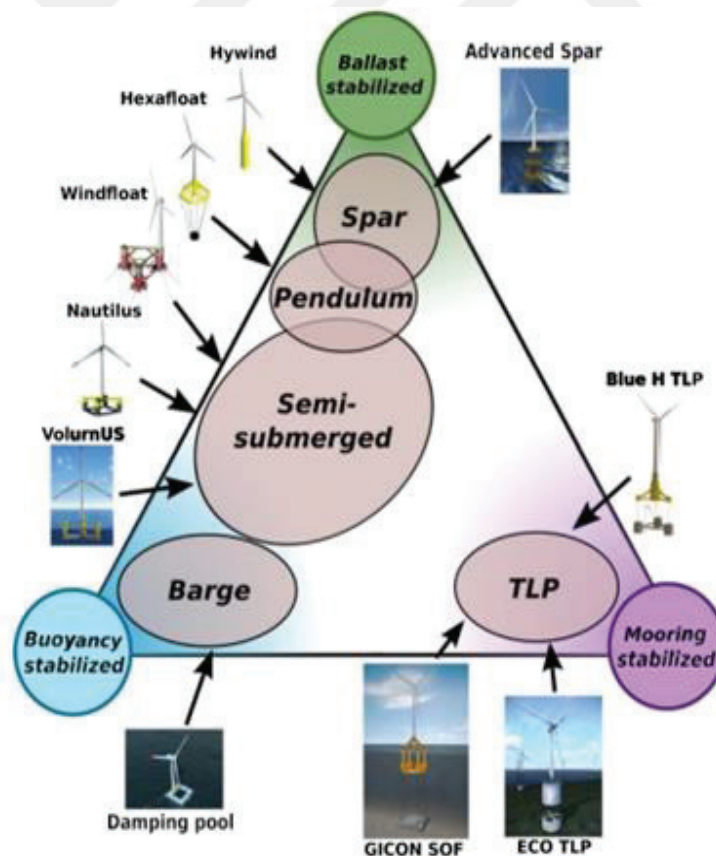


Figure 1.3. Classification of floating platform types
(Source: Faraggiana et al. 2022¹⁶)

The spar-type platform is a large diameter vertical floating cylinder. It contains ballast at a deep point to ensure better stability. In general, with the advantage of a “deep draft” design of the spar platform type, it is more stable in a Semi-submersible platform. Additionally, its configuration is much simpler than all other types, and anchorage system costs are lower than TLP. However, the deep draft design also has negative aspects; transportation and installation processes are much more complicated for ships and cannot be used in shallow water depths. They are especially functional in water depths deeper than 100 m. TLP type also includes pontoons and columns. These columns have a unique structure for this species. The binding arrangement and system for TLP are also unique in terms of design in that they are made with vertically tensioned tendons. These tendons provide stability to the structure; Its movement is naturally quite limited. It is the most stable type. In contrast, high-stiffness design can make the structure vulnerable to high-frequency dynamic loads that can produce resonance in heave and pitch. They can lead to fatigue damage to tendons or total structural failure.^{17,18}

Table 1.1. The positive and negative aspects of basic platforms derived from
(Source: Bashetty et al. 2021¹⁹)

Platforms	Advantages	Disadvantages
Semi-submersible platform	Lower draft requirements than spar for deep waters	Higher wave-induced movements
	Low mooring costs and LCOE	Complex Structure
	Easy installation and maintenance and Lighter weight	Natural frequency values
Spar buoy platform	Lower wave-induced motions	High weight
	Higher stability	Difficult installation and maintenance
	Uncomplicated design	High fatigue loads in the tower
	Low LCOE	Only suitable for deep water
TLP platform	Reduced fatigue loads	Increased mooring expenses
	Lower wave-induced motions	Higher LCOE
	Simple structure	Challenging to tow and install

As seen in Table 1.1, various platforms have some advantages and disadvantages depending on the site and water depth conditions. Besides these essential turbines, many hybrid platforms have been designed for different water depths. This trend is expected to increase gradually. The general trend is to install wind towers on more economical floating foundation systems in deeper waters (> 50 m) where higher and more consistent winds are available.^{20,21} Particularly for water depths between 50 m and 120 m, semi-submersible support structures and tension leg platforms (TLP) are the most common designs. In deeper waters, significantly beyond 120 m, spar-type platforms represent the most reasonable design.²² Each platform type may be more suitable depending on the different water depths.

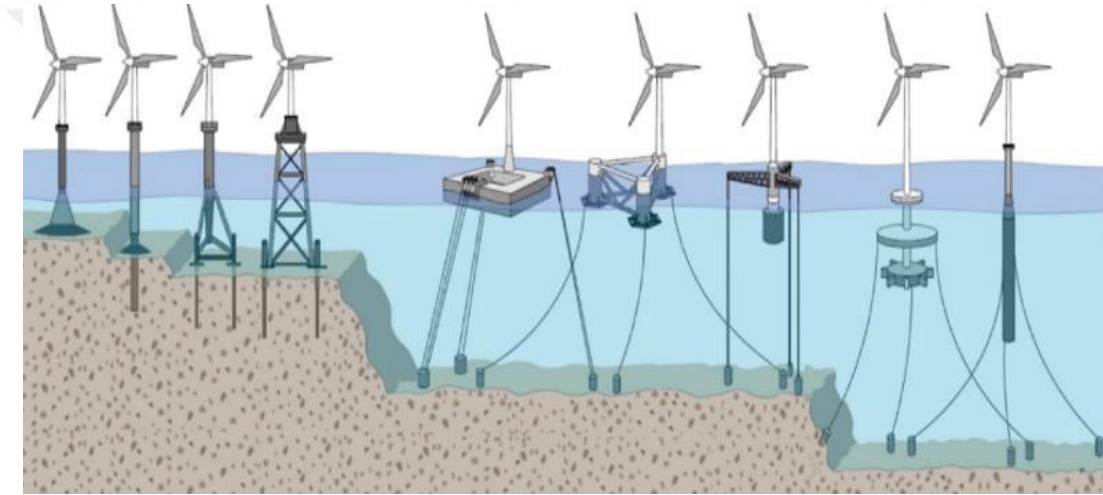


Figure 1.4. Various offshore wind turbine platform types for different water depths
(Source: Jahani et al. 2022²³)

The Levelized Energy Cost parameter is used to determine which platform is more economical. Currently (LCOE) is decreasing yearly for FOWT thanks to engineering development. Offshore wind LCOE fell from 28% to 51% between 2014 and 2020. It is predicted that this trend will continue in the coming years, and therefore, availability will be much higher.²⁴ Based on technological challenges, the advantages and disadvantages of basic floating platforms can be summarized as given in Table 1.1. In terms of LCOE, LCOE for different basic platforms, semi-submersible platforms, mast platforms, and TLP platforms are 88.69–105.59 USD/MWh, 95.36–107.39 USD/MWh, and 113.34–135.11 USD/MWh, respectively.²⁵ Briefly summarized, Floating Offshore Wind Turbines (FOWT) consist of wind turbines placed on floating platforms. These floating

platforms are balanced by design with adequate mass and weight distributions, with mooring lines and anchors securing the structure to the ocean floor. For cheaper platforms, costs can be reduced to more affordable levels by using more efficient and lighter platforms and minimizing the movement of the FOWT. Nowadays, there are unique design solutions for FOWT structures aiming to increase efficiency.²⁶ As will be mentioned in the next section, an innovative platform called FloaTolia²⁷ has been designed at IZTECH, and this design will be compared with other well-known platform designs within the scope of this thesis.

1.1. Aim of the Study

With the development of floating offshore wind turbine technology, there has been a constantly accelerating development in recent years. Numerical and experimental methods can be used in the design of floating platforms. Many different types of accuracy can be used in numerical methods. The most used of these is the Potential flow theory or Morison equation (ME), which is called mid-fidelity and is used to estimate hydrodynamic loads. These methods are also used as a hybrid approach, using the Morison equation for small elements and potential flow theory for other significant components. In this way, the hybrid approach provides comprehensive analysis for both small and large structural elements. Among the programs that use the hybrid approach, OrcaFlex²⁸, AQWA²⁹, and other hydrodynamic programs can be given as examples. Among the programs that obtain hydrodynamic coefficients using only the potential flow solver are programs such as Wave Analysis MIT (WAMIT)³⁰, NEMOH³¹, HAMS³², and Capytaine³³. These programs calculate the hydrodynamic coefficient outputs of the platforms, and Their outputs are given as input to programs such as HAWC2, the 2nd generation of the Horizontal Axis Wind Turbine Simulation Code³⁵, and the Open-Source Fatigue, Aerodynamics, Structures, and Turbulence software OpenFAST³⁶. Similar to these programs, FLEX5³⁴ can also be cited as an example. This thesis aims to compare different platform types and examine the innovative platform designed by IZTECH on a 5 MW National Renewable Energy Laboratory (NREL) reference wind turbine³⁷ using OpenFAST. For this, different programs are used, and one of them is selected to compare the compared platforms. In addition, this thesis uses the F2A³⁹, which combines the FAST v7³⁸ and AQWA programs using a Dynamic Link Library (DLL). Unlike other programs,

this method has been used to highlight the distinction between defining the platform as rigid and flexible and to analyze it with the aim of including the flexible members of the innovative platform. The main topics briefly focused on in this thesis are:

- To give information about the theoretical background
- To explain the methodologies and programs used in numerical analysis.
- Explaining the hydrodynamic loads of the FloaTolia platform and the methods and features to be used to connect it to the 5 MW NREL wind turbine.
- Finding responses for different components using spar, semi-submersible, and FloaTolia platforms with load cases containing different wind and wave conditions.
- To transfer and match the hydrodynamic coefficients using different potential solvers for spar and semi-submersible and compare the most accurate method with the validation study.
- To compare the FloaTolia platform with other known platforms, such as spar and semi-submersible for load cases determined using the selected potential solver.

1.2. Thesis Outline

The organization of this thesis is as follows. The first three chapters are devoted to the general introductory literature review and methodology on the topics in this study. Chapter 1 focuses on the introduction of the platform and floating wind turbine and its development in Türkiye and the world.

Chapter 2 is devoted to researching and evaluating studies that include similar methods used in literature review. In Chapter 3, the theoretical background of different disciplines is given, and more emphasis is placed on aerodynamic and hydrodynamic theories.

In Chapter 4, the programs used in the numerical methods of the thesis are explained, and the methodology of the thesis is mentioned.

In Chapter 5, detailed information is given about the characteristics of the platforms and turbines to be used in the analysis, modeling, and hydrodynamic preprocessing before starting the simulation for the platforms to be used in the analysis, as well as information about the load state to be used in the mesh study and analysis in this process.

In Chapter 6, the analysis results are shared. The graphs obtained here include the differences between platforms and methods.

In Chapter 7, the results are interpreted, and ideas for future work are presented.



CHAPTER 2

LITERATURE REVIEW

FOWT technology is still in its development phase, and the design process remains uncertain. A considerable number of experimental, numerical, and hybrid methods are used in this process. In the numerical part, there are three different model approaches in this process: high, mid, and low fidelity. These models comply with standards and have advantages and disadvantages against each other in terms of time, cost, and Central Processing Unit (CPU) problems. Particularly with mid and high-fidelity methods, the results of the analyses are obtained in the time domain. While high-fidelity models use costly methods such as Computational Fluid Dynamics (CFD) in terms of CPU and time, medium-fidelity models use faster methods such as Blade Element Momentum Theory (BEMT), Morison equation, and potential flow theory. While there are programs such as AQWA²⁹, WAMIT³⁰, NEMOH³¹, HAMS³², Capytaine³³, and Wave Energy Converter Simulator (WEC-Sim)⁴³ in the hydrodynamics section, the output results of these programs are given as input to aero-hydro-servo-elastic programs.

HAWC2³⁵ was developed by the Technical University of Denmark (DTU) and is a hydrodynamic model for FOWT modeling and analyses. It is an aero-hydro-servo-elastic time domain solver program. Bladed40 is an aero-elastic code developed by Det Norske Veritas (DNV). SINTEF's SIMA42, which includes hydrodynamic and mooring modules, was originally developed for the oil and gas industry. SIMPACK⁴¹ is also a general multibody simulation tool with a dedicated wind simulator, which has an elastic module and interfaces with other FAST modules such as HydroDyn, AeroDyn, or Bladed for coupled simulations of FOWTs. The last and most frequently used of these is the aero-hydro-servo-elastic glue code OPENFAST³⁶. Many studies have been done to obtain predictive data about new-generation wind turbines and platform design, validation, verification, and time domain simulations using these programs. The most prominent of these are LIFES50+⁴⁴ and Offshore Code Series⁴⁵⁻⁴⁸. It is especially important to verify the numerical model. Coupled codes or programs can be used before experimental results to ensure the accuracy of the model. In addition, a code-to-code verification process can

also be used. OpenFAST is a program that has undergone several literature validations and verifications due to its open-source nature. In this program, validation and verification studies of widely used platforms such as spar, semi-submersible type platforms, and TLP have been carried out by many users, and they are suitable for use.¹⁶

As seen in Figure 2.1, different fidelity models are shown for various programs. This figure examines the models from a hydrodynamic perspective. As mentioned before, there is a correlation between computational cost and accuracy and fidelity. Programs such as HAMS, WAMIT, NEMOH, AQWA diffraction module, and Capytaine, which is a Python-based linear potential flow BEM solver, are used for analyzing linear potential flow wave theory. These programs can be classified as potential flow solvers. These programs are considered low-fidelity and only provide potential flow solutions. In addition, programs such as AQWA's diffraction and response modules, along with WEC-Sim, offer flexible platform design. These can be used as hybrids by integrating potential flow solvers and the Morison equation. Moreover, these programs include Quadratic Transfer Function (QTF) solvers. While they are considered mid-fidelity compared to potential flow solvers, they have been frequently used. The accuracy of analyses can be further increased when these programs are coupled with the validated OpenFAST program.⁴⁹

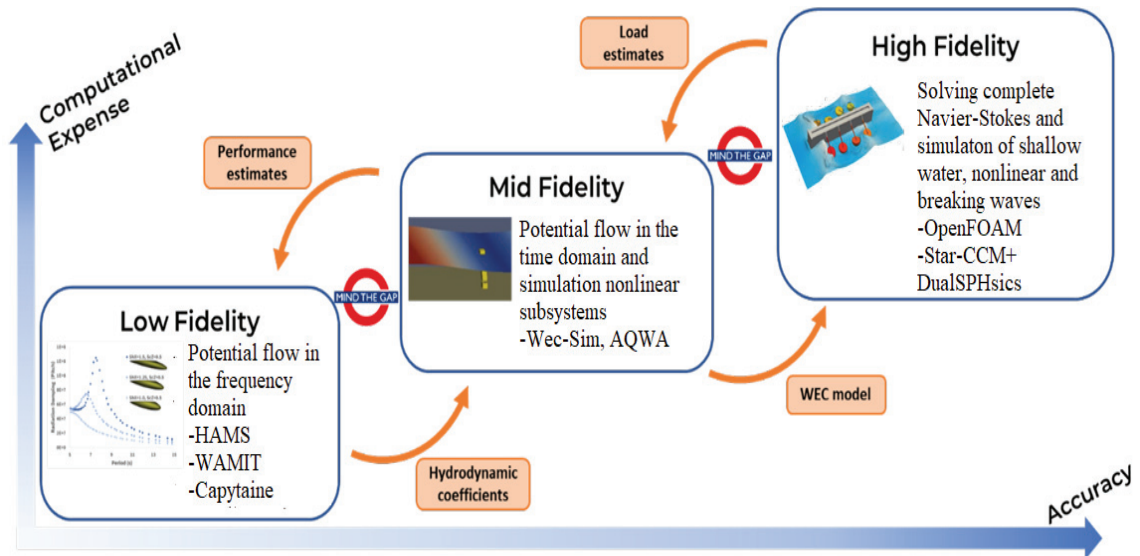


Figure 2.1. The different fidelity levels in WEC numerical modeling
(Source: Ruehl et al. 2023⁴⁹)

As illustrated in Figure 2.2 and according to the reviewed literature, there are several types of analysis. Especially in the initial design stages, frequency-domain analysis is preferred to time-domain analysis thanks to the low computational cost obtained. In addition, time-domain analysis is typically used for parametric design studies that involve less analysis. While potential flow solvers produce frequency domain output, programs such as AQWA and WEC-Sim generate time domain output and give more accurate results. In addition, semi-submersible spar and TLP are the preferred platform types in the analyzed platforms. This thesis has evaluated semi-submersible and spar platforms.

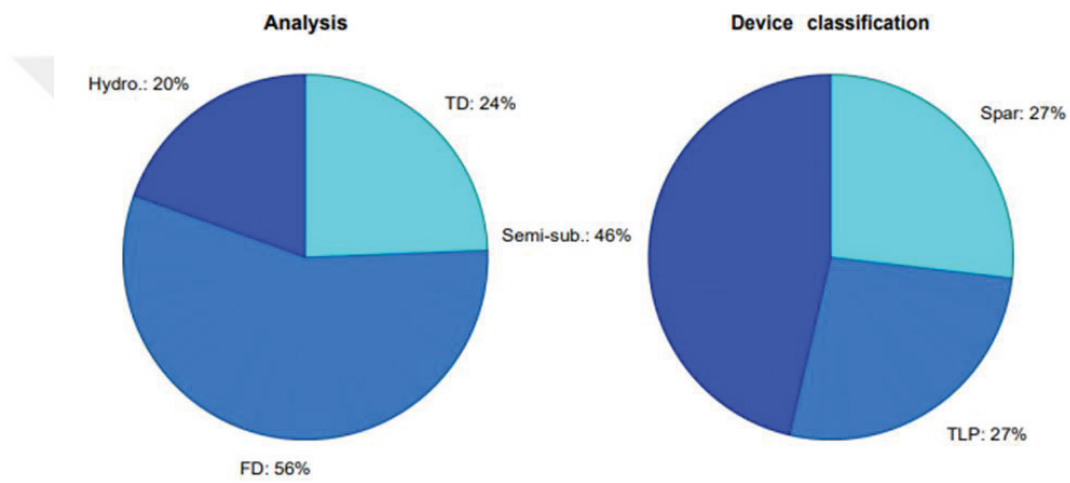


Figure 2.2. Type of platform and simulation analysis used in the literature.
(Source: Faraggiana et al. 2022¹⁶)

2.1. Analysis Types and Examples

As previously stated, there are several different methods for representing hydrodynamic loads in aero-servo-elastic programs, the first and most used of which is to obtain hydrodynamic coefficients and give them as input to the aero-servo-elastic program. This method is not considered a coupled solver, but it provides the representation of the hydrodynamic properties of the platform and is classified as low fidelity. Another method involves the coupling of two distinct programs using a Dynamic Link Library (DLL). Although this method is classified as mid-fidelity, verification has not been done as much as the first method.

2.1.1. Obtaining Hydrodynamic Coefficients (Uncoupled method)

In uncoupled analyses, the behavior of FOWTs under wind and wave conditions is determined by analyses considering the coupling effect of these environmental loads. However, this process involves complexity and difficulties, both experimentally and numerically, considering the interaction between the wind turbine behavior and the floating platform. These difficulties are overcome by adopting a non-coupled analysis approach for FOWT. This method has been used much more than the other and is obtained by giving the frequency domain hydrodynamic output as input to aero-hydro-servo-elastic programs. This method is specifically used as input to OpenFAST; the most well-known of these are FAST (the previous version of OpenFAST) and WAMIT. In this study⁵⁰, the first details of how FOWT is represented through WAMIT output files are explained. Many studies on this method involve using alternative software such as AQWA, HAMS, and NEMOH to create outputs that can serve as alternatives to those produced by WAMIT. Projects such as LIFES50+ D4⁵¹ are one of the most well-known examples. This method has been applied to three different innovative platforms using ANSYS AQWA.

Additionally, a study utilizing HAMS applied hydrodynamic coefficients to the platforms.⁵² In her master's thesis⁵³, Yıldırım Büşra compared multiple potential solvers. Numerical simulations were conducted within the Offshore Code Comparison Collaboration Continuation (OC4) framework, employing ANSYS-AQWA and the FAST open-source code.⁵⁴ These tools were used to analyze the mooring system design of a floating offshore wind turbine, integrating hydrodynamic and aerodynamic simulations to improve structural performance and stability. Furthermore, V-shaped, braceless, semi-submersible platforms were analyzed as uncoupled structures using ANSYS-AQWA.⁵⁵

The Offshore Code Comparison Collaboration, Continued, with Correlation (OC5), was utilized in the DeepCwind semisubmersible platform analysis⁵⁶, where both OrcaFlex and FAST were employed. Also, a finite element-based code developed by Texas A&M University was validated by 1:50 scale MARIN experiment results. According to a study⁵⁷, the hydrodynamic coefficients for a 10 MW wind turbine on a V-shaped semi-submersible platform at a depth of 95 meters are transferred to the HydroD (Sesam) program.

2.1.2. Coupling Programs Using DLLs

There are many studies in the literature on coupling programs that are more advanced in terms of hydrodynamic calculations and more convenient in terms of ease of design with aero-servo-elastic programs. Many studies on various combined programs, where multiple analyses were combined using different numerical models, are described.⁵⁹ The performance of the SIMO-RIFLEX and HAWC2 codes in simulating the complex dynamic behavior of a FOWT is demonstrated in a study⁶⁰. In these programs, structural dynamics are simulated using the Multibody Dynamics (MBD) method, and hydrodynamics are represented by the combination of Potential Flow (PF) and Morison Equation (ME). While evaluating the integrated behavior of the FWTS catamaran type⁶¹, the OpenFAST program was used to analyze the aero-servo-elastic components, and the ANSYS AQWA program was used to calculate the hydrodynamic loads.

In addition to FOWT analyses, the commercial OrcaFlex hydrodynamic program was coupled with the OpenFAST aero-elastic program, and the calculated movements and loads were evaluated together.⁶² It was found that the results of these two programs showed a strong correspondence. The behaviors of OC4 DeepCWind FOWT resulting from a mooring line breaking were examined using ANSYS-AQWA and OrcaFlex programs.⁶³ It has been analyzed by comparing with OpenFAST that the FAST v7 program is aero-servo-elastic integrated with ANSYS-AQWA, called F2A, and thus has sufficient capacity to model the non-linear hydrodynamics and behavior of mooring systems of a 5 MW capacity FOWT.⁶⁴

Simulations in the time domain are conducted mainly by modeling a rigid floating platform. For the analysis of platforms containing more complex and flexible members, the effect on the dynamic responses of a 20 MW capacity FOWT was analyzed using the 'SIMA' code, which is a combination of RIFLEX and SIMO software and can perform non-linear aero-hydro-servo-elastic analyzes.⁶⁵ RIFLEX is used in structural analysis based on nonlinear beam theory, which is used in modeling the platform, tower, and turbine blades. Hydro-aerodynamic loads are calculated using a PF-ME method with combined second-order difference frequency loads. The results highlight the importance of hydro-elastic deformations in coupled dynamic analyses for large-scale floating wind turbines, especially under harsh conditions. In addition to this analysis, the code coupled using FAST v7 and ANSYS-AQWA in the F2A code analysis allows the modeling of

flexible platforms.⁶⁶⁻⁶⁸

The results shown in Fig 2.3 and Fig 2.4 are a previously mentioned FAST v7-ANSYS AQWA coupling process called F2A. This process was conducted by Yang et al. (2020).⁶⁶ It was implemented to predict the nonlinear dynamics of a FOWT subjected to loadings such as wind, wave, and current to increase the simulation capabilities of the numerical tools used to design floating offshore wind turbines (FOWT). The results shown in these figures are OpenFAST comparison results with a case study on a 5 MW Offshore Code Comparison Collaboration (OC3)-Hywind spar platform wind turbine supported by NREL. The results were in perfect agreement with F2A and OpenFAST in predicting the dynamic responses of components such as the blades, tower, and platform of the turbine under wind conditions and wave effects. This proves that FAST's simulation capabilities have been successfully integrated into AQWA.

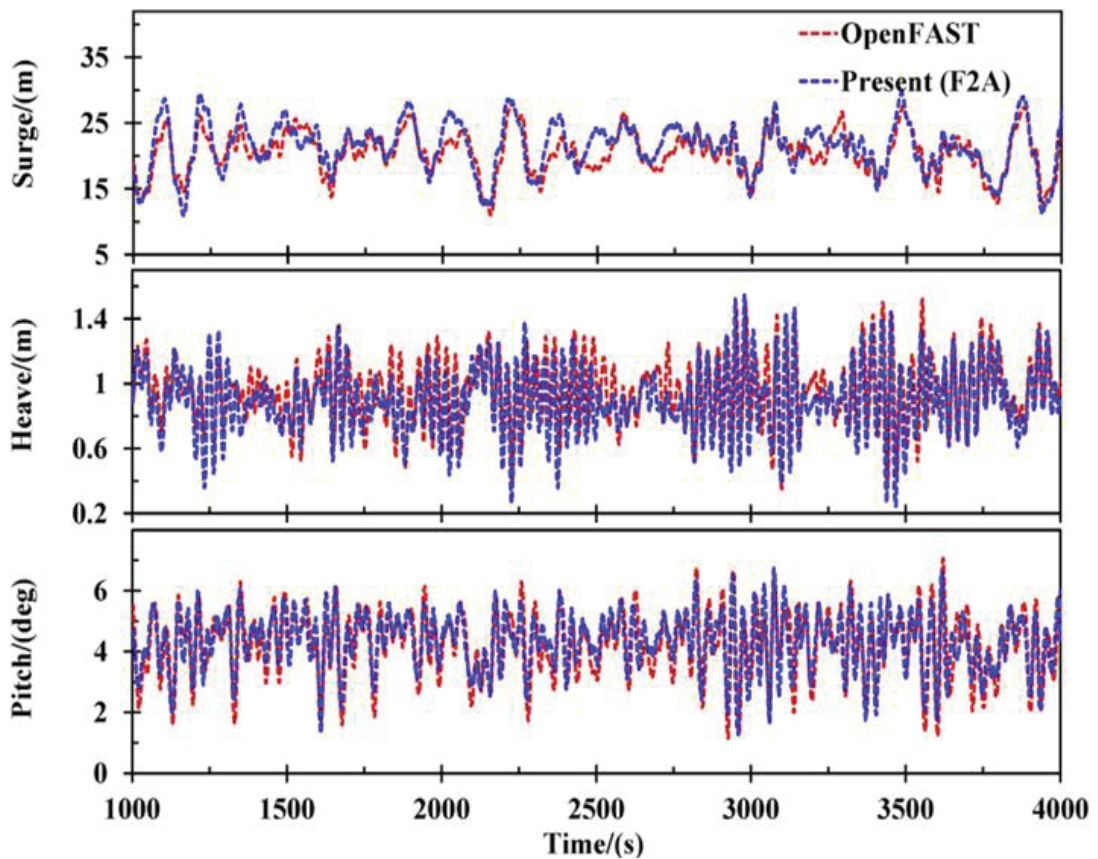


Figure 2.3. Platform motions in turbulent wind conditions reported by Yang et al.

(Source: Yang et al. 2020⁶⁶)

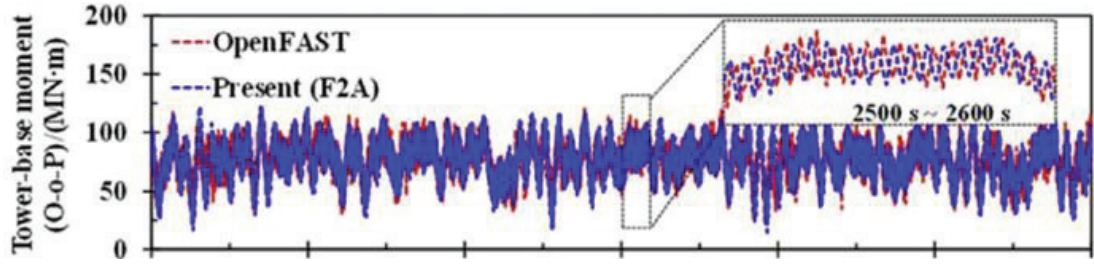


Figure 2.4. Moment loads on the tower base in turbulent wind conditions.

(Source: Yang et al. 2020⁶⁶)

As an alternative to the ANSYS AQWA program, other hydrodynamic solvers have been coupled with FAST, one of which, Wadam and FAST⁶⁹, was analyzed at a depth of one hundred meters and under combined wind and wave conditions for the semi-submersible platform. Under the same platform and conditions, FAST-WAFDUT⁷⁰ for 50-, 100-, and 200-meter depth and SIMA-FAST⁷¹ for only 200 meters were coupled and analyzed.

In this study, within the scope of the literature review, coupled and uncoupled analysis types will be shown, mostly based on NREL 5 MW FOWT and studies using OpenFAST and AQWA. In addition to these programs, several couples of programs were used to combine hydrodynamic and aerodynamic loads. DeepLines was developed as one of the fully coupled aero-hydro-servo-elastic simulation tools for floating offshore wind turbines (FOWTs), as described in the references^{72,73}. The FAST program used the blade element momentum theory (BEMT) method and dynamic stall model correction for aerodynamic loads. In addition, the finite element method (FEM), a high-accuracy method, was used for structural modeling of blades and towers. Another program is DARwind⁷⁴, in which an aero-hydro-servo-elastic coupled vehicle for FOWTs was developed based on Kane's kinetic method and BEMT theory. Finally, MOST (MATLAB for Offshore Wind Turbine Simulation Tool⁷⁵), a program that uses the MATLAB-Simulink environment, has been developed. This tool allows the simulation of innovative non-linear, time-domain numerical models and offers features such as flexibility, versatility, and low computational cost.

CHAPTER 3

THEORETICAL BACKGROUND

Floating offshore wind turbines have a theoretical background covering a range of disciplines, including aerodynamics, hydrodynamics, structural dynamics, and control systems. In Table 3.1, the theoretical background used for the design and analysis of floating wind turbines is comprehensively shown.¹⁶ While methods such as BEM and CFD are used to calculate the aerodynamic loads of the rotor, various calculation methods such as Morison equations and potential flow analysis have been shown in addition to the CFD method to find the loads on the platform in hydrodynamic calculations.

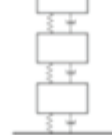
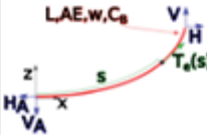
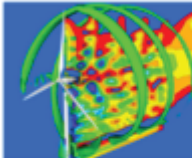
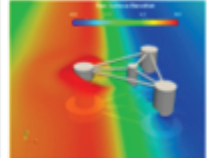
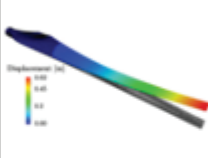
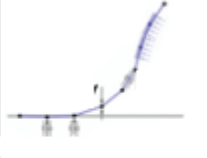
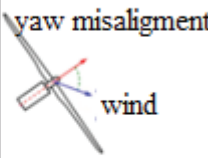
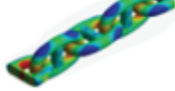
Aerodyna- mics	Hydrodyna- mics	Structural dynamics	Mooring	Control
BEM 	Morrison equation	Stiffness matrix $\epsilon = B_L q_e$	Stiffness matrix $\begin{bmatrix} \frac{F}{L} & \frac{F}{FL} \\ \frac{FL}{L} & \frac{FL}{rad} \end{bmatrix}$	Torque control $\tau = K \cdot \omega^2$
Free wake vortex 	Potential flow 	Multi-body 	Quasi-static 	Pitch control
CFD 	CFD 	FE 	Lumped mass 	Yaw control 
CFD+actuator disk 		Modal analysis 	FE, Finite Differences 	Advanced control models -LQR -MPC -Feed Forward

Figure 3.1. Modeling techniques of a FOWT (Source: Faraggiana et al. 2022¹⁶)

In structural dynamics, techniques such as finite element method (FEM) and modal analysis are used to evaluate the elasticity properties and structural integrity of different materials. In contrast, dynamic and static methods are used to simulate the behavior of loads and mooring lines for mooring dynamics. The control system uses advanced control models and basic control models such as yaw, torque, and pitch control to manage various conditions of the turbine. It is considered that the aerodynamic and hydrodynamic parts of the turbines are exposed to weather and sea conditions. In addition, the structural and controller sections have also been examined theoretically. However, this study focuses more on the numerical modeling method, so the information to be provided will be limited. The scope of the thesis will focus on Blade Element Momentum Theory (BEMT) for Aerodynamics, Morison Equation for Hydrodynamics, and Lumped Mass Theory for Mooring Line Dynamics.

3.1. Aerodynamics

The aerodynamics of FOWTs are more complex, especially since they involve the interaction of the turbine with the air and the movements of the floating platform. To cope with these challenges, a mid-fidelity model called Blade Element Momentum Theory (BEMT) is used, which is preferred over higher fidelity models such as Computational Fluid Dynamics (CFD) and Free Vortex Wake (FVW) due to its computational efficiency, ease of implementation, and sufficient accuracy.

3.1.1. Blade Element Momentum Theory (BEMT)

Among the many different theories that can be applied in terms of aerodynamics in wind turbines, Blade Element Momentum Theory (BEMT)⁷⁶, which is a combination of momentum theory and blade element theory, is classified as mid-fidelity and is considered more computationally efficient. BEMT integrates momentum theory and blade element theory to provide a comprehensive analysis of wind turbine performance. In addition to being efficient and simple, this approach is the most applied model in design and load evaluations due to its reasonable margin of error according to standards. However, the theory does not permit the calculation of the 3D flow along the radial elements of the blades and cannot model the behavior of the wake flow. Instead, it relies

on two-dimensional airfoil aerodynamic coefficients to account for section loads on the blades and uses semi-empirical corrections to represent effects such as dynamic stall or yaw misalignment. In addition, BEMT theory incorporates the Beddoes-Leishman model for dynamic stall calculations and includes Prandtl and skew wake corrections for hub losses.

Momentum theory refers to the control volume analysis of forces in the blade based on the conservation of linear and angular momentum. Blade element theory refers to the calculation of forces in a section of the blade with the function obtained using the blade geometry. BEMT is obtained by combining the results of these approaches. The theoretical foundations and formulas of the wind energy systems shown in this chapter can be found in the book "Wind Energy Explained: Theory, Design and Application", which was examined in detail by Manwell, McGowan, and Rogers (2010)⁷⁷. The formulations and graphics were obtained from this source.

3.1.1.1. Momentum Theory

In theory, the forces on the wind turbine blade and the flow conditions on the blades can be calculated by considering the conservation of momentum. The theory is that axial (a) and angular induction (a') factors are a function of the radius (r) and are based on the annular control volume shown in Figure 3.1.

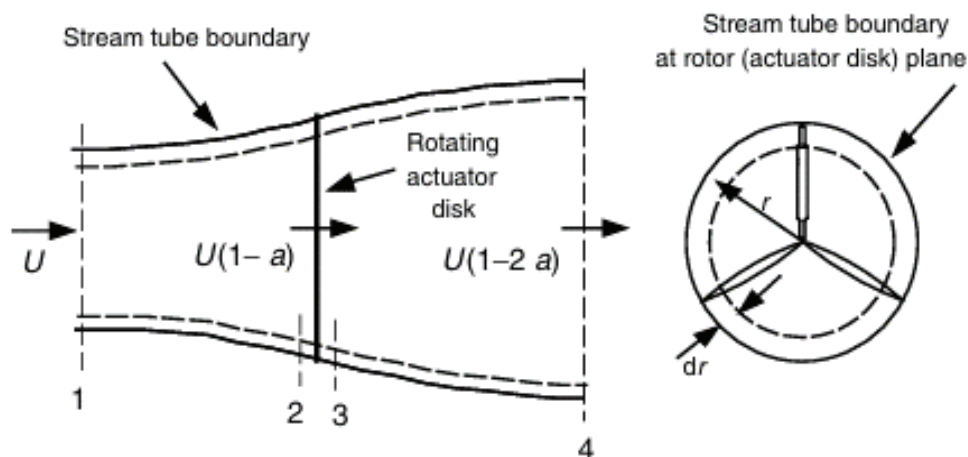


Figure 3.2. The control volume for momentum theory (Source: Manwell et al. 2010⁷⁷)

From the theory, the differential thrust force (dT) is obtained by calculating the conservation of linear momentum using the control volume with radius r , thickness dr , U , velocity of undisturbed air, ρ is the density of air as follows:

$$dT = \rho U^2 4a(1-a)\pi r dr \quad (3.1)$$

The differential in torque (dQ) is obtained as a result of calculating the conservation of angular momentum and using the control volume in the same way:

$$dQ = 4a'(1-a)\rho U \pi r^3 Q dr \quad (3.2)$$

3.1.1.2. Blade Element Theory

In theory, using the angle of attack as a function of the forces on the blades of a wind turbine, the lift and drag coefficients can be expressed. However, it can be considered when analyzing the forces that the lift and drag forces on the blade section are perpendicular and parallel to the effective or relative wind, respectively.

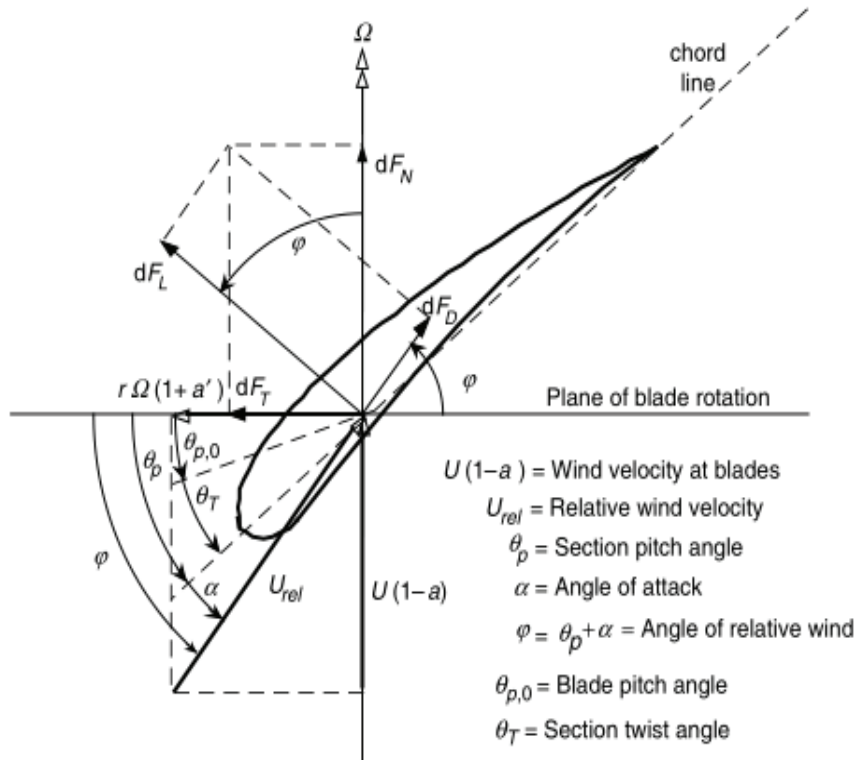


Figure 3.3. Horizontal axis wind turbine blade geometry (Source: Manwell et al. 2010⁷⁷)

The angle of relative wind is calculated as the combination of the section pitch angle and the angle of attack:

$$\varphi = \theta_p + \alpha \quad (3.3)$$

The following formulas can be obtained from Figure 3.2 and Eq. (3.3).

$$\tan\varphi = \frac{U(1-a)}{\Omega r(1+a')} = \frac{1-a}{(1+a')\lambda_r} \quad (3.4)$$

$$dF_L = C_l \frac{1}{2} \rho U_{rel}^2 c dr \quad (3.5)$$

$$dF_D = C_d \frac{1}{2} \rho U_{rel}^2 c dr \quad (3.6)$$

After the geometric transformations, lift (C_l) and drag (C_d) forces can be written in terms of normal (dF_N) and tangential (dF_T) forces:

$$dF_N = dF_L \cos \varphi + dF_D \sin \varphi \quad (3.7)$$

$$dF_T = dF_L \sin \varphi - dF_D \cos \varphi \quad (3.8)$$

Normal force is the same as thrust force $dT = dF_N$. Furthermore, when the tangential force is multiplied by the radius, the torque force is obtained. Lift (C_l) and drag (C_d) coefficients can be written in terms of thrust (dT) and torque (dQ) forces:

$$dF_N = B_2^1 \rho U_{rel}^2 (C_l \cos \varphi + C_d \sin \varphi) c dr \quad (3.9)$$

$$dQ = Br dF_T \quad (3.10)$$

$$dQ = B_2^1 \rho U_{rel}^2 (C_l \sin \varphi - C_d \cos \varphi) c r dr \quad (3.11)$$

3.1.1.3. Blade Element Momentum Theory

In theory, axial and tangential induction factors can be approximated by setting C_d equal to zero. Torque and thrust forces are equalized in both theories, and the following formulas are derived:

$$a/a' = \lambda_r / \tan \phi \quad (3.12)$$

$$a = 1/[1 + 4\sin^2 \phi / (\sigma' C_l \cos \phi)] a' \quad (3.13)$$

$$a' = 1/[(4\cos \phi / (\sigma' C_l)) - 1] \quad (3.14)$$

Derived formulas are found using the iterative method. For the equivalent solution method in the theorem, one starts by assigning values for axial (a) and tangential (a') induction factors, and from these value estimates, the flow conditions and new induction factors are calculated. The steps are as follows:

1. Select estimated values for a and a' .
2. Calculate the angle of the relative wind using Equation (3.4).
3. Calculate the angle attack from $\theta = \alpha + \theta_p$, then C_l and C_d .
4. Iteratively update a and a' with Equations (3.13) and (3.14).

This process is repeated until the newly calculated induction factors reach an acceptable tolerance value compared to the previous ones. This method can be used especially for high-load conditions.⁷⁷

3.2. Hydrodynamics

The Morison Equation calculates hydrodynamic loads for simple structures by considering the kinematic and dynamic effects of water and is generally used for small or surface structures. Potential Flow is a method suitable for structures with more complex geometries, where water is modeled as an incompressible and inviscid fluid. In this thesis,

both methods are examined and used.

3.2.1. Hydrostatic Equations

The total load resulting from linear hydrostatics on the floating platform is obtained by the sum of the two terms as follows:

$$F_i^{HS}(q) = \rho g V_o \delta_{ij} - C_{ij}^{HS} q_j \quad (3.15)$$

In the equation 3.15, $\rho g V_o \delta_{ij}$ refers to the buoyancy force coming from Archimedes' principle. This force is a force directed vertically upwards, proportional to the volume of fluid displaced, and is used only for the displacement of the platform, called heave, denoted by DOF = 3, as shown in Eq. (3.15). ρ is the water density, g is the gravitational acceleration constant, V_o is the volume of fluid displaced when the platform is in its undisplaced position, δ_{ij} is the (i,j) component of the Kronecker-Delta function (i.e., the identity matrix). q represents platform DOFs. Each platform is characterized by degrees of freedom as follows: 1 = surge, 2 = sway, 3 = heave, 4 = roll, 5 = pitch, and 6 = yaw.^{78,50,110}

$$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho g A_0 & 0 & -\rho g \iint_{A_0} dx A & 0 \\ 0 & 0 & 0 & \rho g \iint_{A_0} y^2 dA + \rho g V_o z_{COB} & 0 & 0 \\ 0 & 0 & \rho g \iint_{A_0} x dA & 0 & \rho g \iint_{A_0} x^2 dA + \rho g V_o z_{COB} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (3.16)$$

$C_{ij}^{Hydrostatic}$ represents hydrostatic force and moment changes resulting from the effects of water surface area and Center of Buoyancy (COB) as shown in Eq. (3.16). $F_i^{Hydrostatic}$ represents the cumulative load on the floating platform from linear hydrostatics.^{78,50,110}

3.2.2. Dimensionless Numbers

In the hydrodynamic loads section, the loads resulting from the excitation of incident waves, the output waves emitted from the platform movement, and the effects of the added mass and viscous forces are considered hydrodynamic loads. There are various methods of applying hydrodynamic forces. These methods include different formulations for separated and non-separated flows for a floating platform interacting with surface waves. Using the Keulegan-Carpenter number (KC), which indicates the relative importance of drag forces over inertial forces in an oscillating fluid flow (calculated in Equation 3.17), and the oscillatory Reynolds number (Re), which expresses the ratio of inertial forces to viscous forces of the fluid, two important dimensionless hydrodynamic coefficients used for cylinders and cylinder platform element flows are defined (calculated in Equation 3.18).⁷⁹

$$KC = \frac{uT}{D} \quad (3.17)$$

$$Re = \frac{uD}{\nu} \quad (3.18)$$

In the formulas, D is the cylinder diameter, ν is the kinematic viscosity of the liquid, T is the wave period, and u is the horizontal water particle velocity.

$$u = \frac{\pi H \cosh[k(Z + h)]}{T \sinh(kh)} \quad (3.19)$$

$$L = \frac{2\pi}{k} \quad (3.20)$$

In the formulas, Z represents the local depth, which is expressed as a negative value. h is the water depth, k is the wave number, and H is the wave height is defined. L is wavelength. Wave number (k), wave period, and gravity(g) are used, and wavelength dependence on water depth is calculated by an iterative formula since wavelength dependence on water depth often contains non-linear terms.

$$L = \left(\frac{gT^2}{2\pi} \right) (\tanh(kh)) \quad (3.21)$$

Flow separation becomes essential when the KC number exceeds 2. For values lower than 2, the potential flow theory is valid. In addition, when the diameter/wavelength ratio exceeds 0.2, diffraction effects become important.^{78,79}

3.2.3. Potential Flow Theory

In Figure 3.3, the flow regimes that floating structures are exposed to can be seen as a function of the Reynolds number at different wavelengths/water depths. In this graph, the y-axis is the ratio of wave height to structure diameter (H/D), and the x-axis is the ratio of wavelength to structure diameter (λ/D).

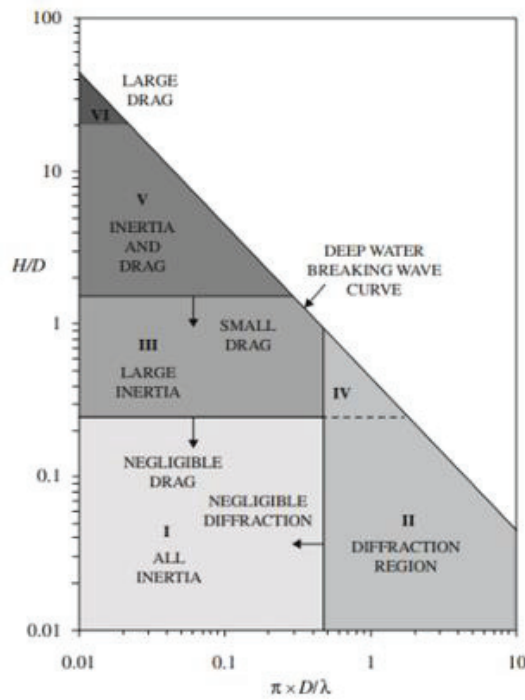


Figure 3.4. Flow regimes regions (Source: Fitzgerald 2016⁸⁰)

If the graphic is examined region by region, Region I, 'All Inertia,' includes situations where wave effects on the structure are small, and inertia dominates. Region II, 'Diffraction Region,' includes situations where wave refraction is effective. Region III, 'Large Inertia,' refers to situations where inertia forces are high and friction remains low. Region IV, "Small Drag," is a transition zone where inertia still prevails, but wave

breaking becomes important. Region V, "Inertia and Drag," both inertia and drag are effective in this zone. In Region VI, "Large Drag" includes situations where drag dominates, especially at large Reynolds numbers. Potential flow theory is used to evaluate the hydrodynamic load in cases where the ratio of the characteristic size (D) to wavelength (L) of the floating platform is greater than 0.2.⁸¹ It may be affected by the presence of a floating platform, especially due to the larger size of the incoming wave. According to this theory, at high Reynolds numbers, viscous effects are ignored as inertial forces dominate viscous forces.⁸² Consequently, hydrodynamic loads are calculated under the assumption of inviscid and irrotational flow derived from diffraction and radiation wave potentials.

From the Navier-Stokes Equations, the Laplace Equation is obtained with assumptions of the incompressible, inviscid. Therefore, the continuity equation can be written as follows using the velocity potentials.

$$\nabla^2 \phi = \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = 0 \quad (3.22)$$

To solve the above equation, boundary value problems must be considered. Dynamic and kinematic boundary conditions must be provided for the base and free surfaces.⁸³ The first boundary condition formulates the velocity approaching zero as it moves away from the water surface. The boundary condition states that the movement of the water surface and wave propagation are represented. It is stated that the sum of the time-dependent change of wave height and local acceleration ($g \frac{\partial \phi}{\partial z}$) is zero, and g is gravity.

$$w_i = \frac{\partial \phi}{\partial z_i} = 0 \text{ at } z = -h \quad \frac{\partial^2 \phi}{\partial t^2} + g \frac{\partial \phi}{\partial z} = 0 \text{ at } z = 0 \quad (3.23)$$

This formula defines the harmonic characteristic properties of the wave, which shows how the waves behave as a function of time relative to a particular point.

$$u = \frac{\partial \phi_i}{\partial x} \rightarrow \frac{\pi H}{T} \frac{\cosh(k(z+h))}{\sinh(kh)} \cos(\omega t - kx) \quad (3.24)$$

Here, H is the wave height, T is the wave period, k is the wave number, z is the water depth, and h is the depth from the water surface to the bottom and ω represents the angular frequency of the wave, and t represents time.

3.2.3.1. Hydrodynamic Coefficient at Representation in the Frequency Domain

The frequency domain approach helps to make more precise calculations, especially for wave and structure interactions, using the following formula and theoretical information. Programs such as WAMIT, HAMS, NEMOH, and AQWA, which are numerical tools called potential flow solvers, allow these calculations and modeling to be made.⁵⁰

$$F_i^{Plt}(t) = A_{ij}(\omega)\ddot{q}_j + \text{Re}\{AX_i(\omega, \beta)e^{j\omega t}\} - [C_{ij}^{Lines} + C_{ij}^{Hs}] - B_{ij}(\omega)\dot{q}_j \quad (3.25)$$

F_i^{Plt} represents the part of the overall external load on the support platform that does not include the loads coming from the wind turbine or the support platform's own weight. A is the amplitude of a regular incident wave characterized by frequency, ω and β represent frequency and direction, C_{ij}^{Lines} and C_{ij}^{Hs} represent the component of the linear restoring matrix from all mooring lines and changes in hydrostatic force and moment. A_{ij} and B_{ij} represents components of the frequency-dependent hydrodynamic-added-mass and damping matrices, respectively. $e^{j\omega t}$ represent harmonic exponential and wave-excitation force is X and Re was used to determine the actual value of the transaction.⁵⁰ Added mass is a concept where spheres oscillating in water appear to have a mass greater than their actual physical mass. This additional apparent mass results from the need to accelerate the object and the surrounding fluid. This phenomenon, known as 'added mass,' was demonstrated by experiments conducted by Chevalier DuBuat and others two centuries ago. Theoretical developments in this field have been confirmed by observations made using different methods by scientists such as Poisson, Green, Plana, Stokes, and Lamb, respectively.¹¹¹ The damping coefficient, which occurs when waves are formed on the free surface as a result of the movements of the object and these waves spread energy outwards, is a coefficient that represents the force that occurs against the movement of an object in proportion to the speed of the object. This coefficient is used

to calculate the effect of waves on the free surface and the energy transfer of this effect to the system.¹¹² Wave-excitation force describes the dynamic force waves exert on floating structures related to hydrodynamics.⁵⁰

3.2.4. Morison Equation

The hydrodynamic loads calculated using linear potential flow theory must be supplemented by the additional loads caused by flow separation. The Morison Equation is used to calculate these loads approximately. The equation calculates the total force acting on a structure and usually includes the sum of the hydrodynamic and hydrostatic forces acting on the structure under wave load. The Morison Equation uses equation (3.26) to give the total force acting on a cylindrical structure:

$$F = \frac{1}{2} C_d \rho D (u - \dot{q}) |u - \dot{q}| + (1 + C_a) \rho \frac{\pi D^2}{4} \dot{u} - C_a \rho \frac{\pi D^2}{4} \ddot{q} \quad (3.26)$$

F is the total force on the structure, C_d and C_a are the drag and added mass coefficients, respectively. ρ is the density of the liquid. D is the diameter of the structure. u represents flow rate. $\dot{q}$ represents the velocity of the structure $\dot{u}$ represents the time derivative of the flow rate, $\ddot{q}$ is the time derivative of the velocity of the structure. Figure 3.4 shows the Oscillatory Reynolds number and drag coefficient in the graph below.

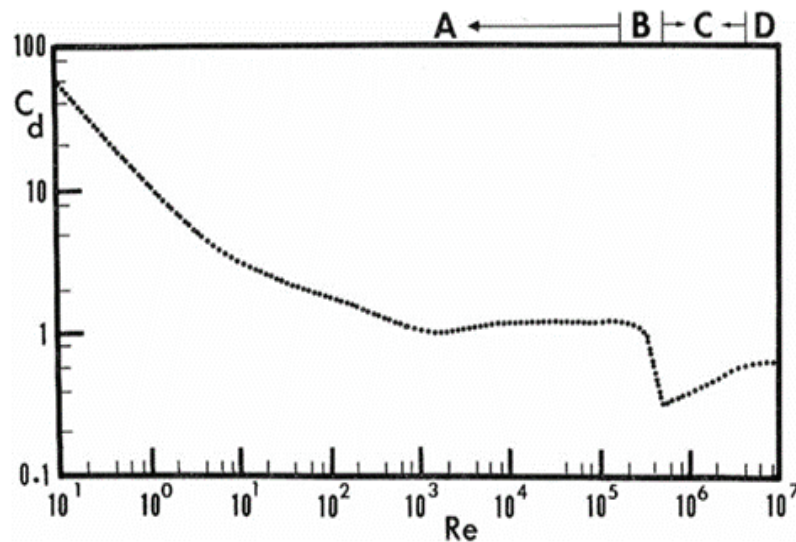


Figure 3.5. Oscillatory Reynolds number versus drag coefficient for cylinders

(Source: Schlichting 1964¹¹³)

3.3. Mooring lines

There are two different methods for mooring line analysis in the literature: static and dynamic. Figure 3.5 shows the features and types of the methods. The accuracy rate increases from static analysis to dynamic analysis. While time-varying movements are calculated for dynamic analysis, these are not calculated in static analysis. Additionally, time-varying effects caused by drag forces, added mass, damping, and acceleration are captured in the dynamic analysis. Dynamic analysis is divided into two: lumped mass and finite element analysis. Although finite element analysis is more complex and produces accurate results, it achieves similar accuracy if the lumped mass resolution is sufficient. In this study, the lumped mass method was used.

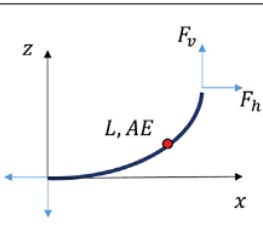
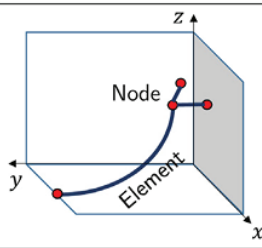
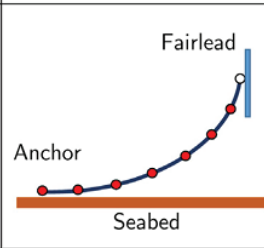
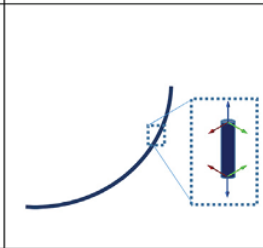
Quasi-static models		Dynamic models	
Single line element	Multi-segment line element	Lumped mass model	Finite element model
			
Incorporates seabed interaction, line elasticity	Incorporates seabed interaction, line elasticity	Incorporates seabed interaction, line elasticity, bending stiffness, inertia and damping	Incorporates seabed interaction, line elasticity, bending stiffness, torsional stiffness, inertia and damping

Figure 3.6. Mooring line models (Source: Subbulakshmi et al. 2022⁵⁸)

Lumped mass models have some disadvantages and advantages. It has a negative feature that torsional rigidity is not considered in the calculations.⁸³ The advantage of this situation is that the same mathematical basis can be used to model both the tower and the mooring lines. This allows the model to function as a common module, simplifying its structure.^{84,85}

The general equation for each node in the lumped mass model is as follows:

$$[m_i + \partial_i]\ddot{r}_i = \left(T_{i+\frac{1}{2}} - T_{i-\frac{1}{2}} + C_{i+\frac{1}{2}} - C_{i-\frac{1}{2}}\right) + (W_i + B_i) + (D_{pi} + D_{qi}) \quad (3.27)$$

$m_i + \partial_i$ represent mass and added mass, $\left(T_{i+\frac{1}{2}} - T_{i-\frac{1}{2}} + C_{i+\frac{1}{2}} - C_{i-\frac{1}{2}}\right)$ represent internal stiffness and damping, $(W_i + B_i)$ are weight and contact respectively, $(D_{pi} + D_{qi})$ are drag.

The system of second-order ordinary differential equations represented in (3.27) can be reduced to the system of first-order differential equations. These are solved step by step using the constant-time stepwise second-order Runge-Kutta (RK2) integration algorithm.⁸⁶

3.4. Structural Background

From a structural perspective, if the frequencies of large dynamic excitation forces coincide with the dynamic amplification characteristics of a wind turbine structure in resonance zones, this can cause large oscillation on the entire platform and cause the fatigue loads of the wind turbine.

Structural vibrations of a wind turbine blade can be defined in two diverse ways and can be classified as in-plane (edge direction) and out-of-plane (blade direction) directions. These are 'Edgewise' modes, where the blade vibrates along the edge parallel to the wind direction, and 'Flapwise' modes, where the blade vibrates perpendicular to the wind direction. In-plane vibrations occur in the rotation plane of the blade. Out-of-plane vibrations are vibrations originating from the rotation plane of the blade. These wind turbine modes must be considered in dynamic analyses of the turbine, especially in resonance and structural fatigue calculations. The graphs of the modes are shown in Figure 3.6. First, vibration modes are shown for the tower of a fixed base turbine, a single blade, and the rotor of a wind turbine. The main sources of dynamic excitation are wind, wave action, rotor instabilities, blade movement, and its harmonics.^{87,88}

FOWT can be exposed to a sizable portion of these dynamic loads with frequencies below 3 Hz throughout its normal life.³⁷

In addition, since the main natural frequencies of the tower bending and FOWT modes in the blade edge and blade direction are close to these values, precautions must be taken against resonance.^{89,90}

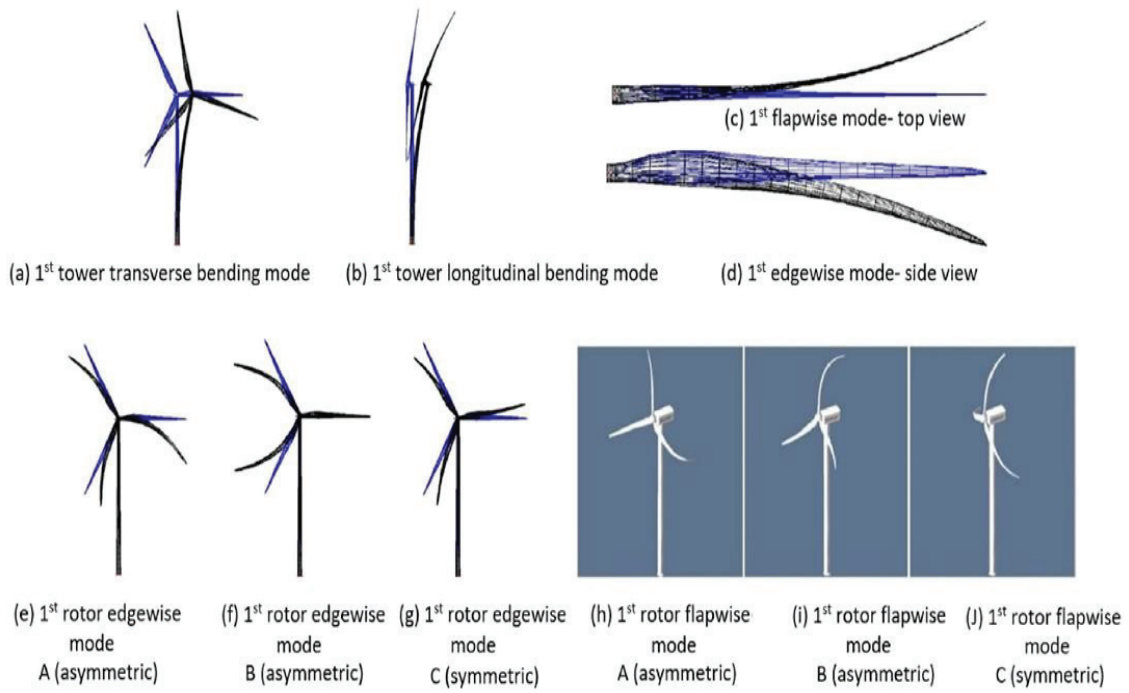


Figure 3.7. Mode shapes of a fixed-bottom wind turbine

(Source: Jahani et al. 2022²³)

Figure 3.7 shows the frequency content of load sources such as wind and waves normalized to their maximum values along with critical modes. Labels such as 1P, 3P, 6P, and 9P are called harmonics depending on the rotation speed of the turbine, where P refers to the rotation frequency of the rotor and the others to its multiples. Figure 3.6 shows the first and second bending of the tower and edgewise flapwise modes of the blade structure. The design aims to avoid wind turbine frequencies in areas that will cause resonance in the yellow regions. To design a more efficient and safer tower structure and foundation, it is essential that the tower's first bending frequency aligns with the rotor speed's first order (1P) and that the blade passing frequency falls within the range of (3P). The values below (1 P) are referred to as the soft-soft region, and designing within this region is undesirable due to the excessive flexibility of the structure and the need to avoid coinciding with excitation frequencies, such as those from wind waves.

Similarly, after (3 P), it will be a stiff-stiff region, and it is considered unnecessarily costly and heavy.²³ Furthermore, the damping caused by wind and waves during the operation of the turbine plays a crucial role in decreasing the amplitude of dynamic amplifications at resonance points.

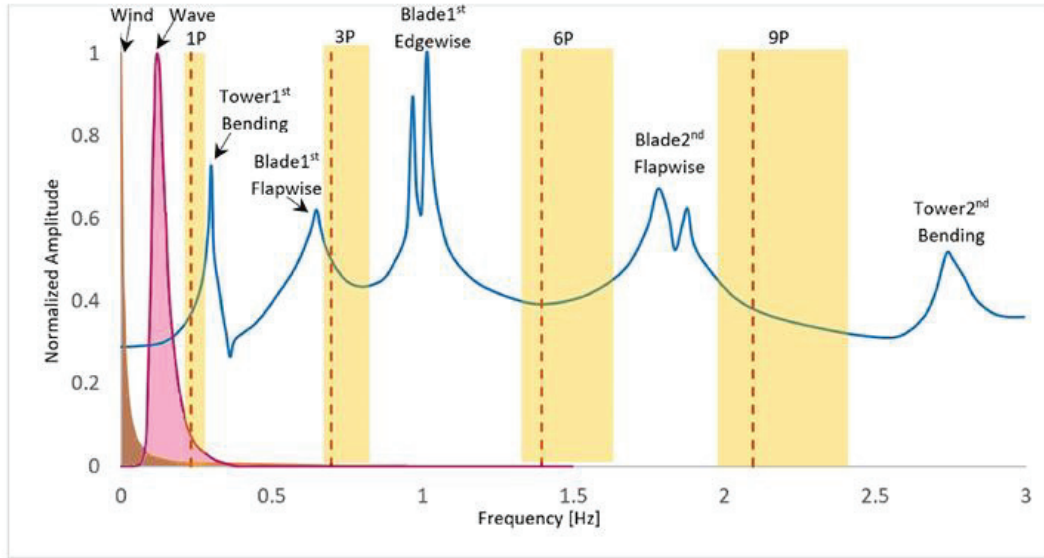


Figure 3.8. Frequency response function and the dynamic loads of a FOWT
(Source: Jahani et al. 2022²³)

3.5. Controller

The controller regulates the turbine's performance in wind turbines by considering the wind speed. The aim here is to keep power production high by minimizing fatigue and overload of the structure. Additionally, the controller controls constant power generation within design limits at wind speeds above the nominal speed and optimizes power generation below the nominal speed.⁹¹

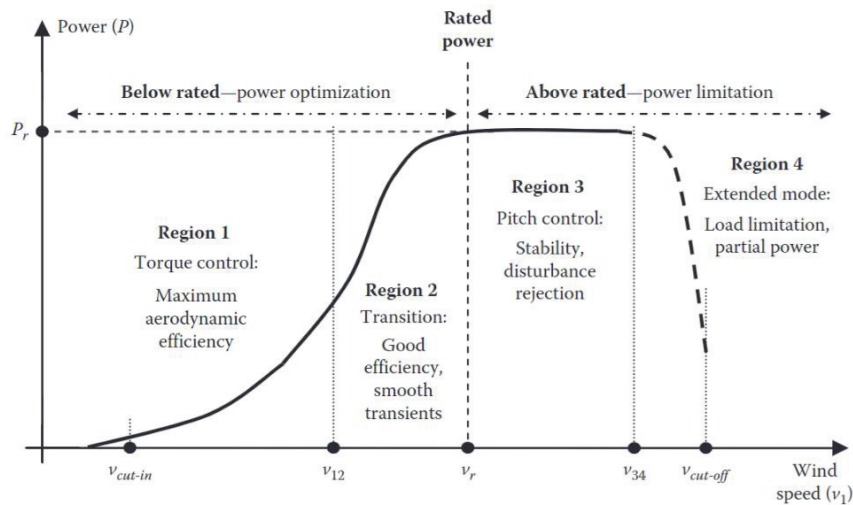


Figure 3.9. Different operating regions of a wind turbine controller
(Source: Garcia-Sanz and Houpsis 2012⁹²)

The operations performed by the controller can be examined in four different regions. Here, critical values such as cut-off and rated speed determine the boundaries of the areas. As seen in Figure 3.8, it is explained as follows:

In Region 1, the aim is to provide maximum aerodynamic efficiency by controlling the torque. In this region, the turbine starts to work "cut-in" to the wind speed, and as the speed increases, the power produced increases.

Region 2 is where the power produced is more uniform and efficient and is limited to nominal power. In this region, the wind speed approaches the nominal wind speed and goes to the transition zone where the turbine operates still efficiently.

In Region 3, the nominal power is kept constant while the pitch controller takes over³⁷ until the cut-out wind speed is reached. This action aims to ensure the stability of the turbine.

In Region 4, the turbine operates at partial power under load limitations to prevent overloads and is the last zone before reaching the "cut-off" speed (the maximum wind speed at which the turbine stops). After this speed, the turbine shuts down for safety reasons. This zone is called Extended Mode.

CHAPTER 4

METHODOLOGY

This study describes the approaches used to analyze the behavior and response of different platform types, such as semi-submersible and spar, one of which is an innovative platform developed at Izmir Institute of Technology (FloaTolia), where the NREL 5 MW floating offshore wind turbine and controller is employed in different wind and wave conditions. In this study, a couple of methods of offshore wind turbine aerodynamics and platform hydrodynamics were carried out with two approaches.

The first approach in this study is the so-called F2A method, which couples AQWA and FAST v7. In contrast, the second approach uses the hydrodynamic properties of the platform and the hydrodynamic coefficients, specifically added mass, radiation damping, and excitation forces matrices mentioned in Chapter 3 as inputs in the frequency domain version of OpenFAST v3.51. The programs used were NEMOH, Capytaine, and AQWA. For both approaches, designs were created using ANSYS Design Modeler, and meshing was performed using ANSYS AQWA using a panel code technique.

BEMRosetta is specifically used to convert the output of various potential flow solvers such as AQWA, Capytaine, and NEMOH into a WAMIT-compatible format, which can then be used as input files for OpenFAST. Additionally, BEMRosetta can also be used for mesh checking. This conversion process allows the seamless integration of hydrodynamic data into OpenFAST simulations. Additionally, PyDatView plays a critical role in the post-processing phase, where it is used to read and analyze output from OpenFAST v3.51 or FAST v7. This tool allows for detailed examination and manipulation of data, facilitating the assessment of simulation results. Thanks to PyDatView, damping, and natural frequencies can be identified during free decay tests, and power spectral density graphs can also be derived from these output files.

These features of both BEMRosetta and PyDatView, which are critical to the simulation workflow, are illustrated in Figure 4.1. The uncoupled methods used in this study are highlighted in orange in the flowchart, while the coupled methods are shown in gray.

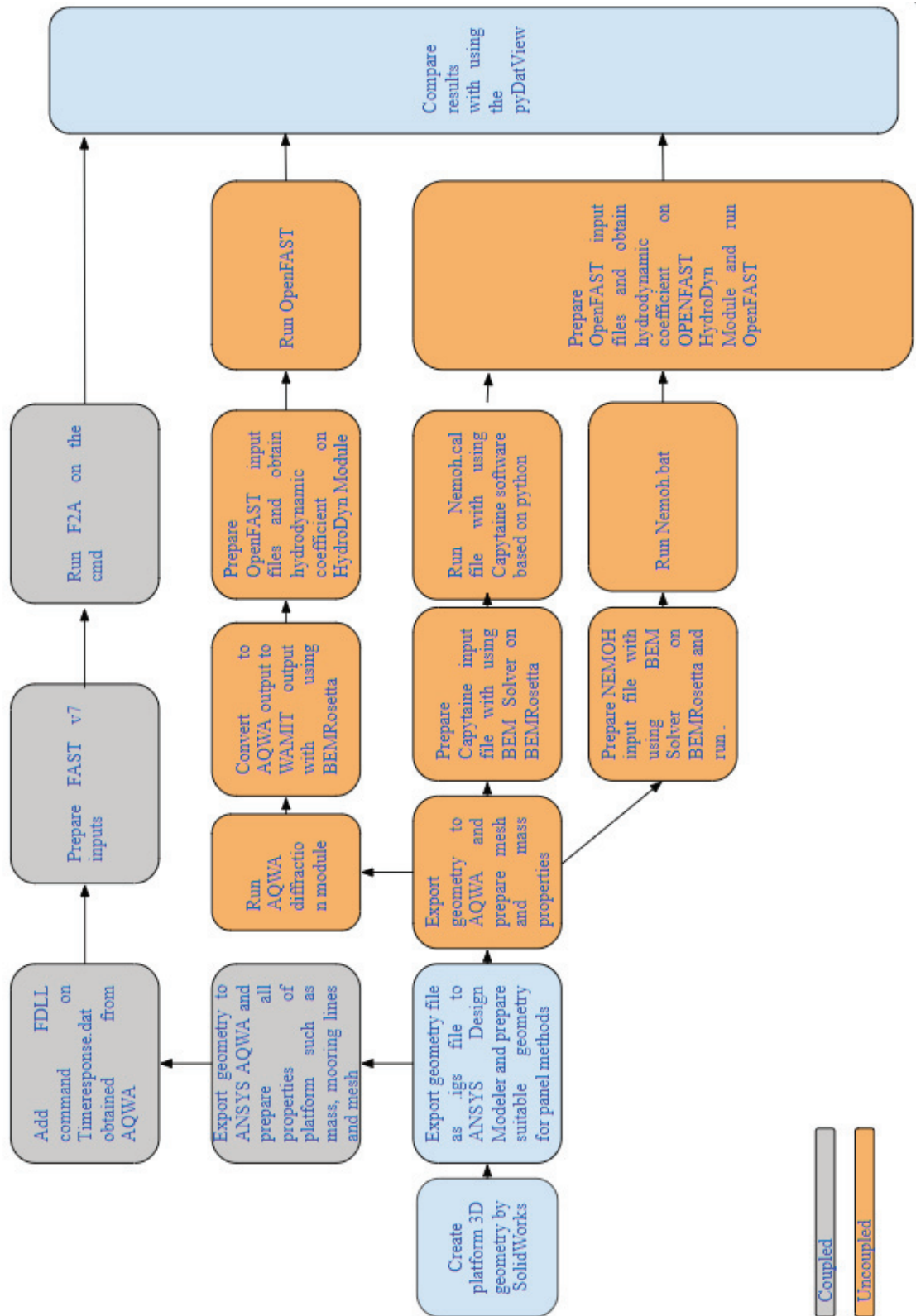


Figure 4.1: The flowchart of thesis

4.1. Aero-Servo-Hydro-Elastic Programs

In the scope of this thesis, OpenFAST was utilized as an aero-servo-hydro-elastic tool in FOWT (Floating Offshore Wind Turbines) modeling and analysis. OpenFAST^{36,93} is the open-source version of the FAST (Fatigue, Aerodynamics, Structures, and Turbulence) program. Developed by the National Renewable Energy Laboratory (NREL), this software enables the simulation of aerodynamics, structural dynamics, servo dynamics, and hydrodynamics, making it suitable for wind turbine design.

4.1.1. OpenFAST

OpenFAST can model critical physics and system connections for FOWTs under loads such as wind, wave, and current, and as stated in the standards, it can model both normal (fatigue) and extreme (ultimate) whole system dynamic response. It allows for finding load values. The program contains eight modules related to different disciplines, and the connection between modules is provided through the glue (driver) code in the OpenFAST program.

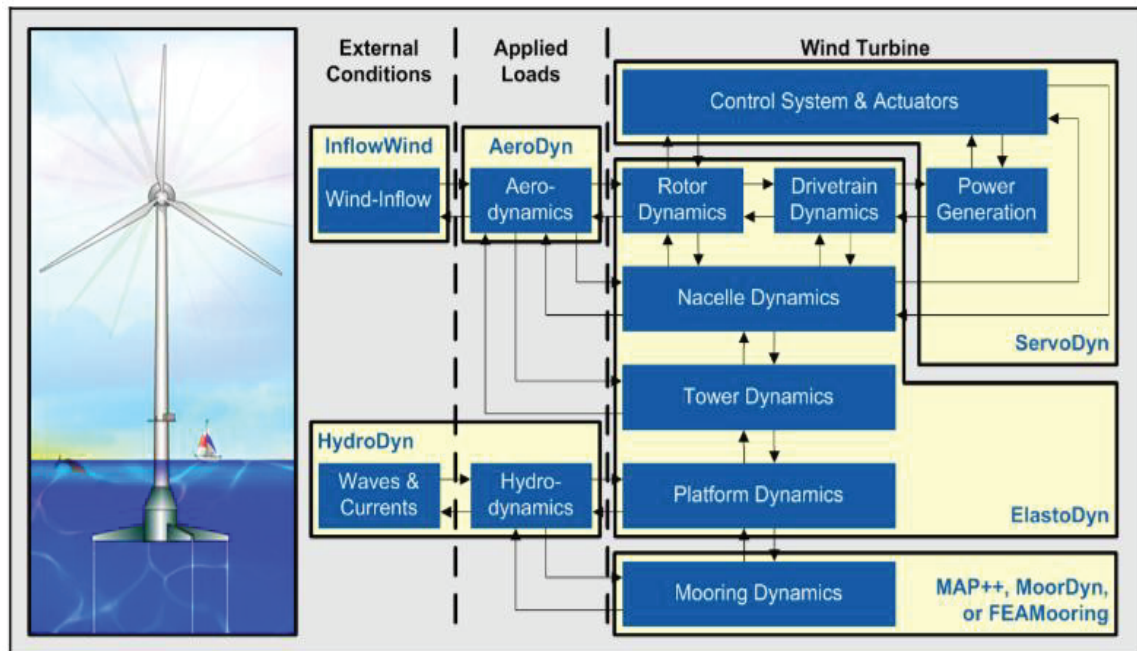


Figure 4.2. OpenFAST modules and control volumes for FOWTs

(Source: Jonkman et al. 2016⁹⁴)

4.1.1.1. AeroDyn

OpenFAST's AeroDyn module uses the standard-compliant and widely used BEMT theory. In addition, it is enhanced with advanced corrections that will make the model more fidelity, such as rotor wake induction, local flow distortions, high induction, tip and hub loss, and dynamic wake. It can model aerodynamics, blade profile aerodynamics, and tower effects.

Aerodynamic calculations in AeroDyn are based on the principles of actuator lines, where three-dimensional (3D) flow around a body is approximated by local two-dimensional (2D) flow in cross sections and distributed compressive and shear stresses are approximated. The lift forces, drag forces, and pitching moments collected at a node within the section are assumed to be spread along the length of each blade and tower, and the 3D aerodynamic loads are calculated and summed. The 2D forces and moments at each node are calculated and summed as spread loads per unit length. This result determines the 3D aerodynamic loads.⁹⁵

4.1.1.2. HydroDyn

OpenFAST's HydroDyn module specializes in analyzing hydrodynamic loads, particularly for large-volume platform members. This module utilizes a potential flow solution that is converted from the frequency domain to the time domain to model these members accurately. To facilitate this modeling, HydroDyn requires specific types of input, namely WAMIT output files. For the first-order potential flow solution, WAMIT output files with .1, .3, and .hst extensions must be given as input to HydroDyn. In addition, the full difference and total frequency of the quadratic transfer function (QTFs), respectively, are based on the first-order or first-plus-second-order potential. It is provided with WAMIT output files with the extensions 10d, .11d, and .12d or .10s, .11s, and .12s. It employs a hybrid approach for thinner elements where viscous effects dominate and in large volume bodies where radiation and diffraction are significant. Additionally, strip theory, which offers an advanced solution, is utilized for modeling these thinner elements. In terms of wave kinematics, linear (Airy) and second-order wave theories (Sharma and Dean) are used.⁹⁶

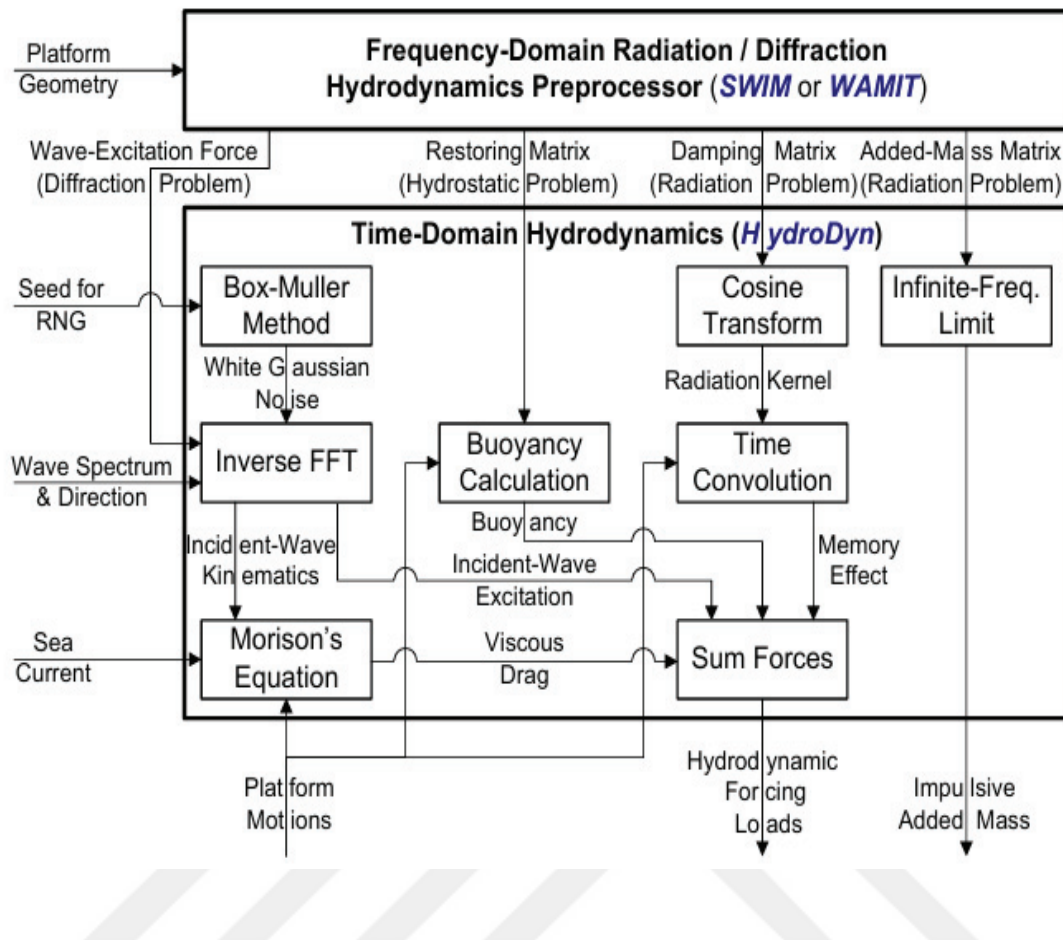


Figure 4.3. The HydroDyn calculation procedure

(Source: Jonkman 2007⁵⁰)

Platform hydrostatic and hydrodynamic matrices, restoring, damping, and additional mass matrices are generated by WAMIT, and similar potential flow solvers are provided as input to HydroDyn as frequency domain. In the time domain, HydroDyn also calculates the viscous drag forces caused by waves and currents using Morison's Equation.⁵⁰

In addition, cosine transformation and time convolution provide time-dependent solutions for radiation and memory effects. The buoyancy of the platform and the impact of the waves on the platform are calculated using buoyancy calculation and incident-wave excitation. In addition, Gaussian noise is generated with the Box-Muller method, and wave movements are estimated with inverse FFT. Also, different seeds can be used to generate random wave inputs.⁵⁰

4.1.1.3. TurbSim and InflowWind

TurbSim software is used to model atmospheric boundary layer flow for wind turbines with the features of wind speed profiling, generating turbulent wind and creating coherent wind fields. As seen in Figure 4.4, a turbulence box is used when using TurbSim. This box is given as input to TurbSim according to an equal grid distance and hub height. In addition, the number of grid nodes should be adjusted according to the blade and tower node distances to increase the resolution of the box. In the TurbSim, the Kaimal model is used, which is one of the two turbulence models (Mann and Kaimal) specified in IEC 61400-1⁹⁷ and fits limited data from short meteorological poles⁹⁸.

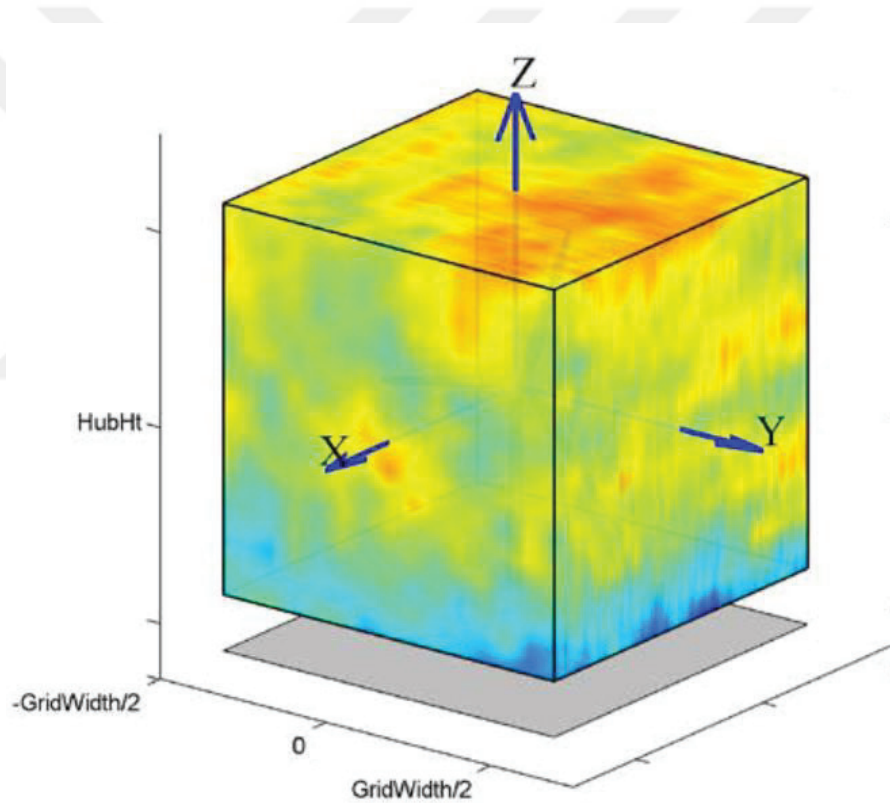


Figure 4.4. Turbulence box around the wind turbine (Source: Jonkman 2014⁹⁸)

In the InflowWind¹⁰⁰ module, the output obtained from TurbSim is used as input wind condition. Additionally, uniform or steady wind flow can be obtained and applied with InflowWind without using the TurbSim program. In both programs, fundamental values such as shear exponent and turbulence intensity must be entered as input. Figure 4.5 shows an example of the distribution of turbulent wind.

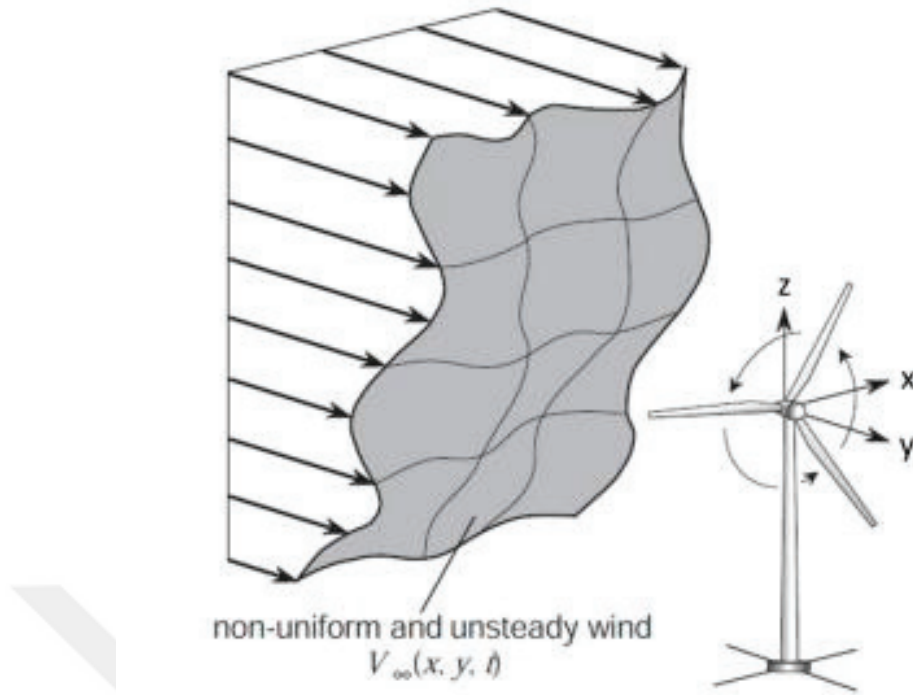


Figure 4.5. Spatial distribution of a wind field around a wind turbine
(Source: Hasegava et al. 2004¹⁰¹)

4.1.1.4. ElastoDyn, ServoDyn MoorDyn

The basic structural dynamics module in the OpenFAST program is called ElastoDyn. Initial parameters can be given, degrees of freedom can be changed, and the mass inertia and position values of the wind turbine and platform can be defined. It uses blades and considers the moderate bending deflection of the tower, and other components, such as the nacelle, hub, and platform, are considered rigid structures. It uses non-linear multibody and modal representation¹⁰². ServoDyn is primarily used to define and assign controller parameters, including structural control options such as tuned mass damper and setting DLL options and properties.¹⁰³ The lumped mass mooring line model is more advanced than dynamic models versus static models. However, the model that gives more accurate results is called MoorDyn in the OpenFAST module. This module is designed for the sole purpose of using features needed to predict the dynamics of typical mooring systems and is, regrettably, not appropriate for modeling cables with bending and torsional stiffness.¹⁰⁴

4.1.2. FAST v7 and AQWA couple (F2A)

F2A is the name given to the process of combining ANSYS-AQWA and FAST v7. Studies of this method can be found in references⁶⁶⁻⁶⁸. A pair of processes were undertaken to enable AQWA to perform a fully linked analysis of FOWTs. The scheme shown in Figure 4.6 has been implemented to integrate the simulation capabilities of FAST into AQWA and calculated via user_force.dll.

External forces are included in the aerodynamic load and structural responses of FOWTs. AQWA also relies on Rankine theory to solve for velocity and pressure potentials in the frequency domain and Green's theorem to obtain solutions for time domain solutions.³⁹

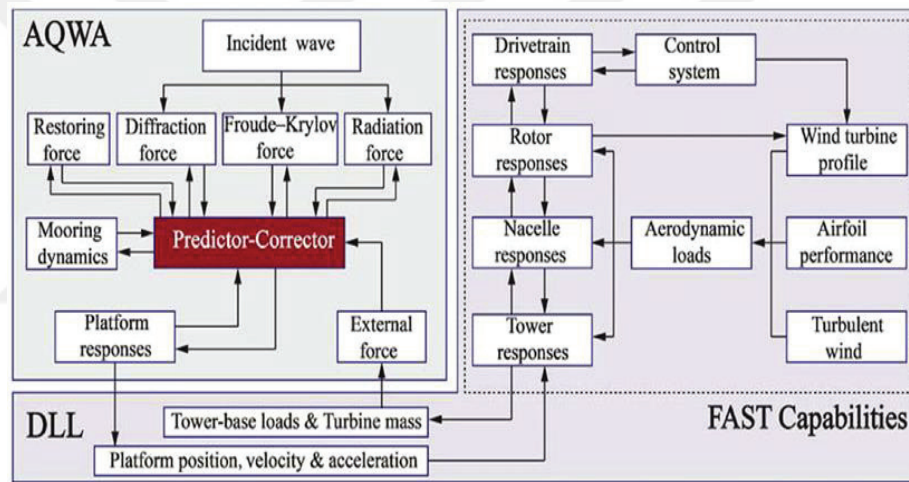


Figure 4.6. Coupling framework on F2A⁶⁶

(Source: Yang et al. 2020⁶⁶)

As seen in Figure 4.6, the program initially calculates external forces such as wave effects and the dynamics of the turbine in AQWA. It transfers the load and motion calculations of the turbine to FAST via DLL. The initial predictions are corrected with a two-stage predictor and corrector. After this, the movements of the turbine and the affecting loads are calculated by combining the initial conditions from AQWA with the calculations obtained from FAST. Since the coordinate systems are different between AQWA and FAST, they are converted to the correct format using transformation matrices, and the turbine's position, speed, and acceleration values are calculated.⁶⁶

4.2. Potential Flow Solvers and Converter Tools

In this section, potential flow solver programs and the BEMRosetta program that helps convert them as input to the OpenFAST program will be explained. The programs here take the hydrodynamic coefficient values as input rather than relying on the coupling process and are classified as low fidelity. Each of these programs includes in its output a 6×6 matrix of added mass and damping, first-order wave excitation (diffraction) loads (3 forces and three moments), and the restoring matrix provided by the buoyancy force.

4.2.1. AQWA

ANSYS AQWA consists of two different modules. The first of these modules is the diffraction module. Its outputs are in the frequency domain using the boundary element method (BEM) and are used to obtain the hydrodynamic coefficients. The method in the diffraction module in ANSYS AQWA is based on potential theory. The 3D panel method is employed as a numerical method where the surface is distinguished by the presence of singularities.²⁹ AQWA outputs the 6×6 additive mass and damping matrix, as well as the first-order wave excitation (diffraction) loads (3 forces and 3 moments) and the restoration matrix provided by the buoyancy force. It can also output full difference and total frequency QTFs on a first-order or first-plus-second-order basis, respectively. ANSYS-AQWA, unlike other programs used, is not an open-source program. In the Hydrodynamic Diffraction module section of the program, the frequency domain output is given as input to HydroDyn. In the Hydrodynamic Response module, time domain output is used in F2A with TimeResponse.dat. Within the scope of this thesis, IZTECH's licensed program was used.

4.2.2. WAMIT

WAMIT³⁰ was developed by researchers at the Massachusetts Institute of Technology and founded in 1999 by WAMIT Inc., Chang-Ho Lee, and J. Nicholas Newman. WAMIT is a commercial computer program used primarily to calculate wave loads and motions of offshore structures. It uses linear and quadratic potential theory in

its calculations. These calculations are solved by the boundary integral equation method, also called the velocity potential panel method. In addition, QTF outputs can be produced as in AQWA. Additionally, WAMIT is the hydrodynamic preprocessor of OpenFAST that is widely used, validated, and verified in many analyses. The hydrodynamic input format (hydrodynamic coefficients) recognized in OpenFAST is the output format of WAMIT. Therefore, OpenFAST can only read input files that are in WAMIT format. In OpenFAST, a program called BEMRosetta is used to convert the files obtained in other potential solver programs into WAMIT output files, and the file extensions are converted to the appropriate format. This study aims to ensure that the outputs of other programs are close to the results using WAMIT output.

4.2.3. NEMOH

NEMOH is a Potential flow solver that enables the calculation of added mass, radiation damping, and diffraction forces of first-order wave loads on offshore structures. NEMOH solves potential flow problems as a first-order problem in the frequency domain to calculate wave loads on offshore structures, especially using the boundary element method. This program has been developed for 30 years by researchers at Ecole Centrale de Nantes. Many verifications have been made and used in research. NEMOH v2.0 was used in our study. In this version, only first-order hydrodynamic coefficients could be calculated without the irregular frequency removal method. Although its accuracy is high in the studies performed, it has lower computational costs and lower accuracy in thin structures.³¹

4.2.4. Capytaine

Capytaine is a Python-based open-source program that allows the interaction between water waves and floating objects to be simulated in the frequency domain. It is modeled through a complete rewriting of NEMOH, an open-source BEM solver for linear potential flow wave theory. Capytaine, unlike other BEM problems, linear potential flow solvers solve the problem of Green's function, which describes the boundary conditions at the free surface and the seabed as a boundary integral. And solves the problem by formulating it as a problem using the Boundary Element Method (BEM). It is sufficient

to discretize only the wet surface problem by solving the boundary conditions on the free surface and the seabed with the Green's function. This differentiates the program from other BEM problems.³³

4.2.5. BEMRosetta

In marine vehicles, ships, and offshore wind turbines, potential flow solver or BEM programs are used to obtain some hydrodynamic coefficients such as radiation damping, added mass, wave diffraction force, and wave excitation force. Most of them are open sources such as NEMOH³¹, Capytaine³³, or HAMS³² or commercial such as WAMIT AQWA and can be saved in incompatible file formats in the output files. BEMRosetta has been modeled to prevent this situation and to ensure the correct use of the obtained hydrodynamic coefficients and their conversion to another format. In this way, data and hydrodynamic coefficients in appropriate formats can be created as input to programs such as OrcaFlex, WEC-Sim, OpenFAST, or DNV Bladed. In addition, the program allows viewing and comparison of mesh structures and geometries and provides the opportunity to obtain output using the BEM solvers mentioned above. It provides calculation and display of underwater surface area, center of buoyancy, hydrostatic stiffness matrix, and other parameters and mesh optimization features as well. In addition, it allows viewing OpenFAST, DeepLines Wind, ANSYS AQWA and CSV, and time domain outputs.¹⁰⁵

4.3. Postprocessing Tools

Various programs and methods can be used for output files in the post-processing phase. One of the most effective tools, which features a specific interface, is PyDatView.

4.3.1. PyDatView

PyDatView¹⁰⁶ is a useful and versatile Python-based open-source tool designed to graph the outputs of wind energy simulation programs such as OpenFAST, HAWC2, FLEX5, and Bladed.

This tool can find values such as max, min, standard deviation (std), mean, etc., from the output of time data. It can also convert the time series as a Probability Density Function (PDF) and Fast Fourier Transform (FFT) from the same output. It can compare the output obtained from different or the same programs at the same time. In addition, it can estimate frequency and damping from a free decay test output. In addition, it has features such as curve fitting, logarithmic scaling of the axes, saving data as Comma-Separated Values (CSV), and exporting the drawing as Portable Document Format (PDF) or Portable Network Graphics (PNG).

The screenshot related to PyDatView is shown in Figure 4.7. In addition to the program interface, the desired graphics can be obtained by coding a Python script file. The usage of the program in the post-processing phase is depicted in Figure 4.8. Additionally, the flowchart provides a detailed explanation of how the processes mentioned are executed, illustrating each step to ensure clarity on the workflow and the integration of scripting with the graphical outputs generated by PyDatView.

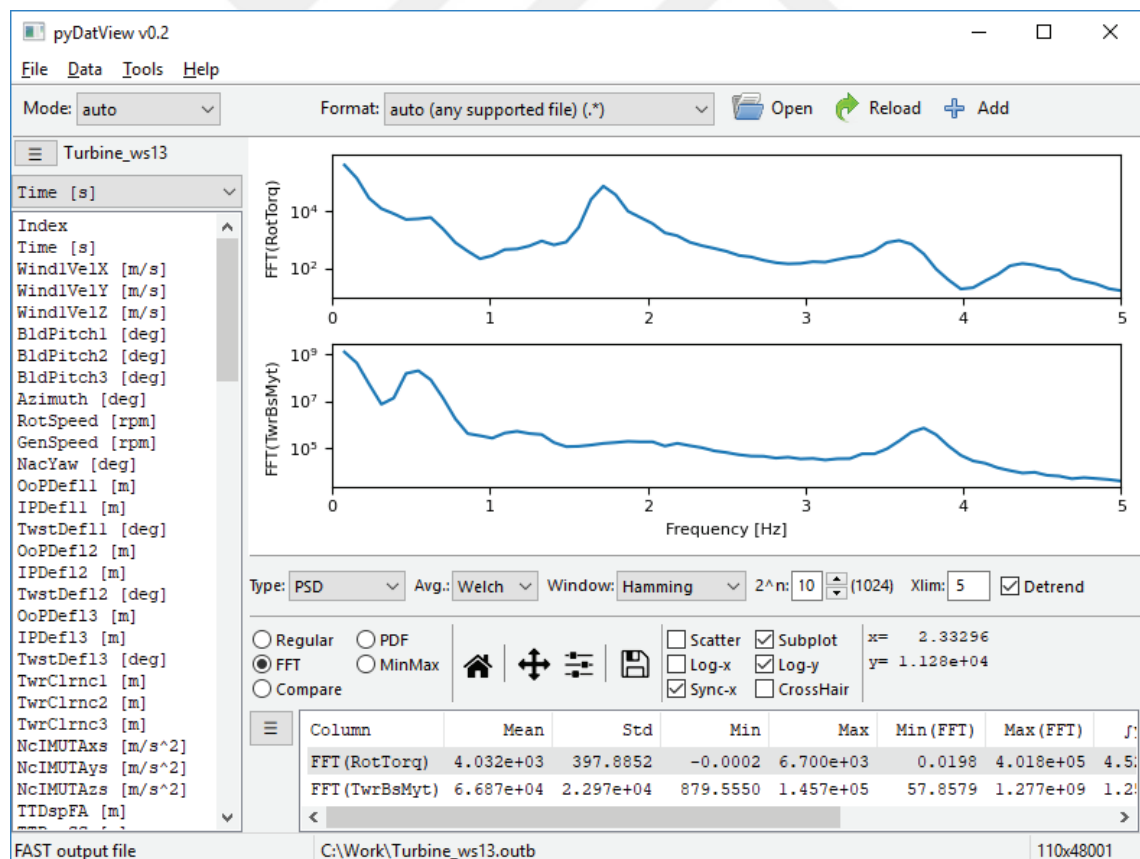


Figure 4.7. The image of the PyDatView interface

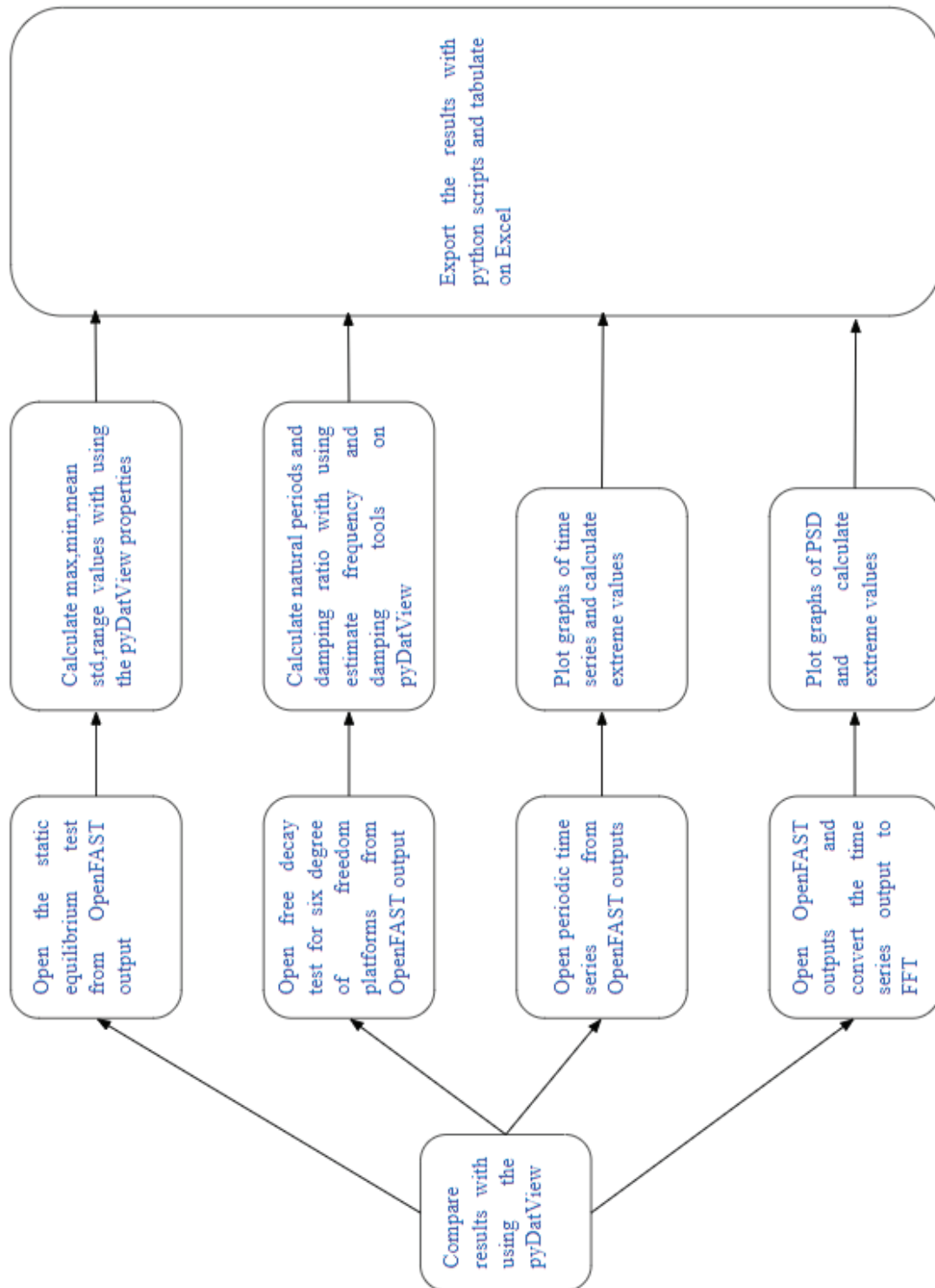


Figure 4.8. The flowchart of post-processing

CHAPTER 5

PLATFORMS AND PREPROCESSING

The FloaTolia floating wind turbine platform²⁷ was designed by researchers of the IZTECH Mechanical and Civil Engineering Departments with TUBITAK funding (217M451). This project was first carried out in the hydraulic laboratory of the IZTECH Department. Experiments were carried out on a 1/40 scaled model of a 300-kW wind turbine. The experimental wave channel facility was 40 m in length, 1 m in width, and 1.4 m in depth.

In addition, the 300-kW FloaTolia platform was hydrodynamically examined in AQWA by Elif Girgin within the scope of her master's thesis¹⁰⁷. This innovative platform is fully submerged, connected by chains to ballast and three floaters, and is designed to be an alternative to various offshore floating turbine platforms such as spar, TLP, and semi-submersible. Within the scope of this thesis, the values required for the 5 MW FloaTolia platform were provided by Elif Girgin, and some of these values were modified to align with the 5 MW NREL³⁷ reference wind turbine. This choice is due to the availability of documentation and resources suitable for comparison with different platforms, such as NREL OC3 Hywind spar¹⁰⁸ and OC4 DeepCwind semi-submersible¹⁰⁹. Since the wave channel size was not appropriate for testing a 1/40 or smaller scale wind turbine, within the scope of this study, the preprocessing of a 5 MW wind turbine was numerically modeled and analyzed using different methods. Different steady and turbulent wind conditions, as well as regular and irregular wave sea conditions, were used in the analyses. These conditions were selected based on the load cases taken from the report titled "Offshore Code Comparison Collaboration (OC3) for IEA Wind Task 23 Offshore Wind Technology and Deployment," written by Jonkman and Musial.⁴⁵ In addition, the same analyses were performed on platforms such as OC3 Hywind spar and OC4 DeepCwind semisubmersible, and the results obtained from the appropriate method were compared.

Figure 5.1 provides a comprehensive three-dimensional illustration of the 5 MW wind turbine mounted on the FloaTolia platform. The figure has been designed to present a visual representation of the turbine and platform in their marine context.

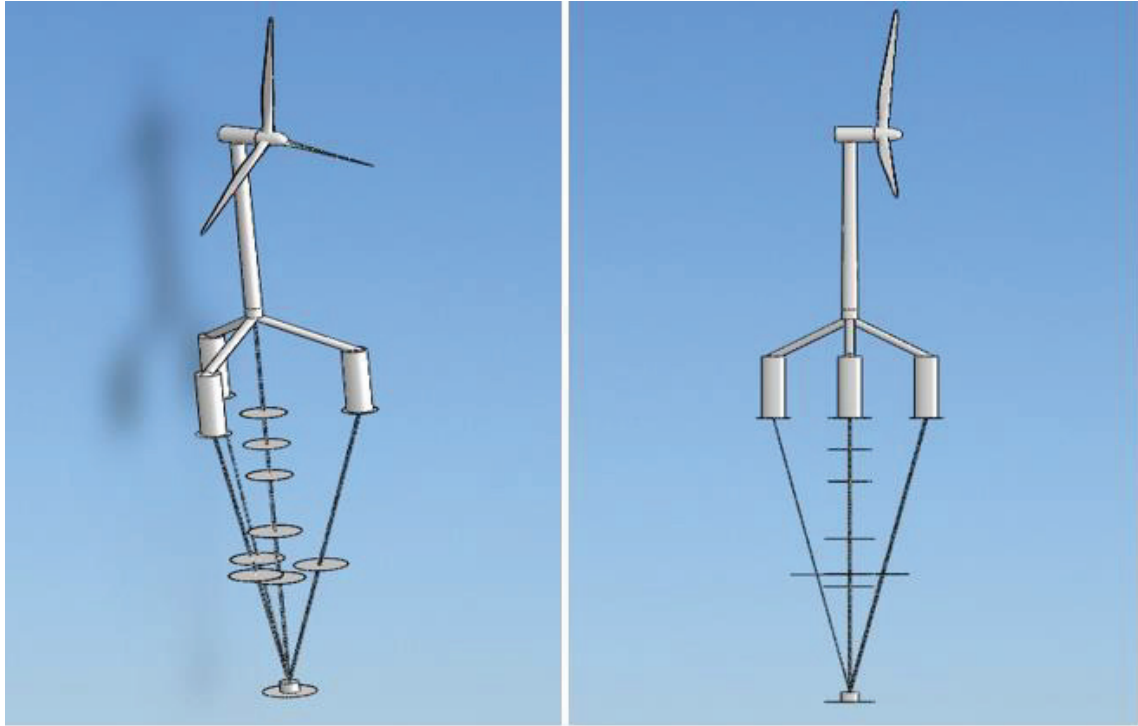


Figure 5.1. 3D drawing of FloaTolia with 5 MW wind turbine

5.1. Wind Turbine Properties

The NREL 5 MW turbine was used with the FloaTolia platform. In this section, the properties of the components, such as the tower, blade, and controller, are given in the following sections.

5.1.1. Tower Properties

The tower used for FloaTolia 5 MW has the same characteristics as the OC4-DeepCwind semi-submersible and the OC3-Hywind spar tower. The only difference with OC3-Hywind is the tower mode shapes; these modes are calculated through the Software for Computing Rotating Beam Coupled Modes (Bmodes) program and are used to represent the flexibility of the tower. This FloaTolia platform uses the same tower features as the OC4-DeepCwind semi-submersible platform. The tower is 10.0 meters above the still water level (SWL). The top point of the tower is 87.6 meters away from sea level. The tower's mass is 249,718 kg, and its center of mass is 43.4 meters. The damping rate for the tower is 1% for all modes. The base diameter of the tower is 6.5 meters.¹⁰⁹

5.1.2. Blade Properties

There are three blades in the wind turbine. The hub radius is 1.5 meters. The precone angle is -2.3 degrees for each blade. The tip radius is 63.0 meters. The structural damping ratio of the blade for all modes is 0.48 %. The total mass of the blade is 17,740 kg, and the center of mass (CM) of the blade is 20.475 meters away from the blade root. The scaling factor of the mass of a blade relative to the total mass of the blade is 4.536%.³⁷

5.1.3. Controller Properties

The NREL 5-MW wind turbine uses a conventional variable speed and variable blade pitch angle control system in which the fixed rotor torque decreases as the wind speed increases above the rated speed. The important values in the controller are as follow^{37,109}:

- Proportional Gain at Minimum Blade-Pitch Setting: 6.276×10^{-3} seconds.
- Integral Gain at Minimum Blade-Pitch Setting: 8.965×10^{-4} seconds.
- Generator Torque in Region 3: 43,093.55 N-m

5.1.4. Floating Platform Structural Properties

The draft of the platform is 190.09 m. The tower is cantilevered on top of the upper floater (UF) of the floating platform, 10 m above the SWL. It is connected to three buoyant floaters (BF) positioned at 120-degree angles from the upper column and bottom of the platform. This is achieved with smaller diameter cross members. These elements are called buoyant legs (BL). In addition, ballast is connected to the platform at a depth of 185 meters. Ballast is connected to the upper-buoyant floaters at four different points with bundle chains.

The following list provides an overview of the most significant components of floating platform structural features:

- The buoyant floater and upper floater are connected by three buoyant legs.
- There are twelve heave plates on the platform.

- The chain system connecting the ballast to the floating buoys is 147.05 meters long. The chain system between the Upper Floater and Ballast is 195 meters.
- Each chain set is a bundle consisting of double chains. Bundle air mass per unit length is 322.38 kg/m.
- The platform is connected to the anchor with three mooring lines. Each mooring line mass per unit length is 161.19 kg/m, and the unstretched mooring line length is 663.70 meters.

Figure 5.2 shows the 3D drawing of the FloaTolia created using SolidWorks.

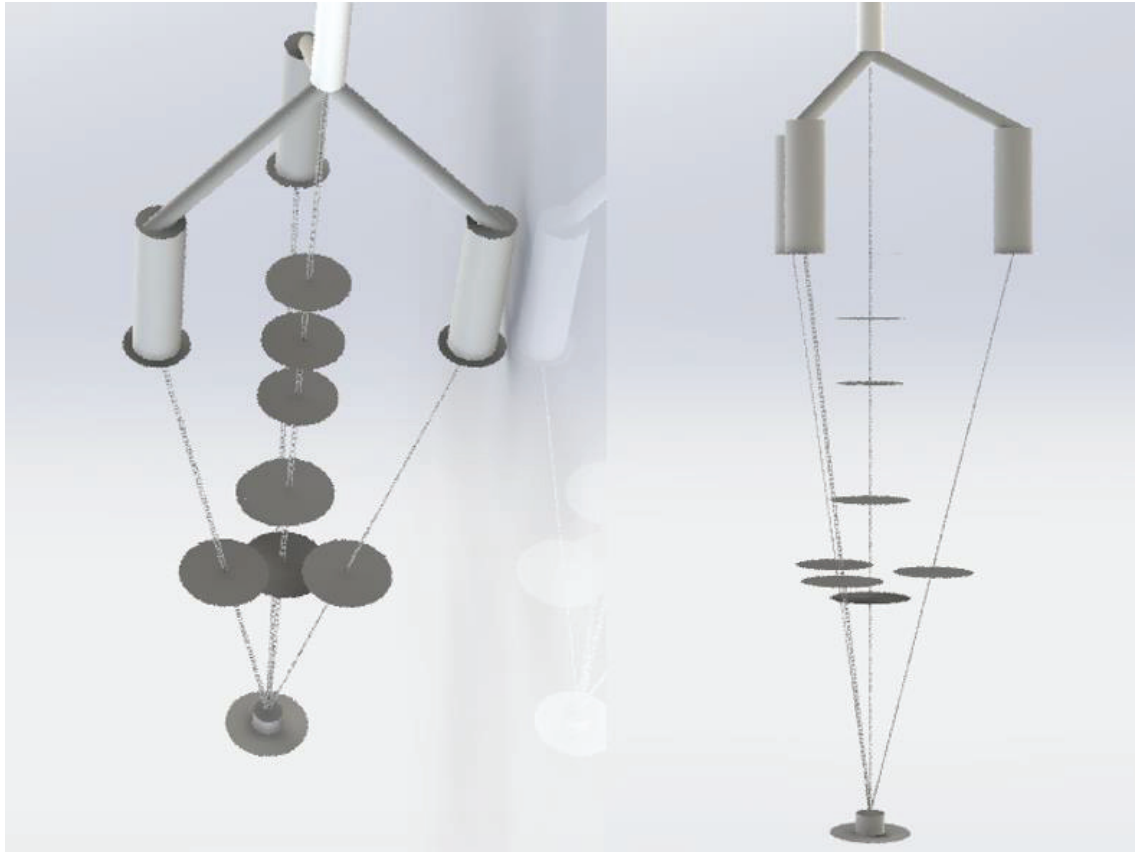


Figure 5.2. 3D drawing of the FloaTolia platform

Tables 5.1 to 5.10 list all platform members. The SolidWorks program was used to find the mass properties, and the values obtained from the drawn platform geometries are shown in the tables. The moment of inertia is taken from the center of mass and aligned with the output coordinate system. In Tables 5.1 and 5.2, the mass and geometric properties of the buoyant and upper floater are given as follows.

Table 5.1. Buoyant floater properties

Buoyant floater height	32.15 m
Diameter of buoyant floaters	8.79 m
Number of buoyant floaters	3
Wall thickness of buoyant floater	0.3 m
Buoyant floaters mass in air	2.08×10^6 kg
Buoyant floaters roll inertia about CM	1.35×10^9 kg/m ²
Buoyant floaters pitch inertia about CM	1.35×10^9 kg/m ²
Buoyant floaters yaw inertia about CM	2.27×10^9 kg/m ²
Buoyant floaters center of mass	-25.56 m
Material	Concrete

Table 5.2. Upper floater properties

Upper floater height	5.00 m
Diameter of the upper floater	6.5 m
Number of upper floaters	1
The wall thickness of the upper floater	0.3 m
Upper floater mass in air	3.65×10^5 kg
Upper floaters roll inertia about CM	2.62×10^6 kg/m ²
Upper floater pitch inertia about CM	2.62×10^6 kg/m ²
Upper floater yaw inertia about CM	2.62×10^6 kg/m ²
Upper floater center of mass	12.5 m
Material	Steel

Table 5.3. Buoyant legs properties

Length of buoyant legs	38.97 m
Diameter of buoyant legs	3.51 m
Number of buoyant legs	3
The wall thickness of buoyant legs	0.0877 m
The angle of buoyant legs in the vertical plane	30.00 deg
Buoyant legs mass in the air	862.374 kg
Buoyant legs roll inertia about CM	1.50×10^8 kg/m ²
Buoyant legs pitch inertia about CM	1.50×10^8 kg/m ²
Buoyant legs yaw inertia about CM	2.56×10^8 kg/m ²
Buoyant legs center of mass	0.25 m
Material	Steel

Table 5.4 Ballast properties

Length of ballast	5.0 m
Diameter of ballast	8.68 m
Number of ballasts	1
The wall thickness of the ballast	-
Ballast mass in air	2.37×10^6 kg
Ballast roll inertia about CM	1.61×10^7 kg/m ²
Ballast pitch inertia about CM	1.61×10^7 kg/m ²
Ballast yaw inertia about CM	2.23×10^7 kg/m ²
Ballast center of mass	-187.5 m
Material	Steel
Length of ballast	5.0 m

Table 5.5. Platform geometry

Column Name	Abbr.	Start location (X, Y, Z)	End location (X, Y, Z)	Length (m)	Wall Thick. (m)
Upper Floater	UF	(0, 0,10)	(0, 0,15)	5	0.3
Buoyant Floater 1	BF1	(32.75, 0, -41.64)	(32.75, 0, -9.49)	32.15	0.3
Buoyant Floater 2	BF2	(-16.37, 28.36, -41.64)	(-16.37, 28.36, -9.49)	32.15	0.3
Buoyant Floater 3	BF3	(-16.37, -28.36, -41.64)	(-16.37, 28.36, -9.49)	32.15	0.3
Buoyant Legs 1	BL1	(32.75, 0, -9.49)	(0, 0,10)	38.2	0.0877
Buoyant Legs 1	BL2	(-16.37, 28.36, -9.49)	(0, 0,10)	38.2	0.0877
Buoyant Legs 1	BL3	(-16.37, -28.36, -9.49)	(0, 0,10)	38.2	0.0877
Ballast	BA	(0, 0, -185)	(0, 0, -190)	5	5

Table 5.6. Middle-chain bundles properties

Number of middle chain bundles	4
Nominal diameter of middle chains (mm)	90.00
Number of chains in the bundle	2
Bundle air mass per unit length (kg/m)	322.38
Length of vertical bundle (m)	195.00
Length of side bundle (m)	147.05
Chain bundles mass in air	205083 kg
Chain bundles center of mass	-105.18 m

Table 5.7. Number of heave plates

Number of vertically suspended heave plates	5
Number of side-suspended heave plates	3
Number of ballast heave plates	1
Number of floaters heave plates	3
Thickness of heave plates (mm)	87.80
The total number of heave plates	12

Table 5.8. Heave properties and geometries

Heave Plate Name	Abbr.	Location (X, Y, Z)	Drag Coef.	Added Mass Coef.	Diameter(m)
Heave Plate 1	HP1	(32.75, 0, -41.64)	2.45	1	12.32
Heave Plate 2	HP2	(-16.37, 28.36, -41.64)	2.45	1	12.32
Heave Plate 3	HP3	(-16.37, -28.36, -41.64)	2.45	1	12.32
Heave Plate 4	HP4	(0, 0, -104.79)	4.8	1	18.48
Heave Plate 5	HP5	(0, 0, -141.76)	4.8	1	18.48
Heave Plate 6	HP6	(0, 0, -41.57)	2.54	1	15.9
Heave Plate 7	HP7	(0, 0, -58.20)	2.54	1	15.9
Heave Plate 8	HP8	(0, 0, -74.83)	2.54	1	15.9
Heave Plate 9	HP9	(14.53, 0, -123.28)	4.8	1	18.48
Heave Plate 10	HP10	(-7.26, 12.58, -123.28)	4.8	1	18.48
Heave Plate 11	HP11	(-7.26, -12.58, -123.28)	4.8	1	18.48
Heave Plate 12	HP12	(0, 0, -190.04)	4.8	1	18.48

The mass of the FloaTolia platform, including ballast and bundle chains, is 5.88×10^6 kg. The roll and pitch inertia of the floating platform around the center of mass (CM) is 4.22×10^{10} (kg/m²) for the x-axis and y-axis of the platform, respectively, and the yaw inertia around the centerline of the floating platform is 2.54×10^9 (kg/m²). The floating platform's center of mass (CM) is 87.41 meters below the sea water level (SWL) along the platform's centerline. The platform's volumetric displacement is 6,546 cubic meters.

Table 5.9. Platform properties

Depth of platform base below SWL (total draft)	190.09 m
The outermost radius of the platform	39.26 m
Platform mass in air	5.88×10^6 kg
Platform roll inertia about CM (kg/m ²)	4.22×10^{10}
Platform pitch inertia about CM (kg/m ²)	4.22×10^{10}
Platform yaw inertia about CM (kg/m ²)	2.54×10^9
Platform center of mass	-87.41 m
Volumetric Displacement	6546 m ³

Table 5.10. Mooring line properties

Mooring system type	Chain catenary
Depth to anchor below SWL	200 m
Depth to fairleads below SWL	9.49 m
Number of mooring lines	3
The angle between adjacent lines on the horizontal plane (deg)	120
Chain air mass per unit length	161.19 kg/m
Transverse drag and added mass coefficient	1
Mooring line pretension	1192.81 kN
Unstretched mooring line length	663.70 m
Radius to anchors from platform centerline	658.43 m
Radius to fairleads from platform centerline	39.26 m
Longitudinal drag coefficient	0.025
Equivalent diameter	0.162 m

5.2. Platform Preprocessing

In this section, the Keulegan-Carpenter (KC) number and the oscillatory Reynolds (Re) number, which are also used in the selection of the methods to be used in platform pre-processing and play an important role in calculating the hydrodynamic loads of the platform interacting with the surface, were calculated for each platform member. It has been explained in previous sections that if the Keulegan-Carpenter (KC) number is less than 2, the flow does not separate around the object, and laminar flow occurs; otherwise, the flow is turbulent and separates on the object. In this case, the Morison equation is used, and experimental data and empirical formulas depending on the oscillator Reynolds number are employed to determine drag and added mass coefficients. Formulations of these numbers are drawn in experimental calculations for cylinders. The calculation of these dimensionless numbers depends on various sea states. Since no site has been determined within the scope of this thesis, the sea states are based on the sea states used on the OC4 semi-submersible platform.¹⁰⁹ Sea State varies from 1 to 8, with wave heights and periods increasing. It is determined as follows in Table 5.11.

Table 5.11. Periodic sea state (SS) definitions used from
(Source: Robertson et al. 2014¹⁰⁹)

Sea State	T (s)	H (m)
1	2.0	0.09
2	4.8	0.67
3	6.5	1.40
4	8.1	2.44
5	9.7	3.66
6	11.3	5.49
7	13.6	9.14
8	17.0	15.24

Equations 3.17 to 3.21 were applied to each platform member, and their graphs were obtained. Equations 3.17 to 3.21 were applied to each platform member, and their graphs were obtained. The Keulegan-Carpenter number was used to find out which theory was valid or not. Oscillatory Reynolds number was calculated to find the drag coefficient value to be used in the Morison equation.

Keulegan-Carpenter and Oscillatory Reynolds numbers vary depending on Sea state conditions. Particularly for thin platform members, a separate analysis was also carried out under the conditions in the load cases ($H = 6$ meters and $T = 10$ seconds), which will be mentioned in the following sections. The reason for this is to determine the drag coefficients in the Morison equation. As seen in Figure 5.3, potential flow conditions are invalid starting from the fifth sea state, and the Morison equation must be used. Therefore, since the conditions used in the study are more severe than the fifth sea state conditions, the Morison equation must be used for buoyant legs. The required added mass and drag coefficient values must be found for the equation.

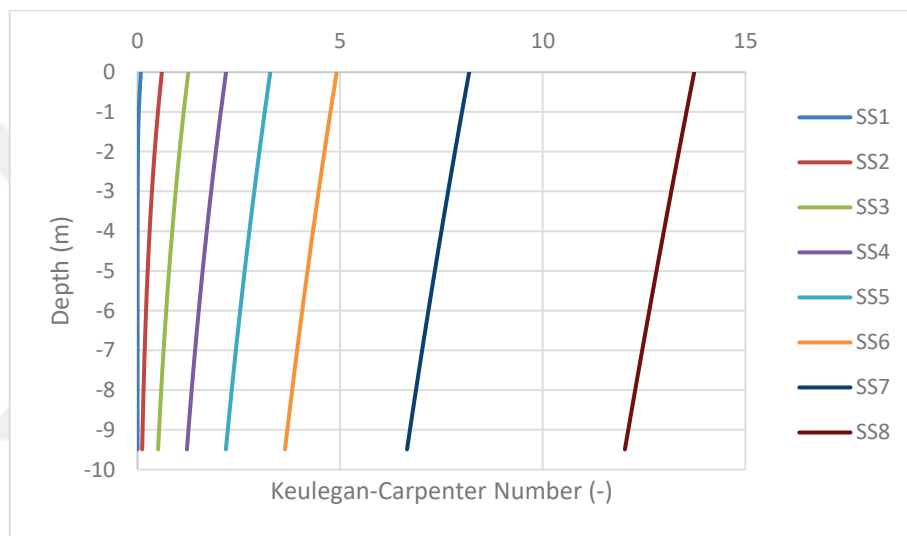


Figure 5.3. The Keulegan-Carpenter numbers for the buoyant legs

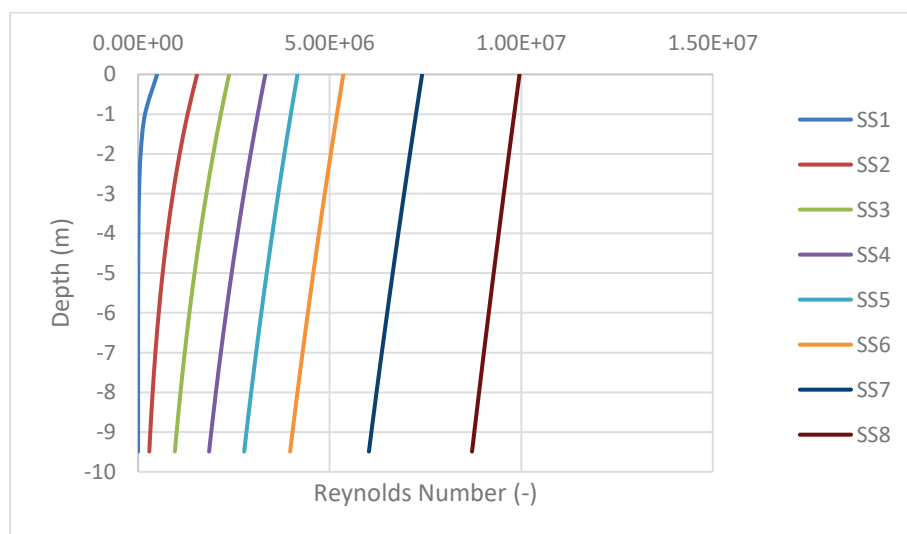


Figure 5.4. The Oscillatory Reynolds numbers for the buoyant legs

As seen in Figure 5.5, only from the eighth sea state onwards, potential flow conditions are invalid, and the Morison equation must also be used. In this study, since the analysis will be made under the conditions of $H = 6$ meters and $T = 10$ seconds, potential flow theory is used for this platform member.

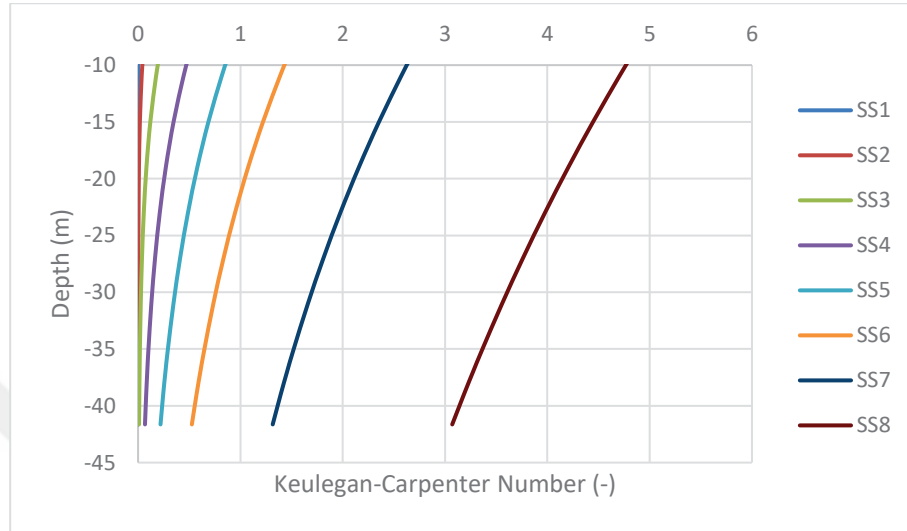


Figure 5.5. The Keulegan-Carpenter numbers for the buoyant floaters

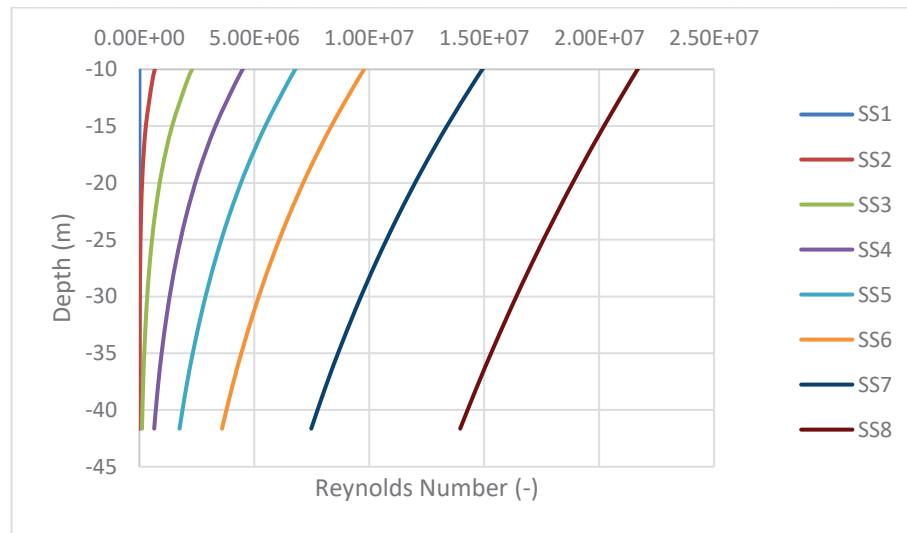


Figure 5.6. The Oscillatory Reynolds numbers for the buoyant floaters

As seen in Figure 5.7, potential flow conditions from any sea state are valid. The reason for this is that the ballast is very deep, and the Keulegan-Carpenter number depends on the depth. For this reason, potential flow theory is used for this platform member.

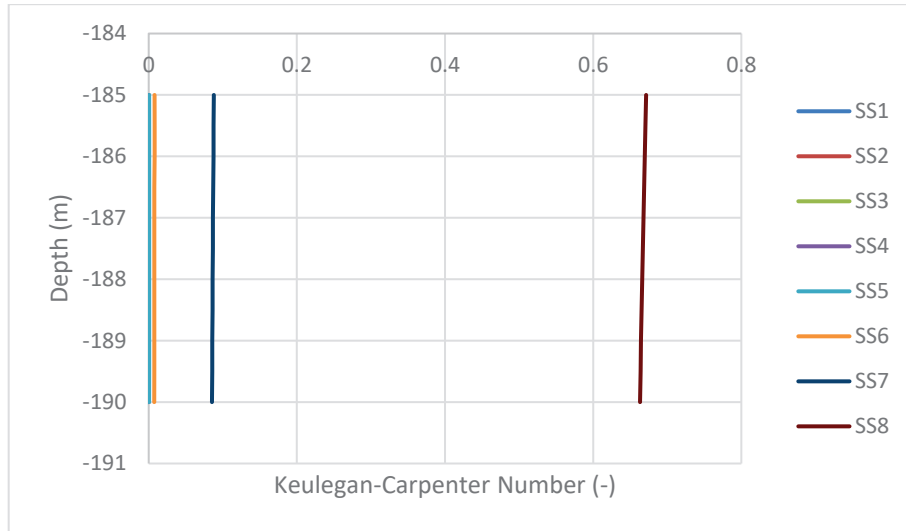


Figure 5.7. Keulegan-Carpenter numbers for the ballast

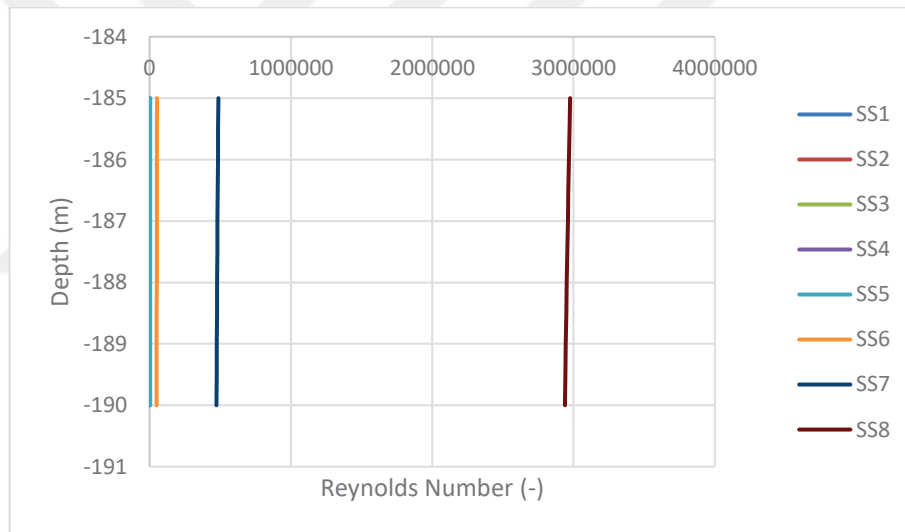


Figure 5.8. Oscillatory Reynolds numbers for the ballast

The calculations for each member of the FloaTolia platform under various wave conditions have shown that situations, where the diameter/wavelength ratio exceeds 0.2, are significant.

Table 5.12 was prepared to display cases where the diameter/wavelength ratio exceeds 0.2. This table was not used as the basis for the calculations of the C_d (drag) and C_a (added mass) coefficients. Notably, for the buoyant legs, which are the thinnest members of the platform, the ratio did not exceed 0.2 in any sea state. On the other hand, the value of 0.2 was exceeded for ballast and buoyant floater in the first two sea states.

Table 5.12. Diameter/wavelength ratio for each platform member

Sea State	1	2	3	4	5	6	7	8
Buoyant Legs	0.563	0.098	0.053	0.034	0.024	0.018	0.012	0.008
Buoyant Floater	1.409	0.245	0.134	0.086	0.06	0.044	0.031	0.02
Ballast	1.391	0.242	0.131	0.084	0.059	0.043	0.03	0.019

The members of the FloaTolia platform have been analyzed for the Oscillatory Reynolds number and Keulegan-Carpenter number, excluding the thinnest element, the buoyant legs, which are solved using the potential flow solver. Additionally, for the buoyant legs, the Morison equation, along with strip theory, has been employed, selecting specific values for $C_a = 0.908$ (Added mass coefficient) and $C_d = 0.69$ (Drag coefficient). The meshing process of all platforms within the scope of potential flow and the determination of C_a and C_d coefficients for FloaTolia buoyant legs members are given in Appendix A.

5.3. Mesh Independency Study

Due to the platforms' different geometry, mesh independence studies were conducted using different mesh sizes. Every mesh operation here was done in ANSYS AQWA and used in other BEM Solvers. Meshes were made from the coarsest to the finest for each platform, and the volume covered by the meshes on the platforms was taken into account.

As can be seen in Figure 5.9, the spar platform has a volume percentage range (90.24%-100%) for five different meshes. Here, particularly after mesh 3, the increase in volume ratio stopped and became constant. As a result, the values after mesh 3 were considered suitable for calculation, and the analyses were performed according to the values of mesh 4, taking into account the computational cost.

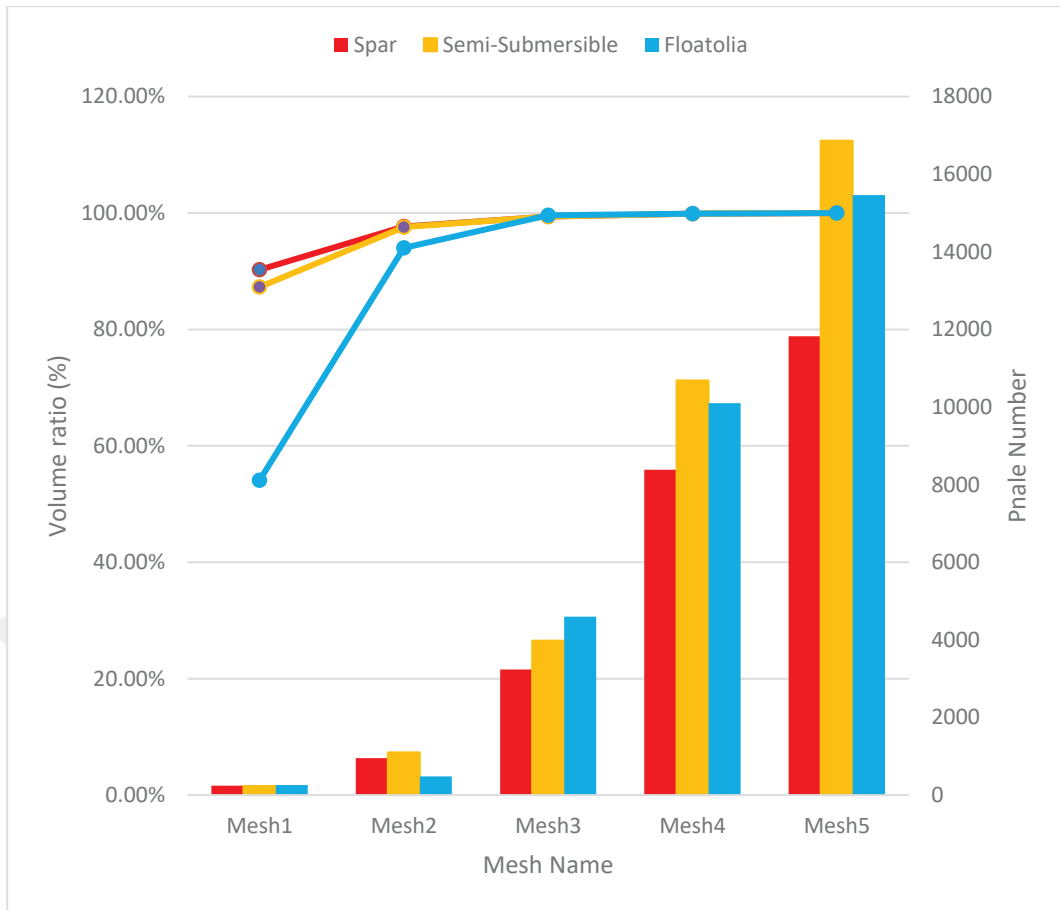


Figure 5.9. Mesh independence chart of the three platforms

As seen in Fig 5.9, the semi-submersible platform has a volume percentage range (87.28.%-100%) for five different meshes. Mesh values have been selected to be similar across each platform. Especially in the coarsest mesh, a lower volume ratio was achieved due to geometric differences. Analyzes were made according to mesh 4 values, as in the semi-submersible platform.

FloaTolia platform has the lowest volume ratio, ranging from 54% to 99.98%. The reason for this is that the platform has a more complex structure. Although the volume ratio was very low and insufficient in the coarsest mesh, this ratio reached more reasonable values in finer meshes. Analyzes were made according to the features of mesh 4, especially considering the computational cost. Mesh drawings of FloaTolia and other platforms are given in Appendix A.

In Table 5.13, the mesh properties values used in the chart for each platform, such as defeaturing tolerance and element size, are given in detail.

Table 5.13. Mesh properties for the three platforms

Mesh Properties	Mesh names	Defeaturing Tolerance(m)	Element Size(m)	Panel Number	Volume ratio (%)
Spar	Mesh1	2	8	244	90.24%
	Mesh2	1	4	954	97.67%
	Mesh3	0.5	2	3238	99.40%
	Mesh4	0.3	1.2	8384	99.89%
	Mesh5	0.25	1	11826	99.99%
Semi-submersible	Mesh1	6	15	237	87.28%
	Mesh2	2	5	1104	97.56%
	Mesh3	1	2.5	3982	99.39%
	Mesh4	0.6	1.5	10684	99.88%
	Mesh5	0.3	1.2	16862	99.99%
FloaTolia	Mesh1	6	15	261	54.08%
	Mesh2	2	5	484	94.01%
	Mesh3	1	2.5	4598	99.59%
	Mesh4	0.6	1.5	10103	99.89%
	Mesh5	0.3	0.8	15463	99.98%

Hydrodynamic coefficient values were calculated for the selected mesh properties through the mesh independence study. The critical point here is that this study was conducted only for the approach in which platform features are transferred by entering hydrodynamic coefficients, which is one of the methods, as input into the OpenFAST program. As a result of this approach, the hydrodynamic properties of platforms, such as the added mass, radiation damping, and extinction force, were calculated as input. For the FloTolia platform, instead of preparing hydrodynamic coefficients as input, also called the F2A method, AQWA and FAST v7 coupled approach was applied.

5.4. Obtaining the Hydrodynamic Coefficients

The graphs given in Figures 5.10 to 5.17 are calculated by using the hydrodynamic coefficients for spar and semi-submersible platforms using four different potential flow solvers such as AQWA, Capytaine, NEMOH, and WAMIT, and show the added mass, radiation damping, and excitation forces based on degrees of freedom (DOF) according

to the period in seconds. The WAMIT results are taken from the OpenFAST⁹³ hydrodynamic input file and are essentially the desired results. Additionally, graphs were drawn for heave, surge, pitch, and yaw movements for each value.

Hydrodynamic coefficient values obtained from potential flow solvers were used to enable the transfer of platforms to aero-hydro-servo-elastic code by including hydrodynamic coefficients as input to the HydroDyn module of the OpenFAST program. The difference in the results obtained between these programs is critical in terms of evaluating the consistency and differences in the predictions of the simulation tools, and it is very effective in wind turbine behavior. The graphs at low period values must be consistent with each other.

Figure 5.10 shows the added mass coefficient values of the spar platform. While all values are very close to each other, there is an approximately 3% difference in surge and pitch values between WAMIT and other potential flow solvers. This difference is quite small, and it is thought to be due to differences in the mesh. As seen in Figure 5.11, the radiation-damping coefficient values of the spar platform are shown. Slightly different from the added mass value, all potential flow solvers gave very close values to each other. As illustrated in Figure 5.12, the excitation force values of the spar platform are shown. The obtained results were found to be highly consistent, particularly at low period values. As the period increased, the potential flow solvers showed slight differences. It is crucial to focus on the low period values. Additionally, the yaw value was higher in the AQWA output than in the others.

Figure 5.13 shows the added mass coefficient values of the semi-submersible platform. Although all values are very close to each other, there is approximately a 2% difference in heave and pitch values between WAMIT and other potential flow solvers. This difference is quite small, and it is thought that the difference here is due to mesh differences, as in the spar platform. In Figure 5.14, the radiation damping coefficient values of the semi-submersible platform have very similar results in all programs as in the spar platform. In Figure 5.15 the excitation force values of the semi-submersible platform are highly correlated for surge and heave motion.

On the other hand, the results generated by WAMIT for pitch motion and AQWA for yaw motion produced very different outcomes compared to the outputs of other simulation programs.

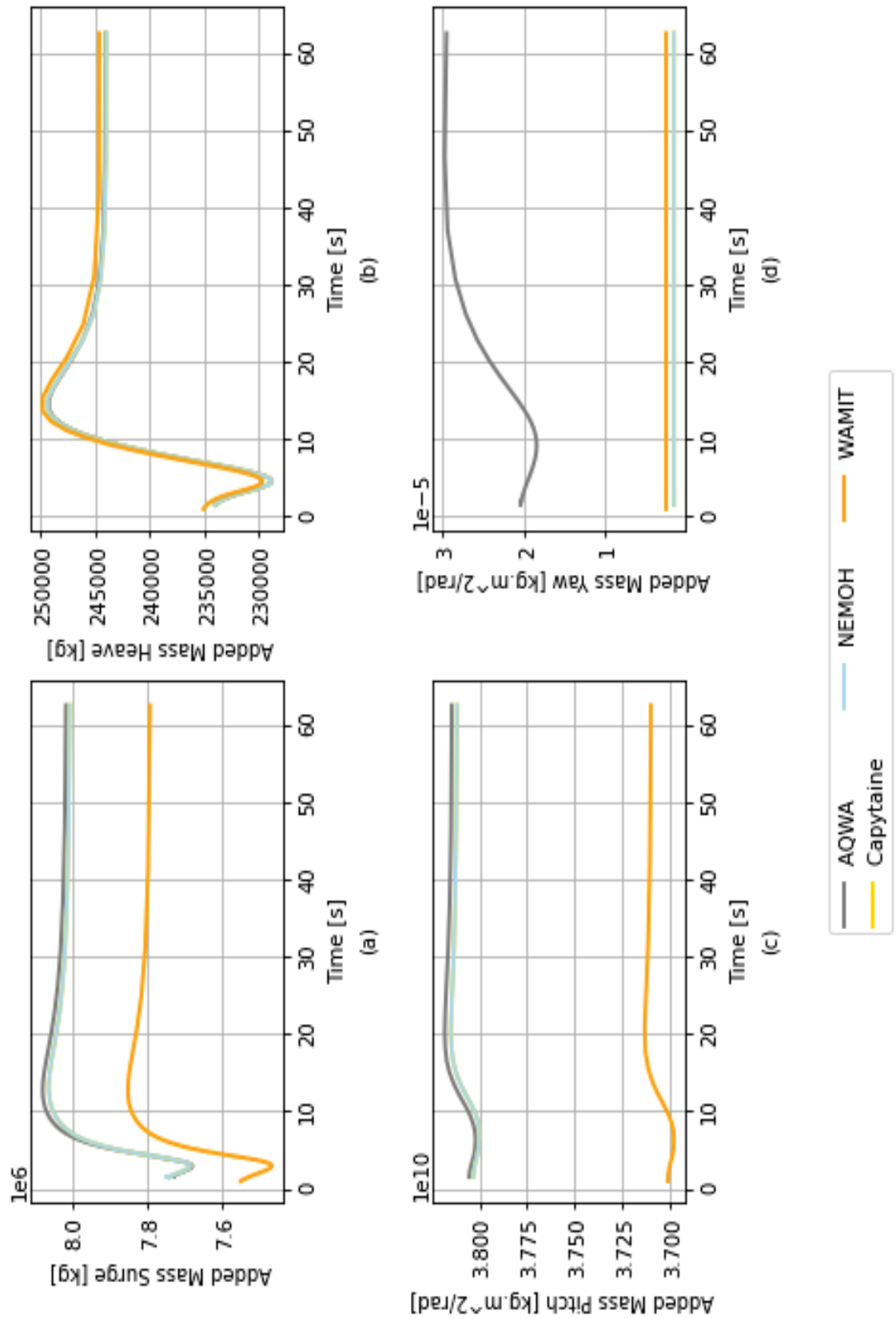


Figure 5.10. Spar platform added mass hydrodynamic coefficients

a) Surge, b) Heave, c) Pitch, d) Yaw

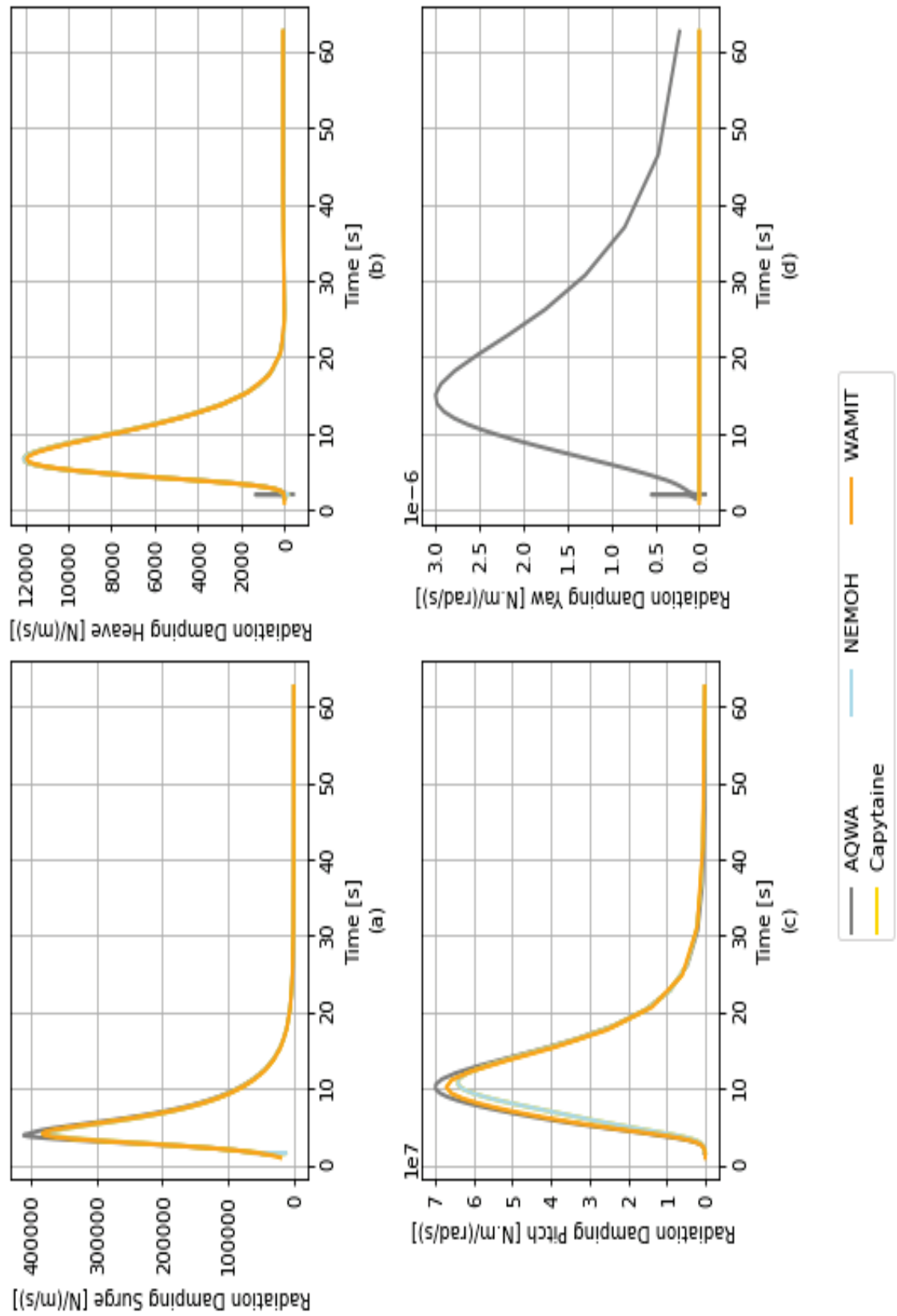


Figure 5.11. Spar platform radiation damping hydrodynamic coefficients

a) Surge, b) Heave, c) Pitch, d) Yaw

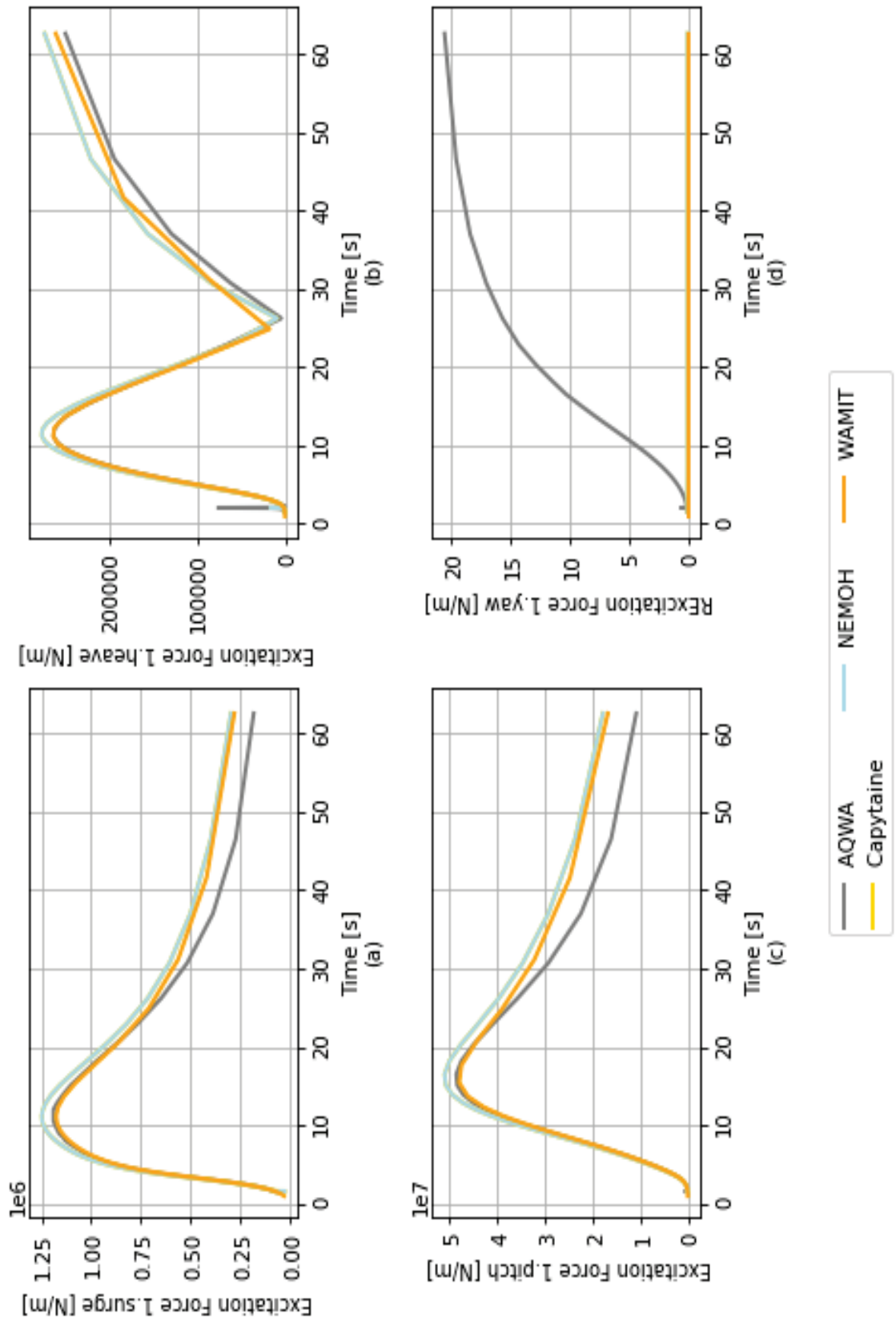


Figure 5.12. Spar platform excitation force hydrodynamic coefficients

a) Surge, b) Heave, c) Pitch, d) Yaw

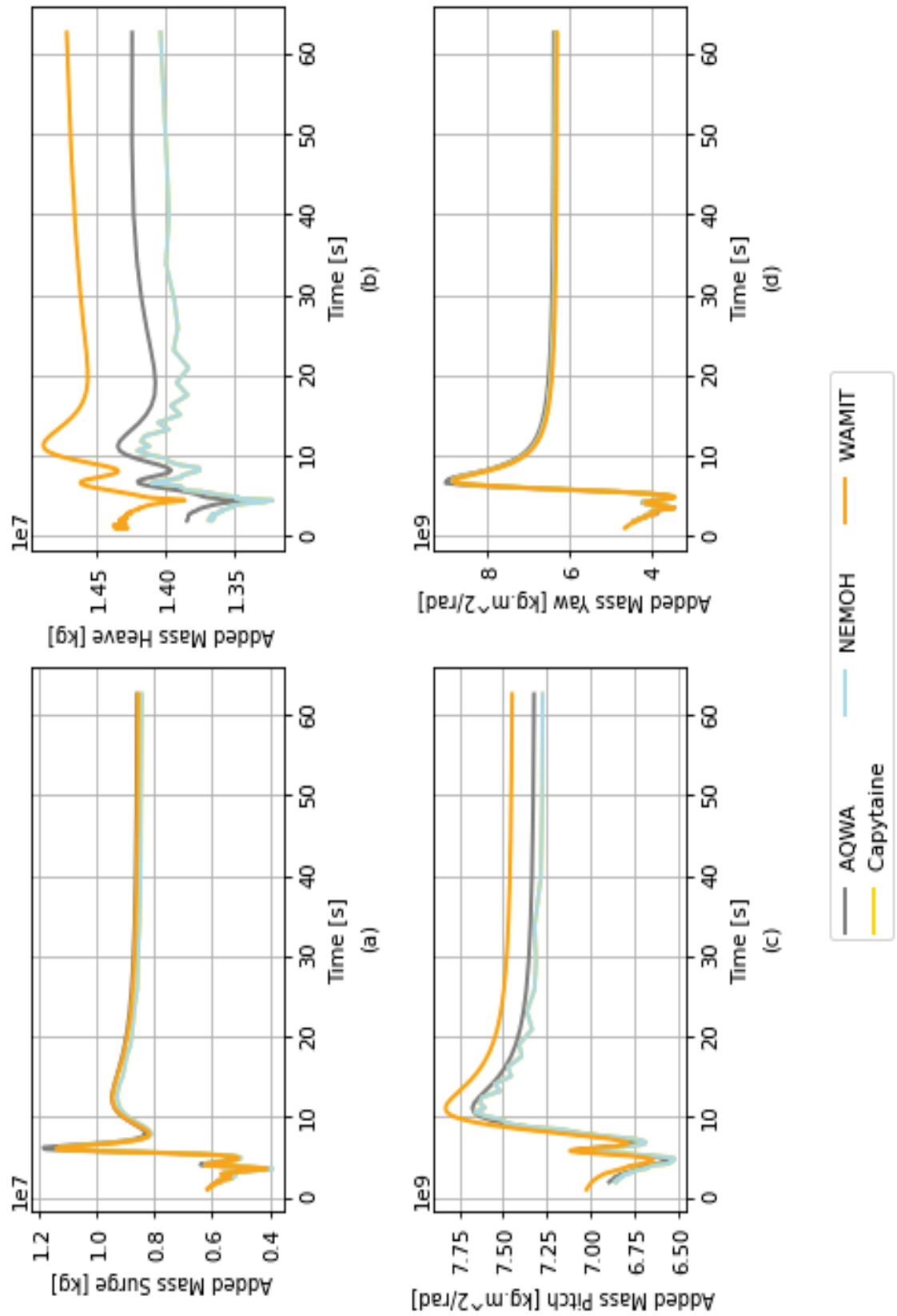


Figure 5.13. Semi-submersible platform added mass hydrodynamic coefficients

a) Surge, b) Heave, c) Pitch, d) Yaw

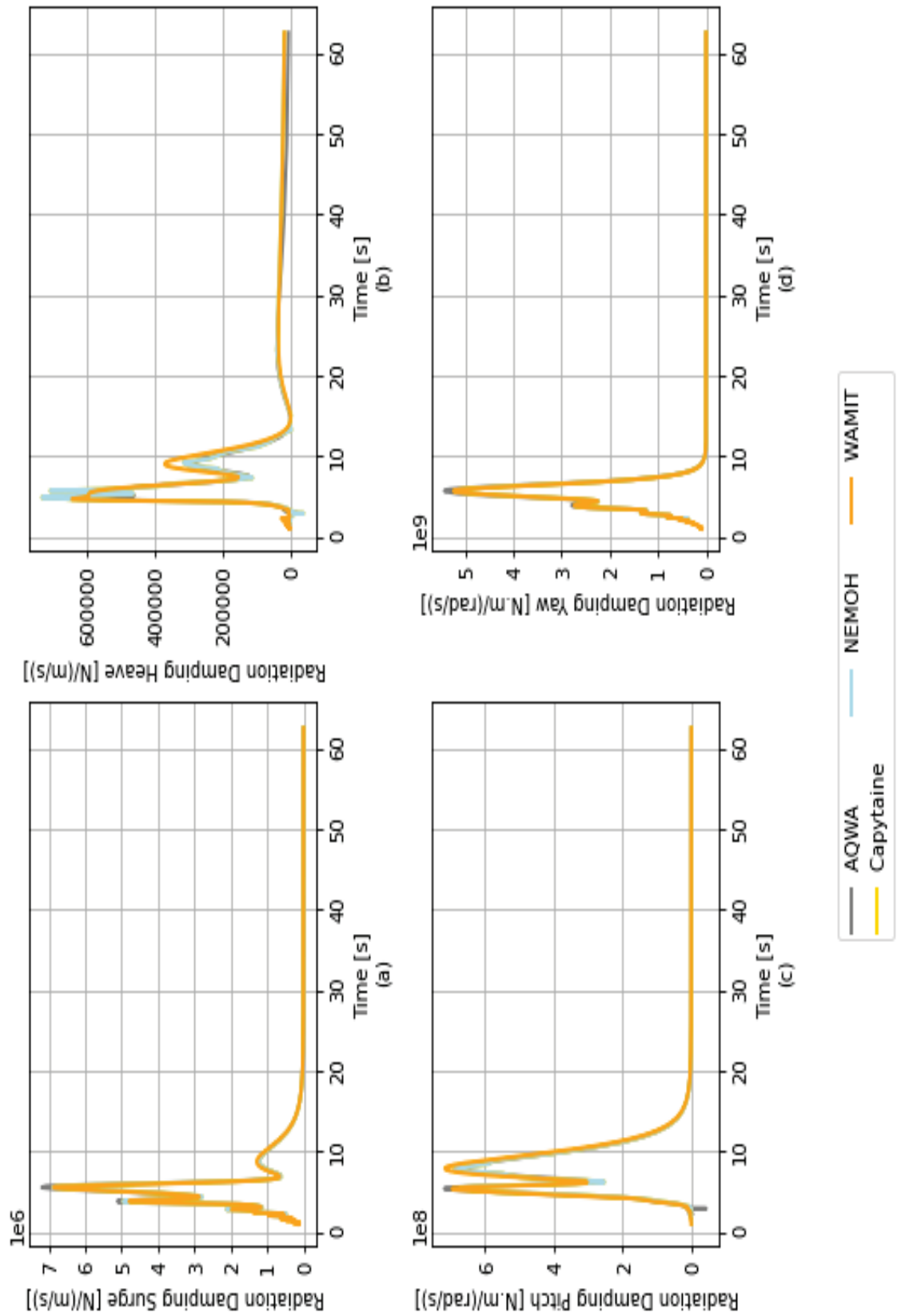


Figure 5.14. Semi-submersible platform radiation damping hydrodynamic coefficients

a) Surge, b) Heave, c) Pitch, d) Yaw

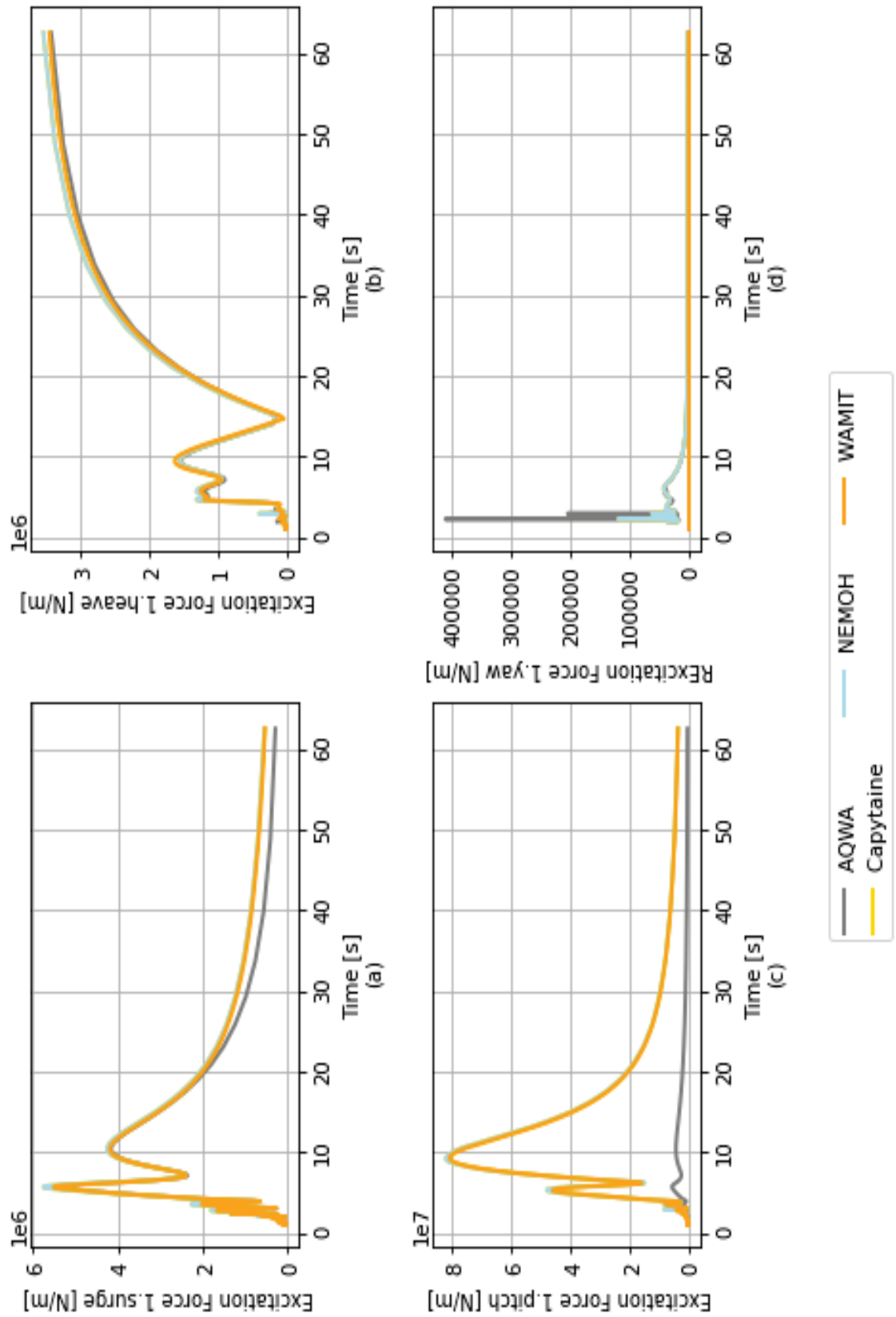


Figure 5.15. Semi-submersible platform excitation force hydrodynamic coefficients

a) Surge, b) Heave, c) Pitch, d) Yaw

The analysis of the FloaTolia platform is conducted using Cappytaine, which, unlike other platforms, gives very similar results to NEMOH and runs much faster. WAMIT was not used as a potential solver due to the lack of OpenFAST inputs and the fact that it is a commercial tool. The hydrodynamic coefficient values of the FloaTolia platform are shown in the graphs from Figures 5.16 to 5.18.

In Figure 5.16, unlike other platforms, the FloaTolia platform uses two potential flow solvers, AQWA and Cappytaine. These two programs give very similar results in terms of added mass coefficients. However, there is a certain amount of offset. In some peak points, the offset amount between the two programs is about 10-20%. This may be because Cappytaine is not as optimized as commercial software such as AQWA, which is why it is thought that performance issues occur when working on large and complex models such as the FloaTolia platform.

In Figure 5.17, the results obtained using Cappytaine and AQWA demonstrate that both programs produce similar responses according to wave periods. Additionally, the responses of both programs have visually similar distributions and levels of response. This situation indicates that Cappytaine and AQWA provide very similar results, specifically for radiation damping coefficients.

In Figure 5.18, the graphs show that the excitation force values produced by Cappytaine and AQWA are quite similar at lower periods but begin to diverge as the period increases, yet they remain significantly correlated. However, in the case of yaw values, AQWA and Cappytaine display considerable differences in output. This discrepancy is thought to be due to Cappytaine not being as optimized as commercial software such as AQWA, which may lead to performance issues when working on large and complex models like the FloaTolia platform.

Despite the complex geometries, AQWA and Cappytaine have delivered highly correlated and closely matched results for the FloaTolia platform. The differences observed can largely be attributed to mesh errors and the challenges associated with modeling the platform.

Additionally, the hydrostatic values from both tools have been quite close. All files with .1, .3, and .hst extensions were used as inputs to HydroDyn. The modeling of thin elements using the Morison equation, and the configuration of heave plates were also meticulously conducted within HydroDyn.

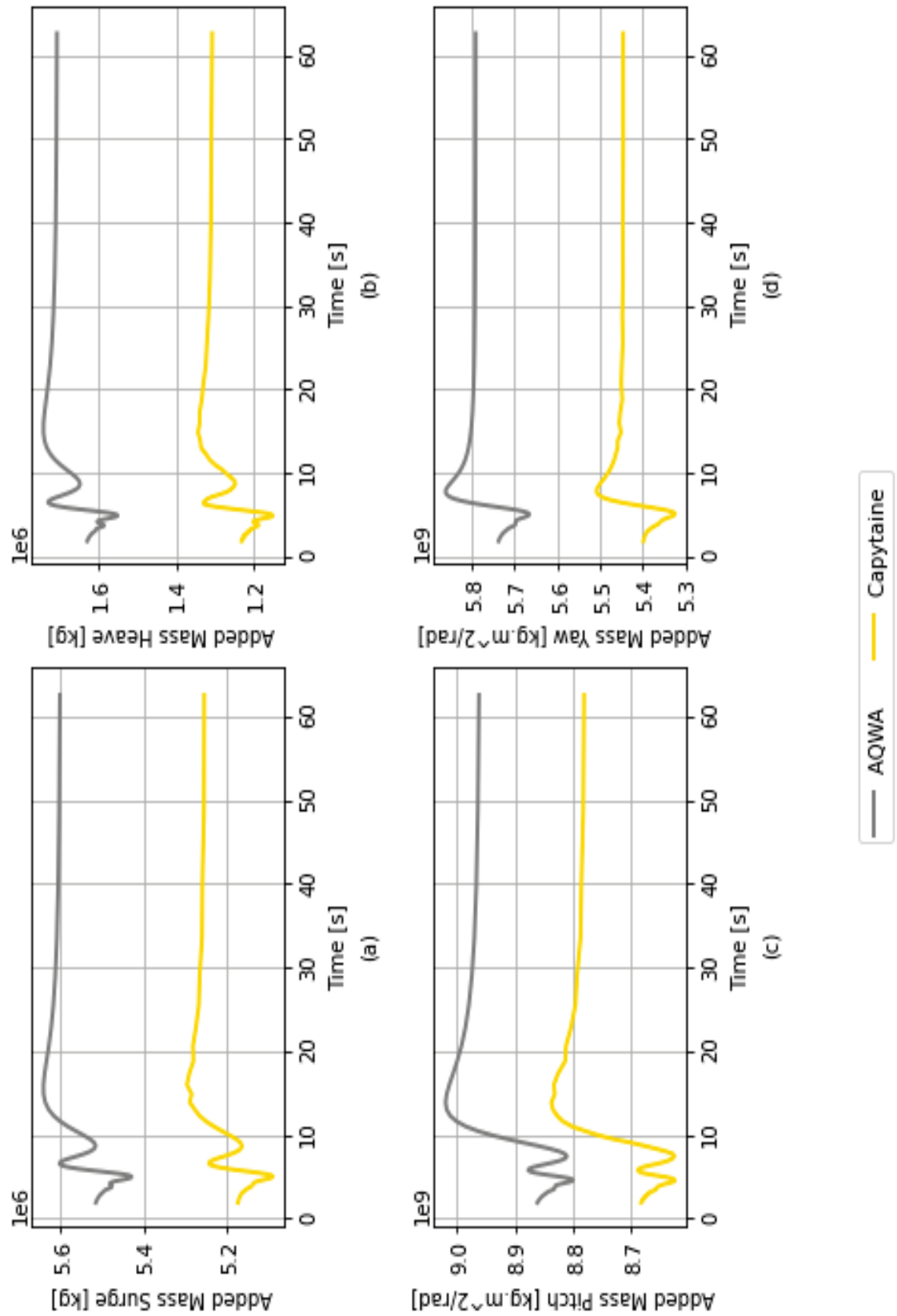


Figure 5.16. FloaTolia platform added mass hydrodynamic coefficients

a) Surge, b) Heave, c) Pitch, d) Yaw

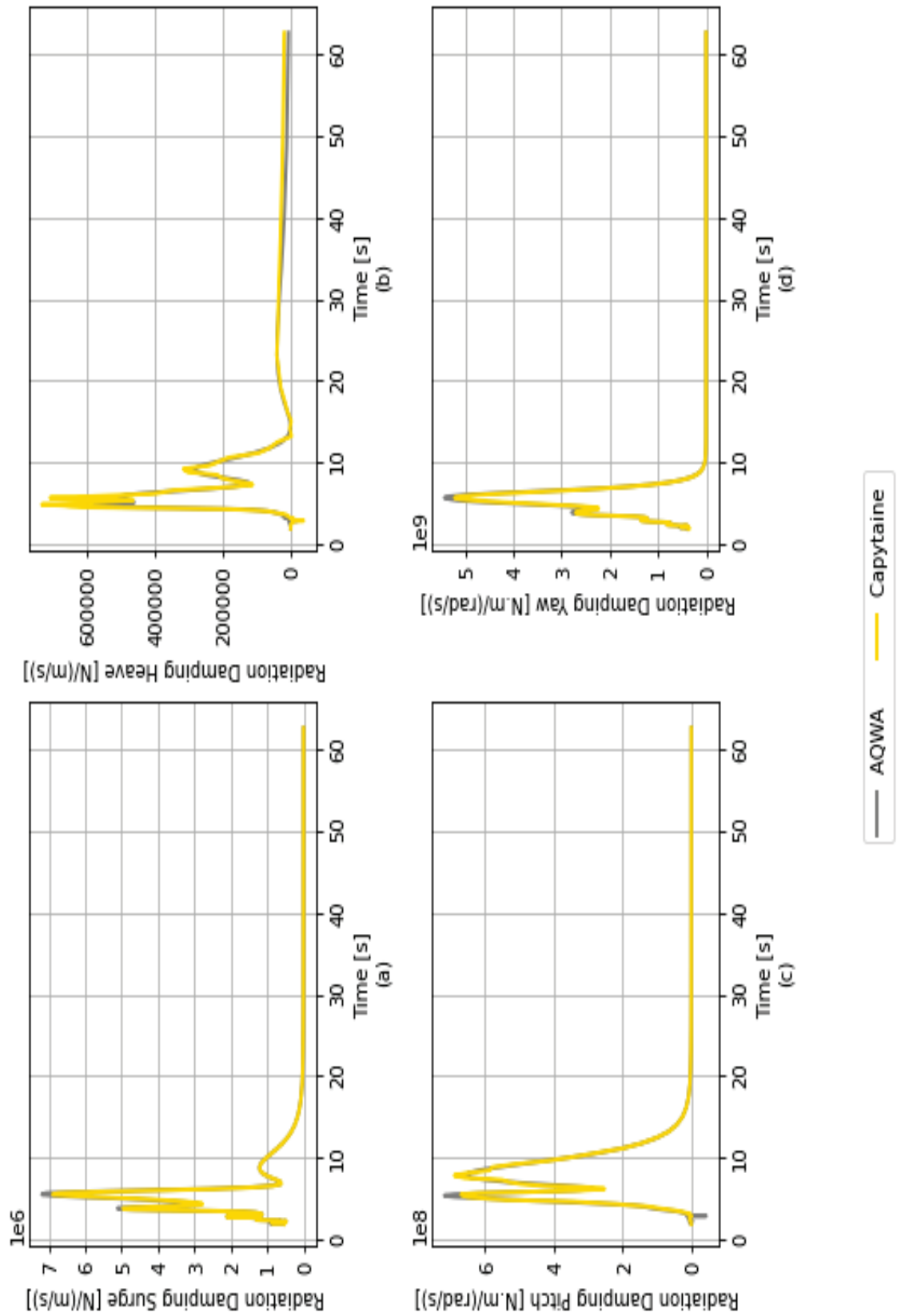


Figure 5.17. FloaTolia platform radiation damping hydrodynamic coefficients

a) Surge, b) Heave, c) Pitch, d) Yaw

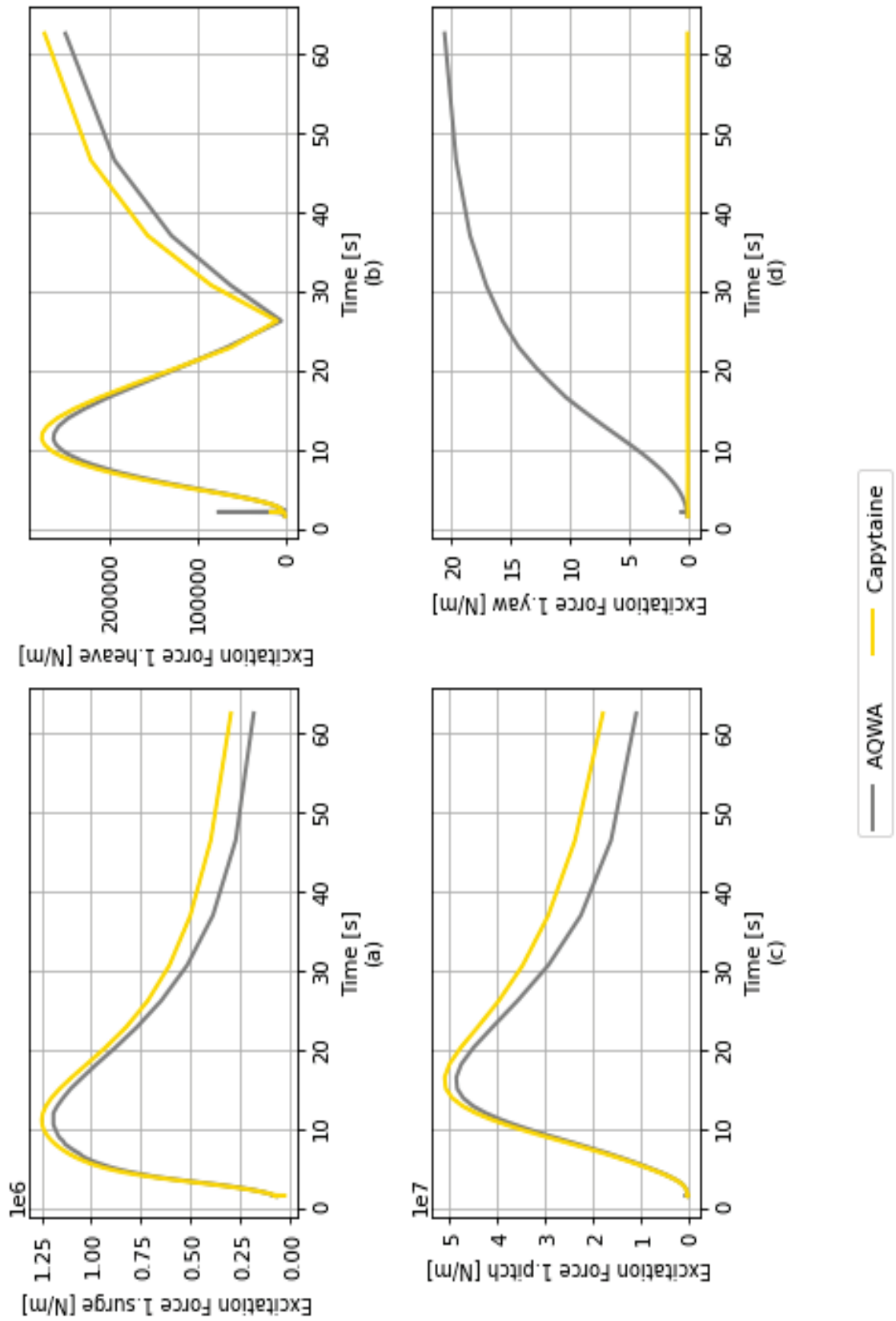


Figure 5.18. FloaTolia platform excitation force hydrodynamic coefficients

a) Surge, b) Heave, c) Pitch, d) Yaw

5.5. Preparation of the FloaTolia Platform as Rigid and Flexible

The FloaTolia platform was developed in the AQWA program for F2A. This is a different approach. The main difference is that OpenFAST uses AQWA instead of HydroDyn, and the ability to be modeled flexible is possible in AQWA and rigid in HydroDyn. For this reason, the FloaTolia platform was modeled in AQWA in two different ways: flexible and rigid, to be verified by modeling with HydroDyn. In Figure 5.19 of the FloaTolia platform, the chain bundle is designed as a discrete component of the upper platform and ballast. It is represented as flexible by connecting the ballast member to the upper platform with chain bundles. As a result, the ballast can move independently, similar to what has been observed.

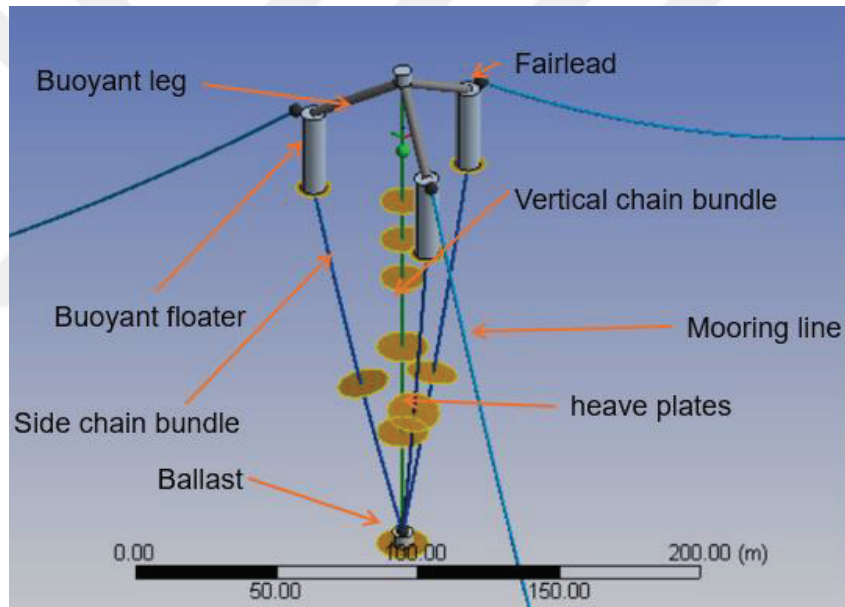


Figure 5.19. Flexible model design of the FloaTolia platform

It is possible to model FloaTolia, spar, and semi-submersible platforms as rigid in the HydroDyn module. To observe the differences between flexible and rigid platforms and to compare them with the design modeled in HydroDyn, the FloaTolia platform was designed as rigid in the AQWA program, as given in Figure 5.20. In this instance, it was not possible to create a model of the chains due to their integration with the upper platform and the ballast. The AQWA software allows for the modeling of chain bundles between two distinct platforms or connections to anchor platforms. Here, the weights of the chain bundles were integrated into the platform's design, and the center of mass was specified

based on the previous calculations.

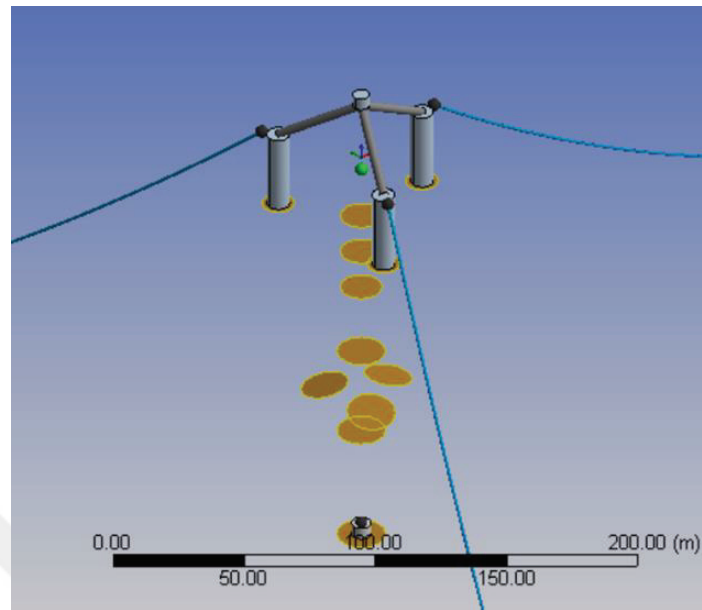


Figure 5.20. Rigid model design of the FloaTolia platform

Additionally, as seen in Figure 5.21, the configurations of the mooring lines and their sequencing are organized as follows: The direction from which the wind blows is designated as parallel to "mooring line 1." The other mooring lines are positioned at 120-degree angles in a clockwise direction from this line and are identified as "mooring line 2" and "mooring line 3." This sequence is applied to all platforms and establishes a standard for the arrangement of mooring lines.

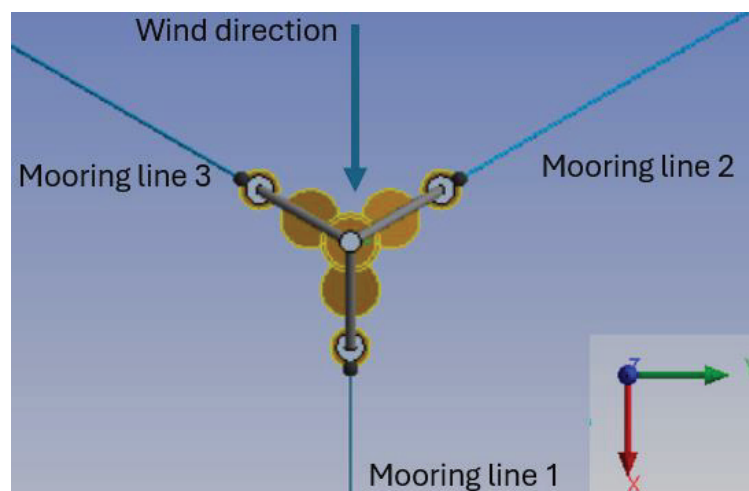


Figure 5.21. Mooring lines configurations

5.6. Load Cases

In this study, similar to the study⁴⁵, load cases were selected and applied with an innovative platform to calculate the dynamic response of wind turbines to external influences and various environmental conditions. These load cases involve simulating the turbine in various situations to measure its durability and stability against factors such as wind and waves. This simulation identifies weak points for necessary design improvements. As seen in Table 5.14, eight different load cases will be examined, and these load cases will be simulated for wind turbines containing spar, semi-submersible, and innovative platforms. Simulation results will include time-series data, statistical outputs, and PSD (Power Spectral Density) graphics.

Table 5.14. Load case table used from (Source: Jonkman and Musial 2010⁴⁵)

Load Case	Wind Conditions	Wave Conditions	Analysis Type
1.2	None: air density = 0	Still water	Eigen analysis
1.3	None: air density = 0	Still water	Static equilibrium test
1.4	None: air density = 0	Still water	Free-decay test time series
4.1	None: air density = 0	Regular Airy: H = 6 m, T = 10 s	Periodic time-series
4.2	None: air density = 0	Irregular Airy: Hs = 6 m, Tp = 10 s,	Time-series statistics, PSDs
5.1	Steady, uniform, no shear: Vhub = 8 m/s	Regular Airy: H = 6 m, T = 10 s	Periodic time-series
5.2	Turbulent: Vhub = 11.4 m/s, $\sigma_1 = 1.981$ m/s	Irregular Airy: Hs = 6 m, Tp = 10 s	Time-series statistics, PSDs
5.3	Turbulent: Vhub = 18 m/s, $\sigma_1 = 2.674$ m/s	Irregular Airy: Hs = 6 m, Tp = 10 s	Time-series statistics, PSDs

In load case 1.2, the combined system eigenfrequencies were found by gravity and free decay tests, ignoring air and water density. The purpose of this load case is to determine the modal frequencies of the floating wind turbine.

In load case 1.3, whether the floating platform is in static equilibrium is tested.

In load case 1.4, natural frequency and damping values are obtained by performing free decay tests for surge, pitch, heave, and yaw movements of the floating wind turbine.

In load case 4.1, the hydro-elastic response of the floating platform under regular wave conditions is examined.

In load case 4.2, the hydro-elastic response of the floating platform under irregular wave conditions obtained by using the JONSWAP wave spectrum is examined, and the hydro-elastic power spectra are found.

Load case 5.1 is to find the aero-hydro-servo-elastic response of the floating platform in regular waves and steady wind conditions.

Load case 5.2 is to find the aero-hydro-servo-elastic response of the floating platform in irregular waves and turbulent wind conditions and obtain the power spectra output.

Load case 5.3 is to find the aero-hydro-servo-elastic response of the floating platform in irregular waves and high turbulent wind conditions and obtain the power spectra output. The conditions here are defined as extreme environmental conditions, and the durability of the wind turbine is tested.

CHAPTER 6

RESULTS

This section presents the findings from various analyses. Different approaches were evaluated to assess the static and dynamic behavior of each platform and wind turbine under conditions such as static equilibrium, free decay tests, eigenvalue analysis, steady and turbulent wind, and regular and irregular wave conditions.

Eigenvalues and damping values were evaluated using a free decay test. The results in wind and steady wind conditions are displayed through time series outputs within a timeframe between 400 and 520 seconds. The analyses in irregular wave and turbulent wind conditions are presented through tabulated PSD (Power Spectral Density) graphics and statistical data based on frequency components obtained using FFT (Fast Fourier Transform), covering a 600-second duration.

In addition, the results obtained from WAMIT, which is seen as a reference, are shown for spar and semi-submersible platforms. Differences between approaches using AQWA and other open-source potential flow solvers are highlighted. The effects of geometric shape and mesh design for platforms were explained.

The most suitable approaches for the FloaTolia platform were selected and used together with the F2A method. In addition to providing hydrodynamic coefficients as input to OpenFAST(OF) as in other platforms, both rigid and flexible platform members were designed and analyzed with F2A, an AQWA-FAST v7 coupled model. Here, the source of the resonance caused by the flexible platform was investigated, shown in the PSD graphic at different frequencies, and solution suggestions were presented. The importance of the 2nd harmonics pitch and 2nd harmonics heave motions of the platform was emphasized.

In addition, by comparing the three platforms with each other, loads such as thrust on the wind turbine components, tower top moments, and blade root moments were calculated, and it was determined that the FloaTolia platform was exposed to less load because low pitching angles due to mooring line design.

6.1. Load Cases Results

Within the scope of this study, certain load cases were applied for different analysis types in various wind and wave conditions, as shown in Table 5.14. With these analyses, the behavior of three different platforms will be closely examined. Analysis was performed between 400-520 seconds for load cases 4.1 and 5.1. Analysis was carried out between 30-630 seconds for load cases 4.2, 5.2, and 5.3. 600-second analyses were performed for load cases 1.2, 1.3, and 1.4. Eigenvalues in load case 1.2 were found using free decay tests.

6.1.1. Spar Platform

The Spar platform is a cylindrical and ballasted floating structure that lowers its center of gravity deep into the water to maintain stability. The geometry of this platform is quite simple and cylindrical, which means there are no complex details in its structural design. Due to this simplicity, no issues with mesh quality were encountered during the analysis processes. This is because cylindrical structures have simpler shapes that reduce errors during mesh creation, making the modeling process more straightforward and efficient.

6.1.1.1. Load Case 1.2 on Spar Platform

Natural periods for the spar platform gave the same and correlated results. It is thought that the reason NREL-FAST⁴⁵ has lower periods is that it uses an older version, and the platform design lacks some additional values. In this analysis, WAMIT-OpenFAST and other methods demonstrate good compatibility. The AQWA-OpenFAST, Capytaine-OpenFAST, and NEMOH-OpenFAST platforms show values 0.60% higher in surge and sway modes and 0.42% higher in roll and pitch modes compared to WAMIT-OpenFAST. However, the heave values are consistent with the values of WAMIT-OpenFAST, and the yaw values are precisely the same. All data is presented in Figure 6.1.

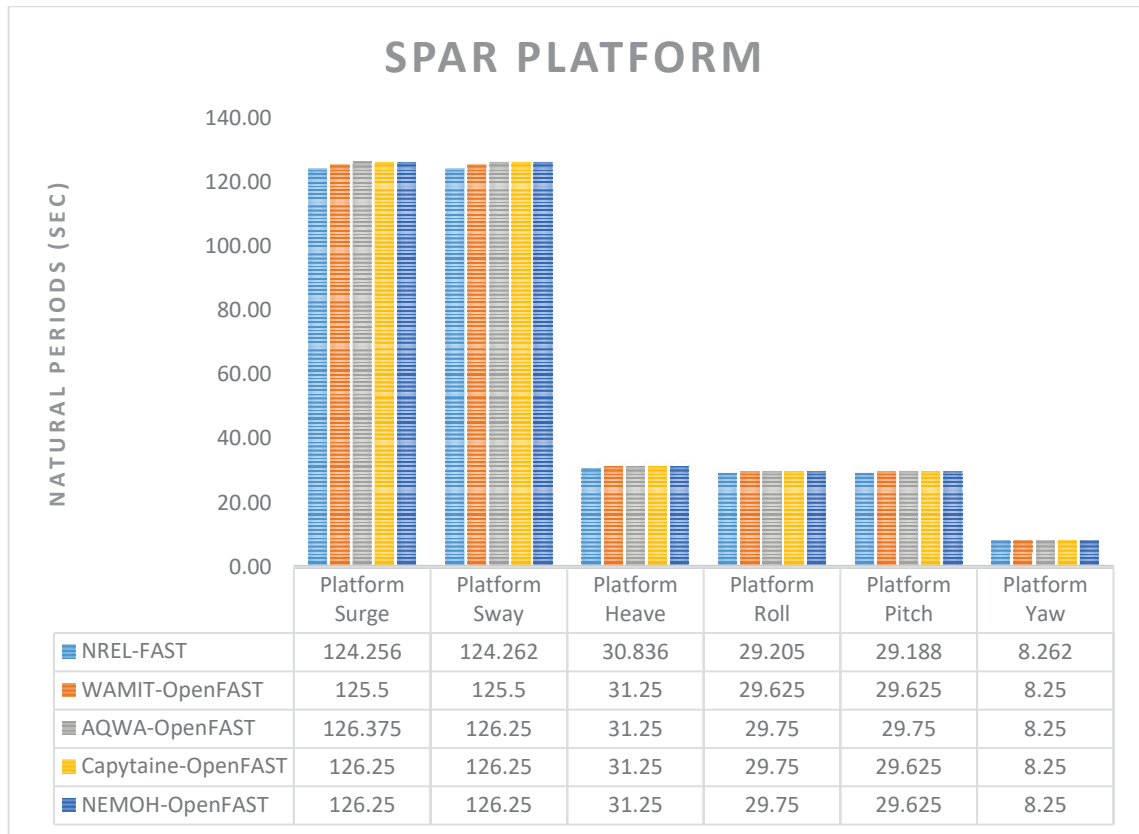


Figure 6.1. Spar platform natural periods for each method

6.1.1.2. Load Case 1.3 on Spar Platform

In the static test, the results for the spar platform from each program converge towards zero across all six degrees of freedom (DOF), as clearly demonstrated in Table 6.1. As shown in the table, the values in the surge, sway, heave, roll, pitch, and yaw modes are approaching zero, indicating that the platform is in static equilibrium.

Table 6.1. Spar platform static test results

Load Case 1.3 (mean)	AQWA OpenFAST	Capytaine OpenFAST	NEMOH OpenFAST	WAMIT OpenFAST
Surge (m)	-7.82E-02	-7.82E-02	-7.82E-02	-7.87E-02
Sway (m)	2.00E-04	2.00E-04	2.00E-04	2.00E-04
Heave (m)	2.09E-02	2.10E-02	2.10E-02	2.09E-02
Roll (deg)	-2.00E-04	-2.00E-04	-2.00E-04	-2.00E-04
Pitch (deg)	-6.40E-02	-6.28E-02	-6.28E-02	-6.44E-02
Yaw (deg)	1.75E-09	-1.93E-9	-3.37E-9	3.63E-09

6.1.1.3. Load Case 1.4 on Spar Platform

This study examined free decay tests performed using four different hydrodynamic models for the spar platform. The initial displacement and angle values for surge, heave, pitch, and yaw were oscillated and compared over time using outputs from WAMIT-OpenFAST, Capytaine-OpenFAST, AQWA-OpenFAST, and NEMOH-OpenFAST potential flow solvers. Preliminary results show no significant differences between models, with correlation and consistency across all degrees of freedom.

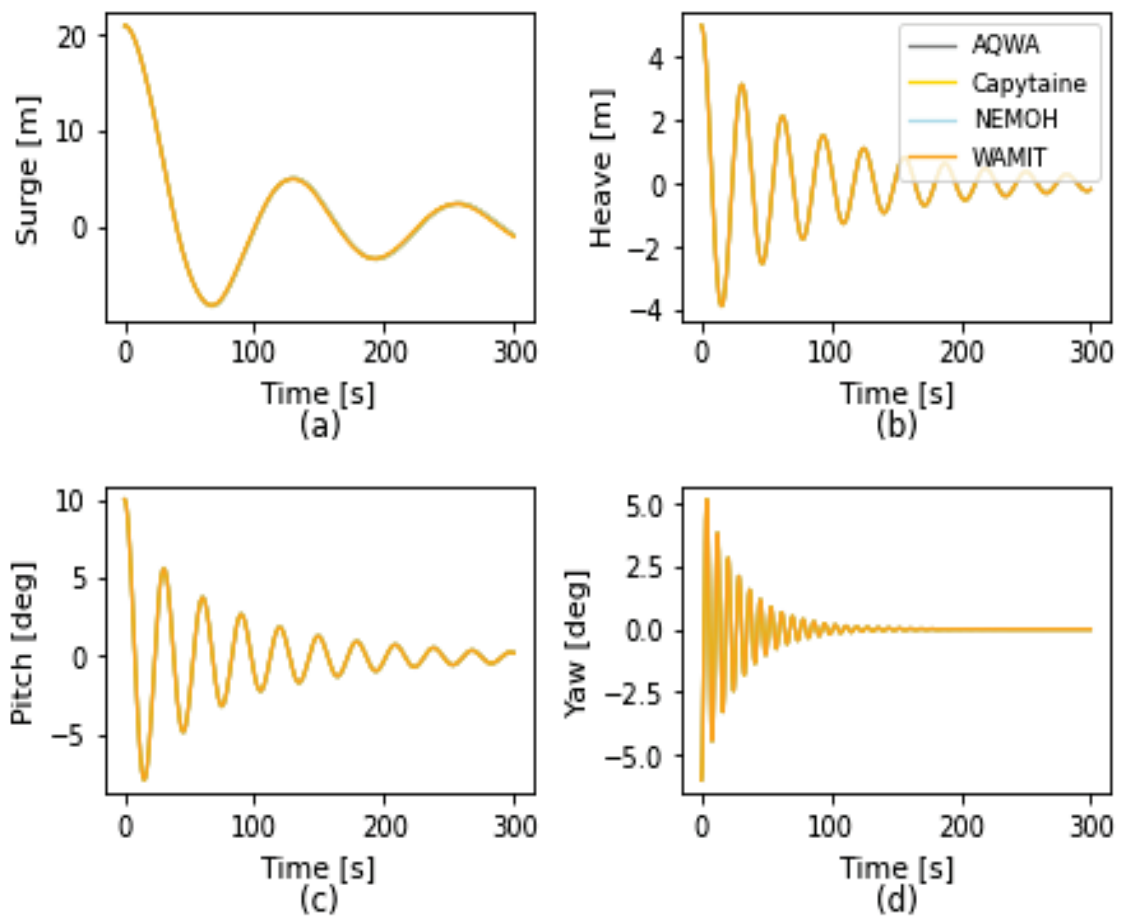


Figure 6.2. Spar platform free decay test results: a) Surge, b) Heave, c) Pitch, d) Yaw

6.1.1.4. Load Case 4.1 on Spar Platform

As with the free decay tests in load case 4.1, the entire method is compatible with WAMIT-OpenFAST and is the same. The analyses were carried out only under regular wave conditions.

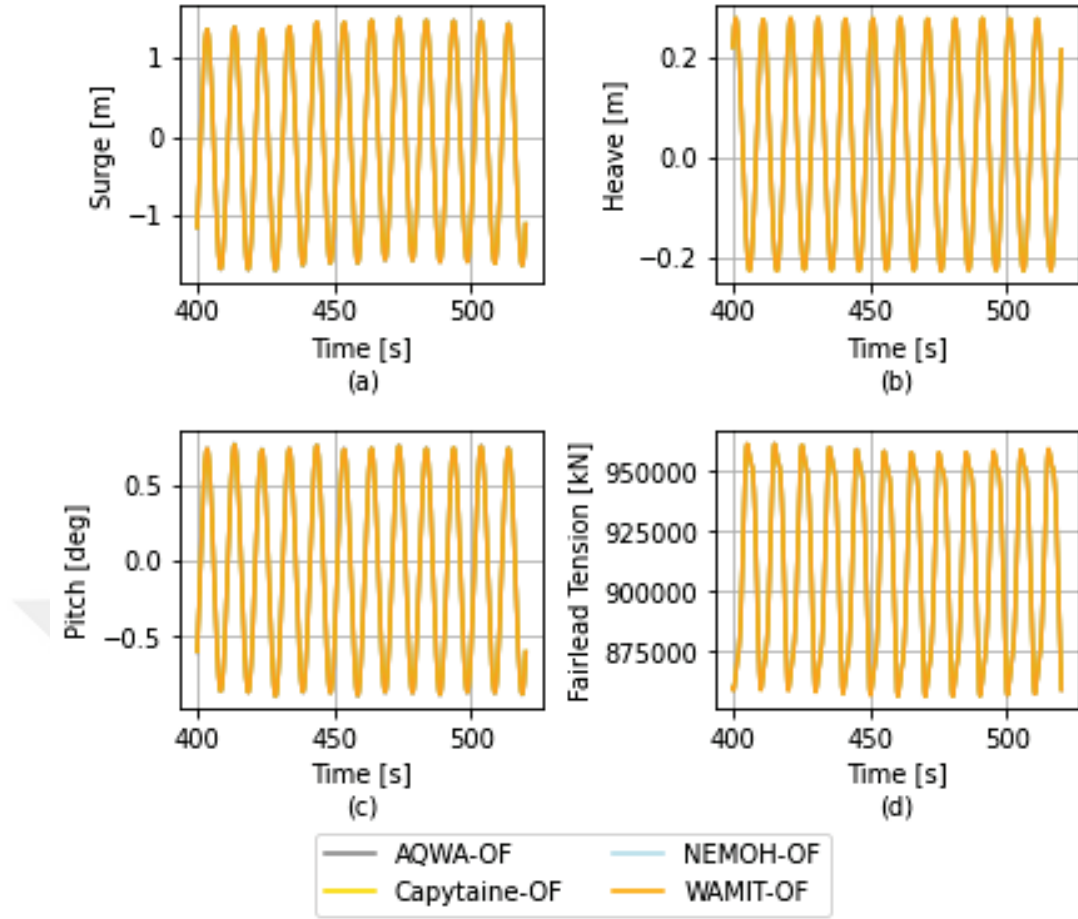


Figure 6.3. Spar platform periodic time series for load case with regular waves and without wind: a) Surge, b) Heave, c) Pitch, d) Fairlead 1 Tension

6.1.1.5. Load Case 4.2 on Spar Platform

Load case 4.2 is the case where only the wave is irregular, and there is no wind. And the statistics and values are shown in Table 6.2. The results obtained under load case 4.2 with four different simulation tools (AQWA, Capytaine, NEMOH, WAMIT) are shown in Table 6.2. When AQWA-OpenFAST, Capytaine-OpenFAST, and NEMOH-OpenFAST results are compared with WAMIT-OpenFAST at min values of load case 4.2, 100.52% for surge (m), 99.68% for heave (m), 100.00% for pitch (deg), and 100.00% are calculated for fairlead 1 tension (kN). At max values, 100.47% for surge (m), 99.62% for heave (m), 99.90% for pitch (deg), and 100.00% for fairlead 1 tension (kN). In mean values, it is 90.97% for surge (m), 99.37% for heave (m), 91.26% for pitch (deg), and 100.00% for fairlead 1 tension (kN). According to these results, the three potential flow solver programs provide values close to the WAMIT-OpenFAST results.

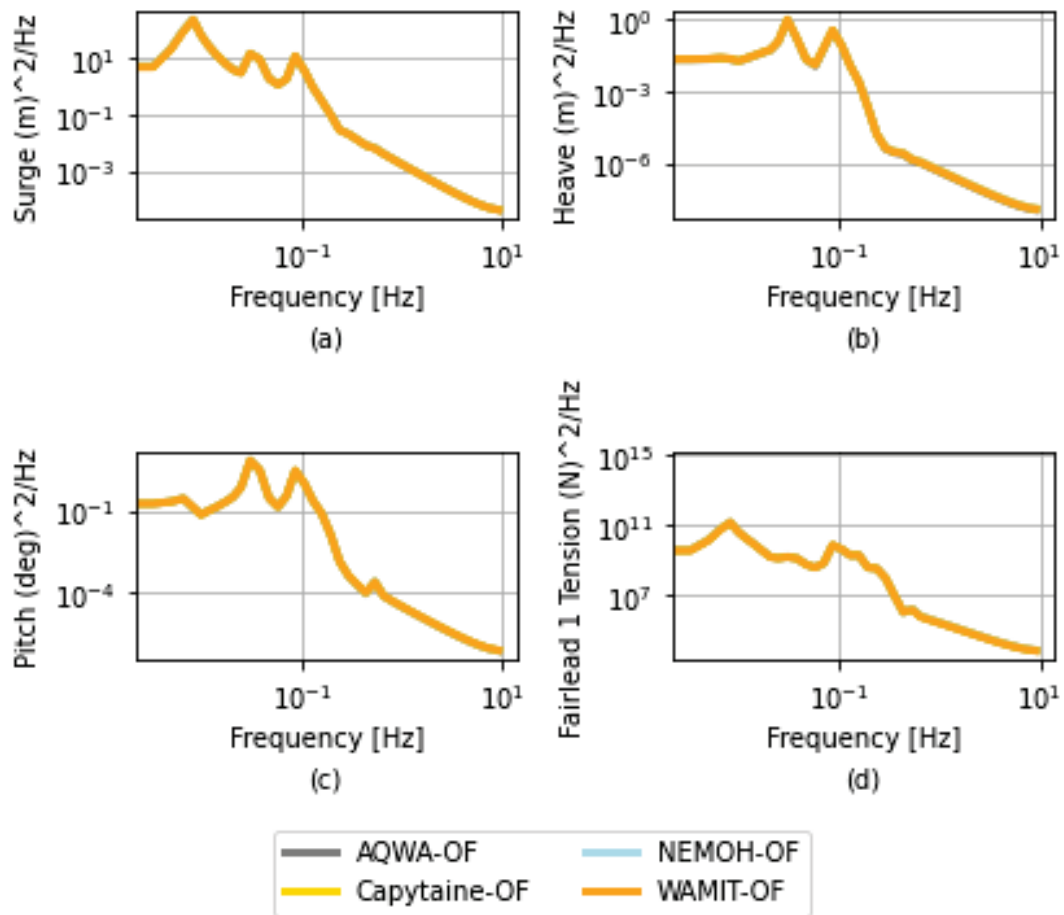


Figure 6.4: Spar platform PSD graphs for load case with irregular waves and without wind: a) Surge, b) Heave, c) Pitch, d) Fairlead 1 Tension

Table 6.2. Load case 4.2 Statistical results spar platform

Load Case 4.2 (min)	AQWA OpenFAST	Capytaine OpenFAST	NEMOH OpenFAST	WAMIT OpenFAST
Surge (m)	-3.88E+00	-3.88E+00	-3.88E+00	-3.86E+00
Heave (m)	-6.04E-01	-6.15E-01	-6.15E-01	-6.17E-01
Pitch (deg)	-1.85E+00	-1.86E+00	-1.86E+00	-1.86E+00
Fairlead 1 Tension (kN)	7.84E+05	7.84E+05	7.84E+05	7.84E+05
Load Case 4.2 (max)	AQWA OpenFAST	Capytaine OpenFAST	NEMOH OpenFAST	WAMIT OpenFAST
Surge (m)	6.45E+00	6.46E+00	6.46E+00	6.43E+00
Heave (m)	5.16E-01	5.29E-01	5.29E-01	5.31E-01
Pitch (deg)	1.92E+00	1.93E+00	1.93E+00	1.92E+00
Fairlead 1 Tension (kN)	1.03E+06	1.03E+06	1.03E+06	1.03E+06
Load Case 4.2 (mean)	AQWA OpenFAST	Capytaine OpenFAST	NEMOH OpenFAST	WAMIT OpenFAST
Surge (m)	-2.63E-02	-2.62E-02	-2.62E-02	-2.88E-02
Heave (m)	1.58E-02	1.57E-02	1.57E-02	1.57E-02
Pitch (deg)	-5.23E-02	-5.22E-02	-5.22E-02	-5.27E-02
Fairlead 1 Tension (kN)	9.10E+05	9.10E+05	9.10E+05	9.10E+05

6.1.1.6. Load Case 5.1 on Spar Platform

As in load case 5.1, the methods give the same results at 8 m/s steady wind speed and regular wave conditions. Here, values from 400 seconds to 520 seconds are taken.

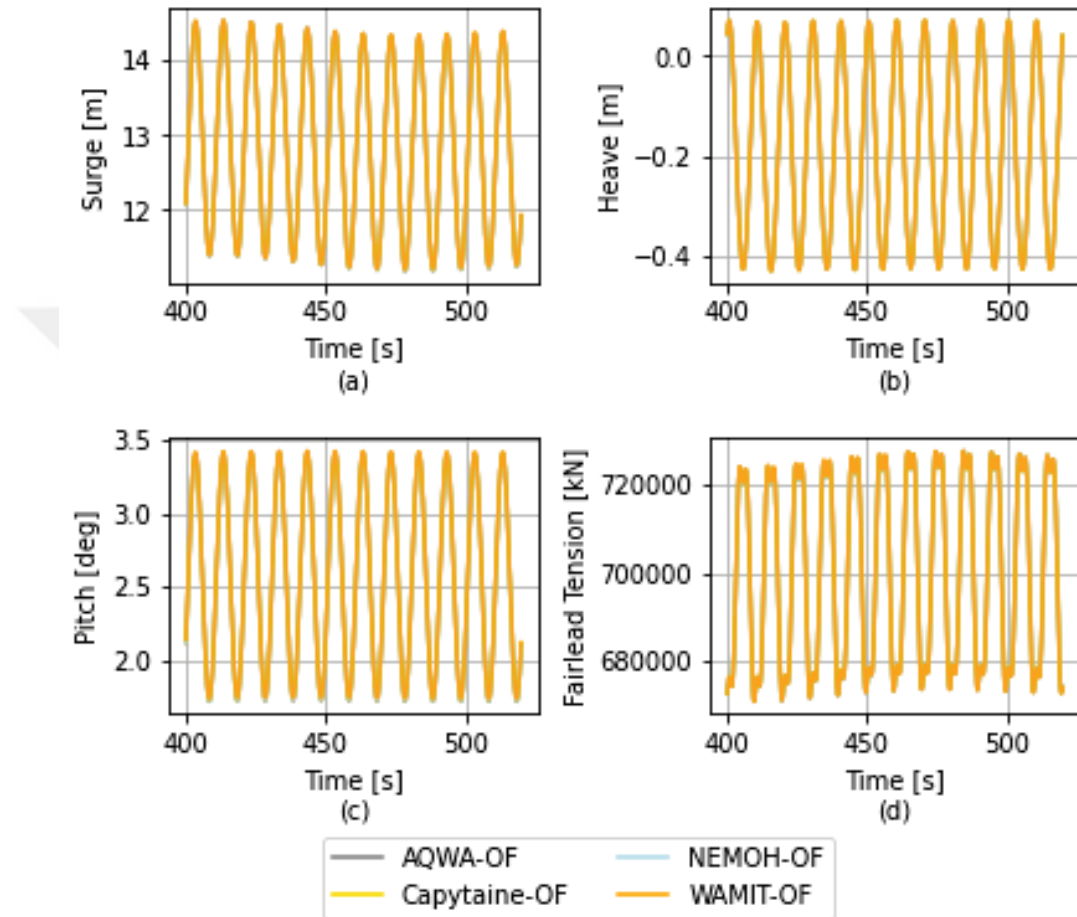


Figure 6.5. Spar platform periodic time series for load case with regular waves and steady wind: a) Surge, b) Heave, c) Pitch, d) Fairlead 1 Tension

6.1.1.7. Load Case 5.2 on Spar Platform

The analyses conducted in this study span a time from 30 seconds to 630 seconds., and the first 30 seconds are not considered. In addition to load case 4.2, Power Spectral Density (PSD) plots are shown for the tower components included in the analysis of wind conditions.

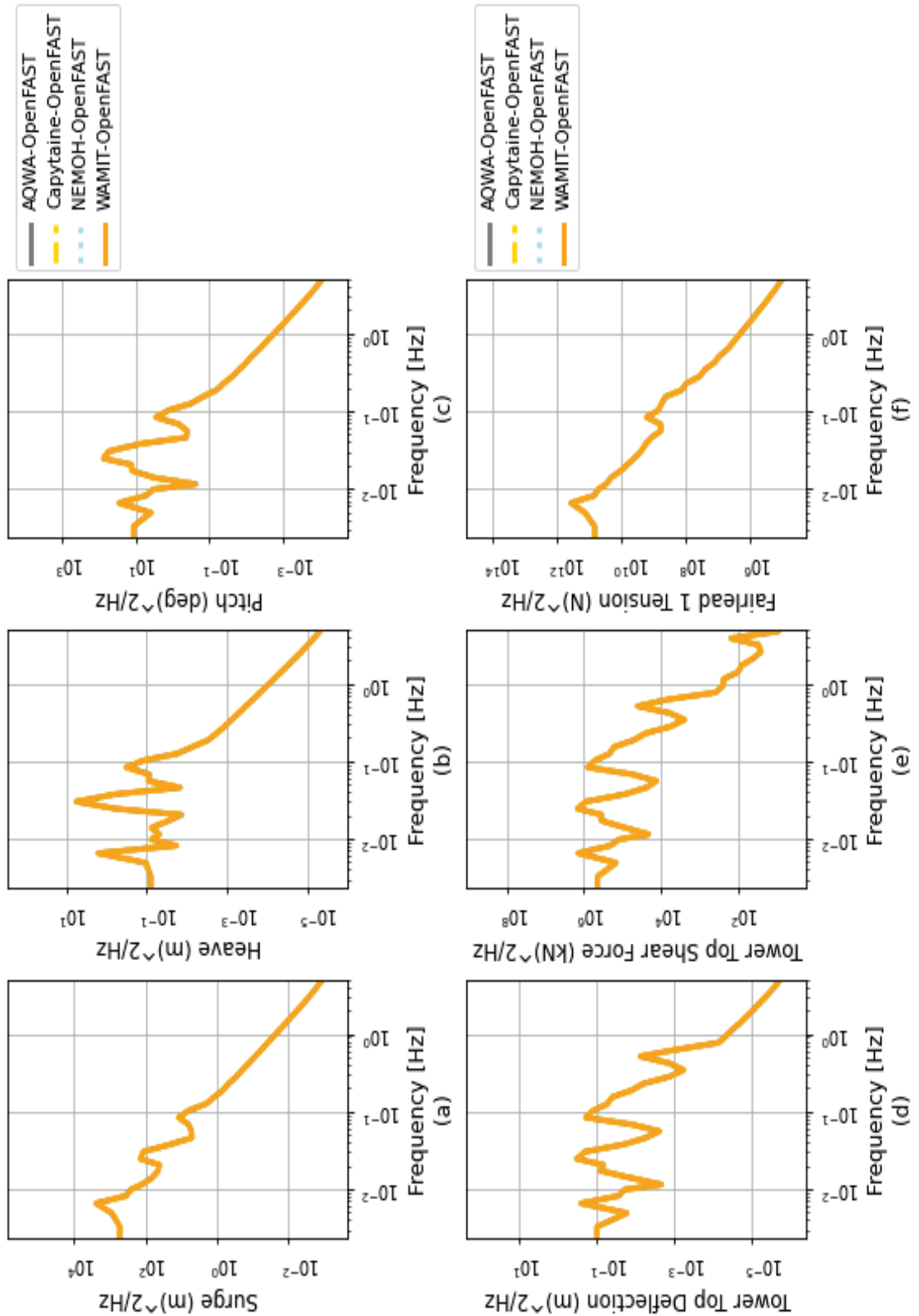


Figure 6.6. Spar platform PSD graphs for load case 5.2: a) Surge, b) Heave, c) Pitch, d) Tower Top Deflection e) Tower Top Shear Force f) Fairlead 1 Tension

As seen in Table 6.3, in load case 5.2, all methods have similar results in irregular wave conditions with a nominal speed of 11.4 m/s. There is significant consistency across programs across all values. Percentages for mean values: 100.00% for surge (m), 99.31% for pitch (deg), 99.75% for tower top deflection (m), 99.75% for tower top shear (kN) compared to WAMIT-OpenFAST for the three programs have a rate of 99.77% and 100.00% for fairlead 1 tension (kN). All programs calculated almost identical results for this analysis.

Table 6. 3. Load Case 5.2 statistical results for spar platform

Load Case 5.2 (min)	AQWA OpenFAST	Capytaine OpenFAST	NEMOH OpenFAST	WAMIT OpenFAST
Surge (m)	7.22E+00	7.24E+00	7.24E+00	7.25E+00
Heave (m)	-9.77E-01	-9.77E-01	-9.77E-01	-9.80E-01
Pitch (deg)	5.90E-01	5.90E-01	5.90E-01	5.99E-01
Tower Top Def.(m)	-1.01E-01	-9.95E-02	-9.95E-02	-1.05E-01
Tower Top Shear (kN)	-1.70E+02	-1.67E+02	-1.64E+02	-1.76E+02
Fairlead 1 Tension (kN)	5.39E+05	5.40E+05	5.40E+05	5.40E+05
Load Case 5.2 (max)	AQWA OpenFAST	Capytaine OpenFAST	NEMOH OpenFAST	WAMIT OpenFAST
Surge (m)	2.74E+01	2.74E+01	2.74E+01	2.74E+01
Heave (m)	1.81E-01	1.88E-01	1.88E-01	1.86E-01
Pitch (deg)	7.74E+00	7.74E+00	7.74E+00	7.79E+00
Tower Top Def.(m)	7.01E-01	7.01E-01	7.01E-01	7.05E-01
Tower Top Shear (kN)	1.51E+03	1.51E+03	1.51E+03	1.53E+03
Fairlead 1 Tension (kN)	7.56E+05	7.56E+05	7.56E+05	7.56E+05
Load Case 5.2 (mean)	AQWA OpenFAST	Capytaine OpenFAST	NEMOH OpenFAST	WAMIT OpenFAST
Surge (m)	2.12E+01	2.12E+01	2.12E+01	2.12E+01
Heave (m)	-4.54E-01	-4.54E-01	-4.54E-01	-4.54E-01
Pitch (deg)	4.30E+00	4.30E+00	4.30E+00	4.33E+00
Tower Top Def.(m)	3.97E-01	3.97E-01	3.97E-01	3.98E-01
Tower Top Shear (kN)	8.75E+02	8.75E+02	8.76E+02	8.77E+02
Fairlead 1 Tension (kN)	6.06E+05	6.06E+05	6.06E+05	6.06E+05

6.1.1.8. Load Case 5.3 on Spar Platform

An extreme wind speed of 18 m/s in spar platform load case 5.3 gives similar results in the same percentage as load case 5.2. The analysis here is calculated from 30 to 630 seconds, as in every irregular wave analysis. The extreme wind speed of 18 m/s in load case 5.3 gives the same percentage of similar results as in load case 5.2 in irregular wave conditions.

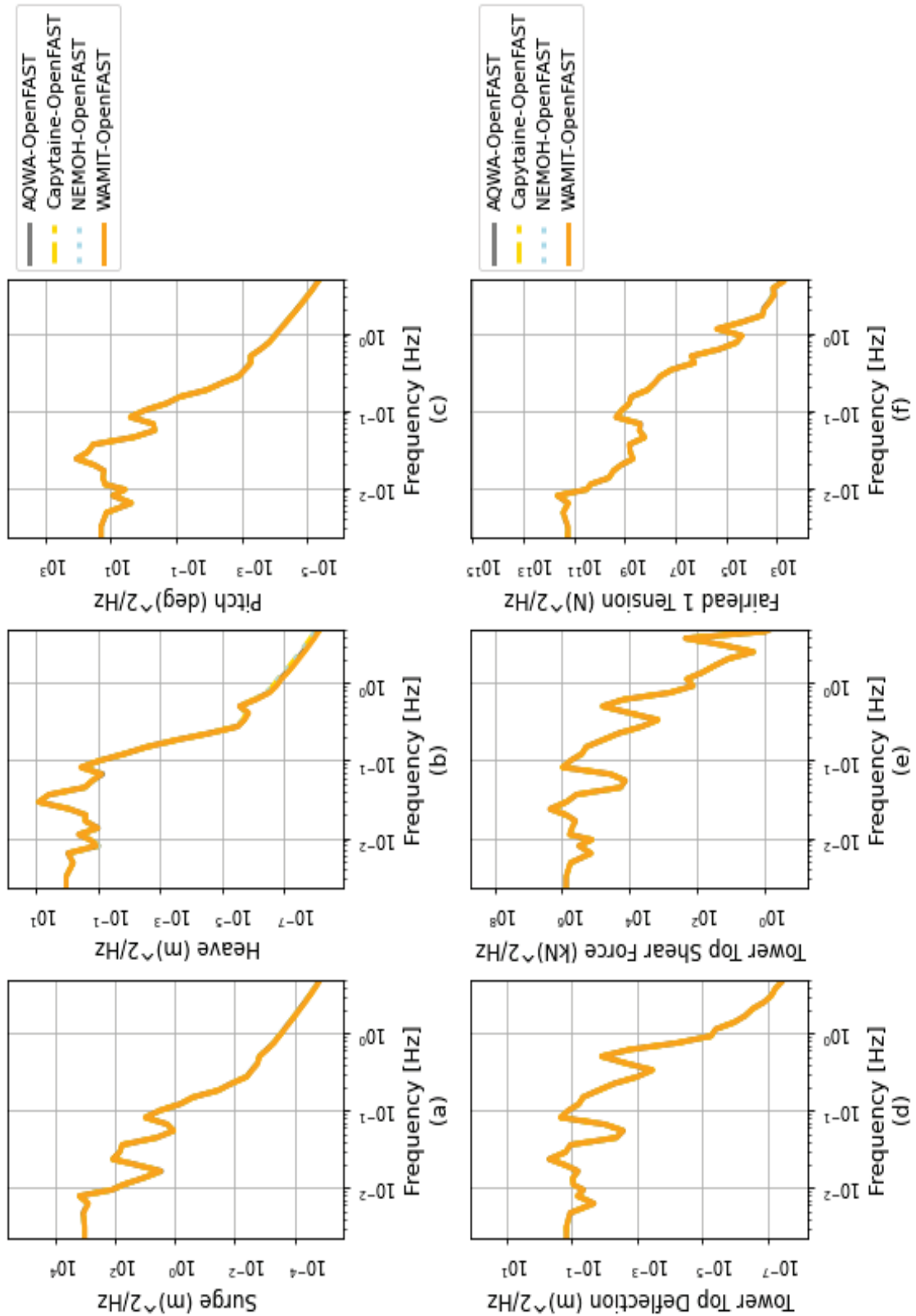


Figure 6.7. Spar platform PSD graphs for load case 5.3: a) Surge, b) Heave, c) Pitch, d) Tower Top Deflection e) Tower Top Shear Force f) Fairlead 1 Tension

Percentages for mean values of spar platform load Case 5.3: AQWA-OpenFAST results compared to those of WAMIT-OpenFAST, 99.30% for surge (m), 100.00% for heave (m), 99.65% for pitch (deg), tower top deflection (m) It is 99.62%, 99.63% for tower top shear (kN) and 100.00% for fairlead 1 tension (kN). Capytaine-OpenFAST and NEMOH-OpenFAST results are similar at the same rates (99.30%, 100.00%, 99.65%, 99.62%, 99.63%, and 100.00%) when compared to those of WAMIT-OpenFAST. According to these results, all three programs give the closest values to WAMIT-OpenFAST results.

Table 6.4. Load case 5.3 statistical results for spar platform

Load Case 5.3 (min)	AQWA OpenFAST	Capytaine OpenFAST	NEMOH OpenFAST	WAMIT OpenFAST
Surge (m)	7.42E+00	7.42E+00	7.42E+00	7.45E+00
Heave (m)	-1.54E+00	-1.55E+00	-1.55E+00	-1.56E+00
Pitch (deg)	-1.71E+00	-1.71E+00	-1.71E+00	-1.70E+00
Tower Top Def. (m)	-8.36E-02	-8.30E-02	-8.30E-02	-8.40E-02
Tower Top Shear (kN)	-2.40E+02	-2.39E+02	-2.39E+02	-2.42E+02
Fairlead 1 Tension (kN)	5.52E+05	5.52E+05	5.52E+05	5.53E+05
Load Case 5.3 (max)	AQWA OpenFAST	Capytaine OpenFAST	NEMOH OpenFAST	WAMIT OpenFAST
Surge (m)	2.52E+01	2.52E+01	2.52E+01	2.53E+01
Heave (m)	7.32E-01	7.41E-01	7.41E-01	7.49E-01
Pitch (deg)	8.36E+00	8.36E+00	8.36E+00	8.40E+00
Tower Top Def. (m)	7.85E-01	7.85E-01	7.85E-01	7.86E-01
Tower Top Shear (kN)	1.77E+03	1.77E+03	1.77E+03	1.78E+03
Fairlead 1 Tension (kN)	7.94E+05	7.94E+05	7.94E+05	7.94E+05
Load Case 5.3 (mean)	AQWA OpenFAST	Capytaine OpenFAST	NEMOH OpenFAST	WAMIT OpenFAST
Surge (m)	1.42E+01	1.42E+01	1.42E+01	1.43E+01
Heave (m)	-2.13E-01	-2.13E-01	-2.13E-01	-2.13E-01
Pitch (deg)	2.85E+00	2.85E+00	2.85E+00	2.86E+00
Tower Top Def. (m)	2.64E-01	2.64E-01	2.64E-01	2.65E-01
Tower Top Shear (kN)	5.37E+02	5.37E+02	5.37E+02	5.39E+02
Fairlead 1 Tension (kN)	6.85E+05	6.85E+05	6.85E+05	6.85E+05

6.1.2. Semi-Submersible Platform

Semi-submersible platforms have a semi-submerged structure and contain pontoons and vertical columns that allow them to provide stability on the water using

ballast and buoyancy and have a large surface area. Various analyses have been made in analyzes such as Offshore code comparison collaboration continuation within IEA wind task 30: Phase II results regarding a floating semisubmersible wind system¹¹⁴ and OC5 project phase II: validation of global loads of the DeepCwind floating semisubmersible wind turbine⁴⁷. In this context, natural period results were compared with the results from OpenFAST simulations.

6.1.2.1. Load Case 1.2 on Semi-Submersible Platform

In this graph, natural periods calculated by various potential flow methods are compared. The graph contains the natural periods for the six degrees of freedom of the platform. Although all methods produce similar results for platform surge and platform sway, the results from NREL-FAST¹¹⁴ indicate slightly lower values. The natural periods for Platform heave range from 17.212 sec to 17.438 sec, while for Platform roll and Platform pitch, all methods are around 26 sec and 25.375 sec. Natural periods for platform yaw range from 75.758 seconds to 79.5 seconds, with the results from NREL-FAST¹¹⁴ showing the lowest value. In this context, WAMIT and other approaches produce very similar results.

In addition, in the free decay test results of the OC5 Project Phase II: Validation of Global Loads of the DeepCwind Floating semisubmersible Wind Turbine⁴⁷ project, 107 seconds for surge, 112 seconds for sway, 17.5 seconds for heave, 32.8 seconds for roll, 32.5 seconds for pitch, and 80.8 seconds for yaw were obtained.

When these values are compared as percentages with the outputs of the analyses, the WAMIT-OpenFAST platform shows lower values: 6.31% for surge, 0.22% for sway, 0.71% for heave, 20.73% for roll, 20.26% for pitch, and 2.30% for yaw. The AQWA-OpenFAST platform is 5.99% lower for surge, 0.44% lower for sway, 1.43% lower for heave, 21.17% lower for roll, 20.55% lower for pitch, and 2.69% lower for yaw. The Capytaine-OpenFAST platform is 5.73% lower for surge, 0.44% lower for sway, 0.71% lower for heave, 22.56% lower for roll, 20.79% lower for pitch, and 2.50% lower for yaw. The NEMOH-OpenFAST platform has lower values of 5.73% for surge, 0.44% for sway, 0.71% for heave, 21.82% for roll, 21.02% for pitch, and 2.39% for yaw.

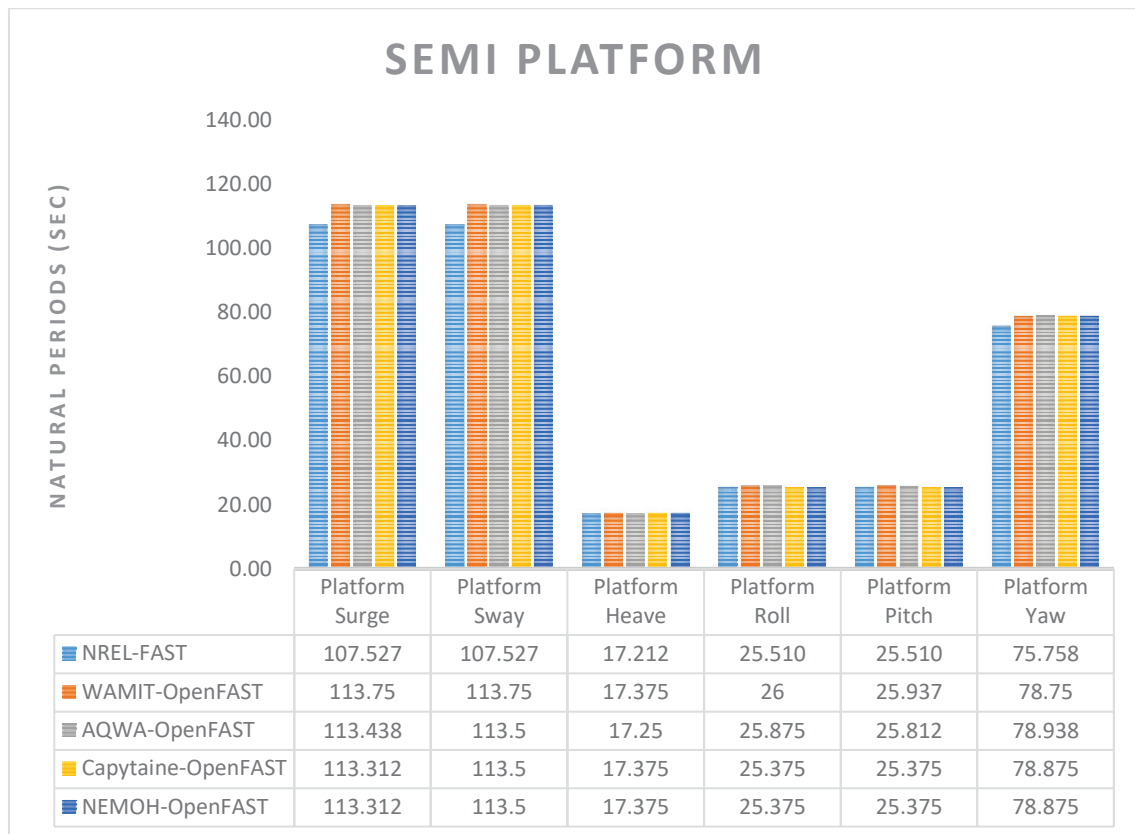


Figure 6.8. Semi-submersible platform natural periods for each method

6.1.2.2. Load Case 1.3 on Semi-Submersible Platform

As shown in Table 6.5, the values in the surge, sway, heave, roll, pitch, and yaw modes are the mean values of a 600-second analysis, similar to those observed for the spar platform, indicating that the semi-submersible platform is in static equilibrium. If the analysis duration were extended, these values would converge even closer to zero.

Table 6.5. Semi-submersible platform static test results

Load Case 1.3 (mean)	AQWA OpenFAST	Capytaine OpenFAST	NEMOH OpenFAST	WAMIT OpenFAST
Surge (m)	-3.80E-03	-3.20E-03	-3.20E-03	-4.00E-03
Sway (m)	1.10E-05	1.01E-05	1.01E-05	1.86E-05
Heave (m)	-8.10E-03	-8.20E-03	-8.20E-03	-8.00E-03
Roll (deg)	-2.00E-04	-2.00E-04	-2.00E-04	-2.00E-04
Pitch (deg)	-8.19E-02	-7.67E-02	-7.67E-02	-8.32E-02
Yaw (deg)	-7.32E-07	5.12E-06	8.70E-06	1.10E-06

6.1.2.3. Load Case 1.4 on Semi-Submersible Platform

In this study, free decay tests were performed using four different hydrodynamic models for the semi-submersible platform, and they were examined. Using the outputs obtained from WAMIT, Capytaine, AQWA, and NEMOH potential flow solvers, the initial displacement and angle values for surge, heave, pitch, and yaw were calculated, and their changes over time were compared. Preliminary results showed correlations and minimal differences in all degrees of freedom. Additionally, the damping ratios were found to be very similar, and the period values are presented in Figure 6.8. Notably, the pitch values for NEMOH-OpenFAST and Capytaine-OpenFAST were approximately 2% lower compared to WAMIT-OpenFAST.

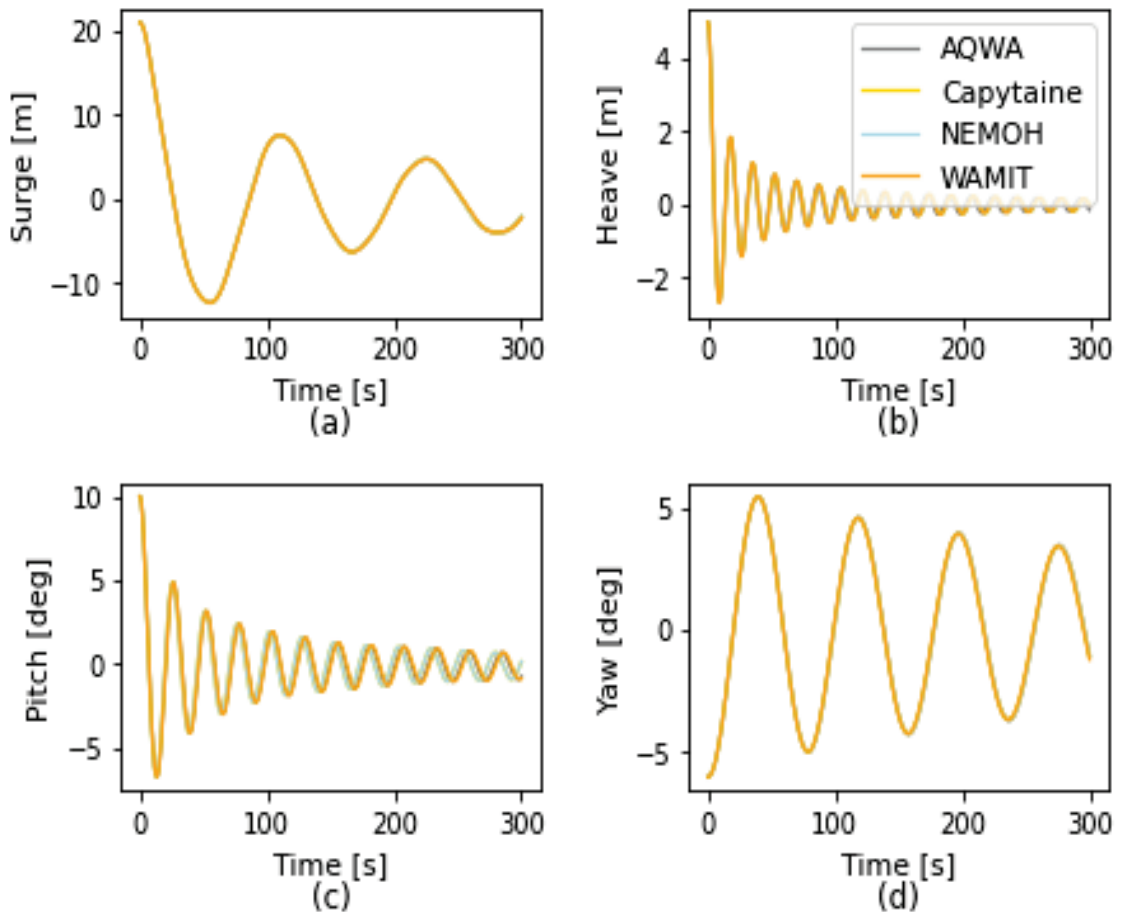


Figure 6.9. Semi-submersible platform free decay test results:

a) Surge, b) Heave, c) Pitch, d) Yaw

6.1.2.4. Load Case 4.1 on Semi-Submersible Platform

In load case 4.1, WAMIT-OpenFAST is slightly different from the others and has a positive offset of approximately 10 percent in surge, pitch, and heave motion. fairlead tension 1 values are quite similar for all programs.

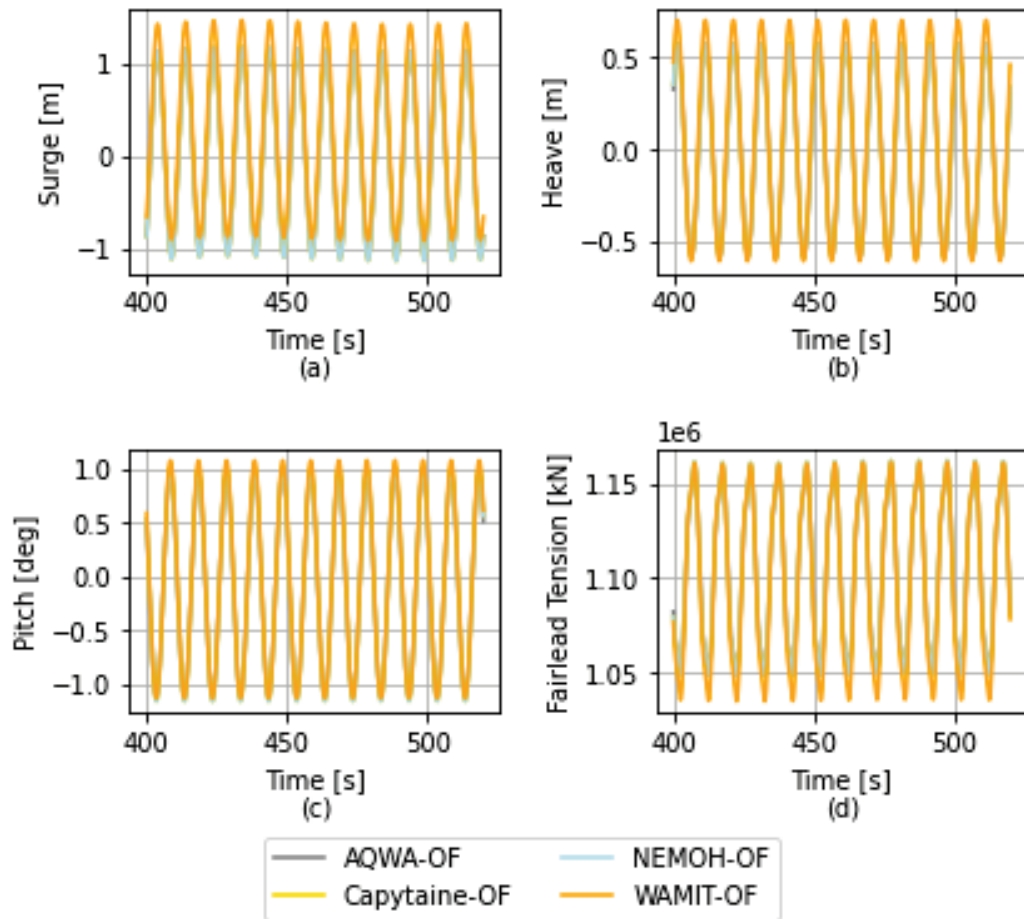


Figure 6.10. Semi-submersible platform periodic time series for load case with regular waves and without wind: a) Surge, b) Heave, c) Pitch, d) Fairlead 1 Tension

6.1.2.5. Load Case 4.2 on Semi-Submersible Platform

A comparison of four different programs shows that there is a general similarity between them, but there are differences with WAMIT-OPENFAST results due to fine-tuning of models or calculation methods, as well as mesh structure. In Table 6.6, the minimum, maximum, and mean values in the OpenFAST outputs obtained using different potential flow solvers (AQWA, Capytaine, NEMOH, and WAMIT) are prepared for the

4.2 load case without wind and irregular wave conditions. In Table 6.6., the percentage calculations for load case 4.2 are as follows: for min values, AQWA-OpenFAST results compared to WAMIT-OpenFAST, 117.53% for surge (m), 88.43% for heave (m), 94.19% for pitch (deg), and 102.52% for Fairlead 1 Tension (kN). For Capytaine-OpenFAST and NEMOH-OpenFAST, these values are 105.38%, 77.69%, 83.87%, and 104.28%, respectively. For max values, AQWA-OpenFAST results are 86.62% for surge (m), 86.05% for heave (m), 92.62% for pitch (deg), and 101.56% for Fairlead 1 Tension (kN). For Capytaine-OpenFAST and NEMOH-OpenFAST, it is 77.94%, 72.39%, 87.48%, and 100.00%, respectively; for mean values, AQWA-OpenFAST results are 70.17% for surge (m), 159.54% for pitch (deg), and 101.83% for Fairlead 1 Tension (kN). For Capytaine and NEMOH, it is 56.58%, 151.99%, and 101.83%, respectively. These data show that the AQWA-OpenFAST output gives the closest results to the WAMIT-OpenFAST output for mean, min, and max values.

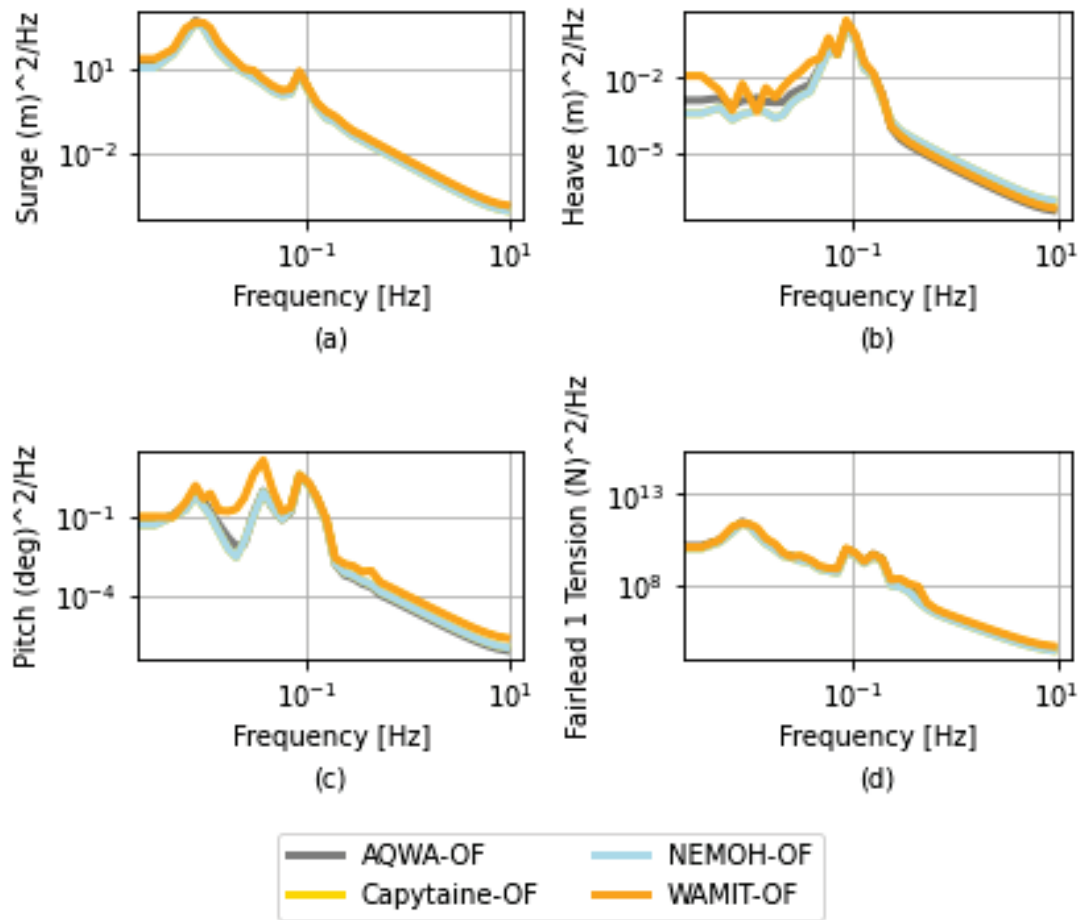


Figure 6.11. Semi-submersible platform PSD graphs for load cases with irregular waves and without Wind: a) Surge, b) Heave, c) Pitch, d) Fairlead 1 Tension

Table 6.6. Load case 4.2 statistical results for semi-submersible platform

Load Case 4.2 (min)	AQWA OpenFAST	Capytaine OpenFAST	NEMOH OpenFAST	WAMIT OpenFAST
Surge (m)	-5.90E+00	-5.29E+00	-5.29E+00	-5.02E+00
Heave (m)	-5.35E-01	-4.70E-01	-4.70E-01	-6.05E-01
Pitch (deg)	-1.46E+00	-1.30E+00	-1.30E+00	-1.55E+00
Fairlead 1 Tension (kN)	9.34E+05	9.50E+05	9.50E+05	9.11E+05
Load Case 4.2 (max)	AQWA OpenFAST	Capytaine OpenFAST	NEMOH OpenFAST	WAMIT OpenFAST
Surge (m)	6.99E+00	6.29E+00	6.29E+00	8.07E+00
Heave (m)	5.86E-01	4.93E-01	4.93E-01	6.81E-01
Pitch (deg)	9.54E-01	1.03E+00	1.03E+00	1.81E+00
Fairlead 1 Tension (kN)	1.30E+06	1.28E+06	1.28E+06	1.28E+06
Load Case 4.2 (mean)	AQWA OpenFAST	Capytaine OpenFAST	NEMOH OpenFAST	WAMIT OpenFAST
Surge (m)	-6.61E-02	-5.33E-02	-5.33E-02	9.42E-01
Heave (m)	-7.20E-03	-7.80E-03	-7.80E-03	1.15E-02
Pitch (deg)	-7.61E-02	-7.25E-02	-7.25E-02	-4.77E-02
Fairlead 1 Tension (kN)	1.11E+06	1.11E+06	1.11E+06	1.09E+06

6.1.2.6. Load Case 5.1 on Semi-Submersible Platform

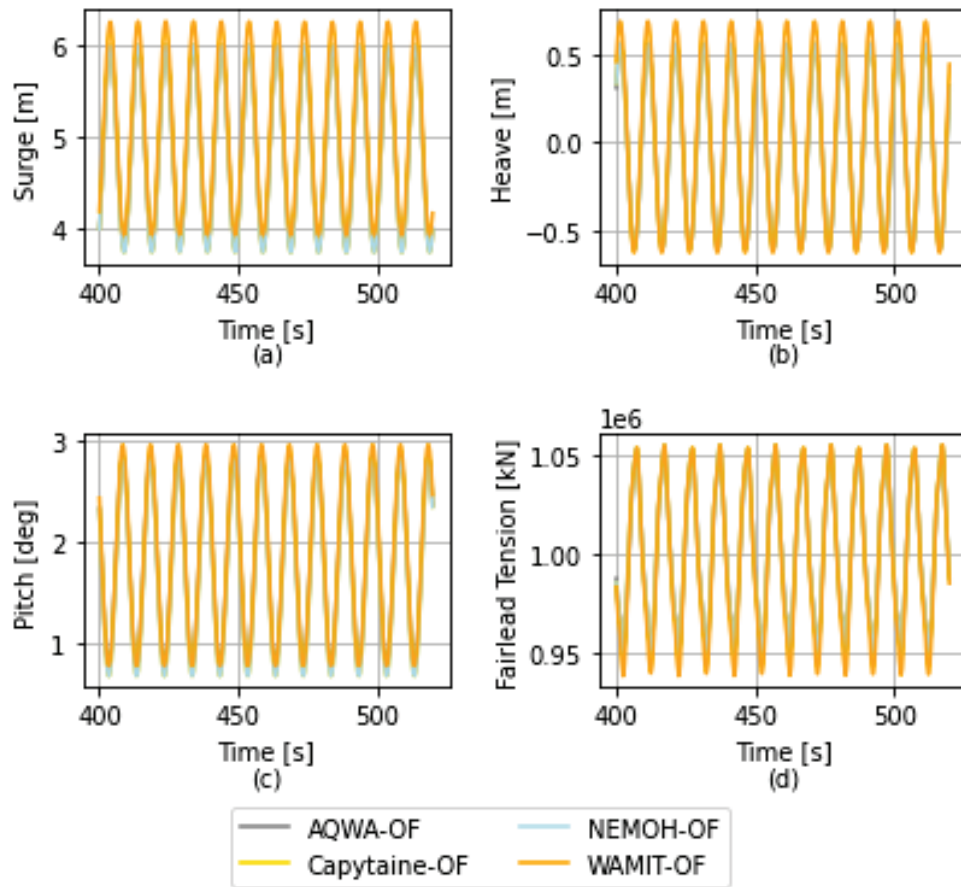


Figure 6.12. Semi-submersible platform periodic time series for load case with regular waves and steady wind: a) Surge, b) Heave, c) Pitch, d) Fairlead 1 Tension

6.1.2.7. Load Case 5.2 on Semi-Submersible Platform

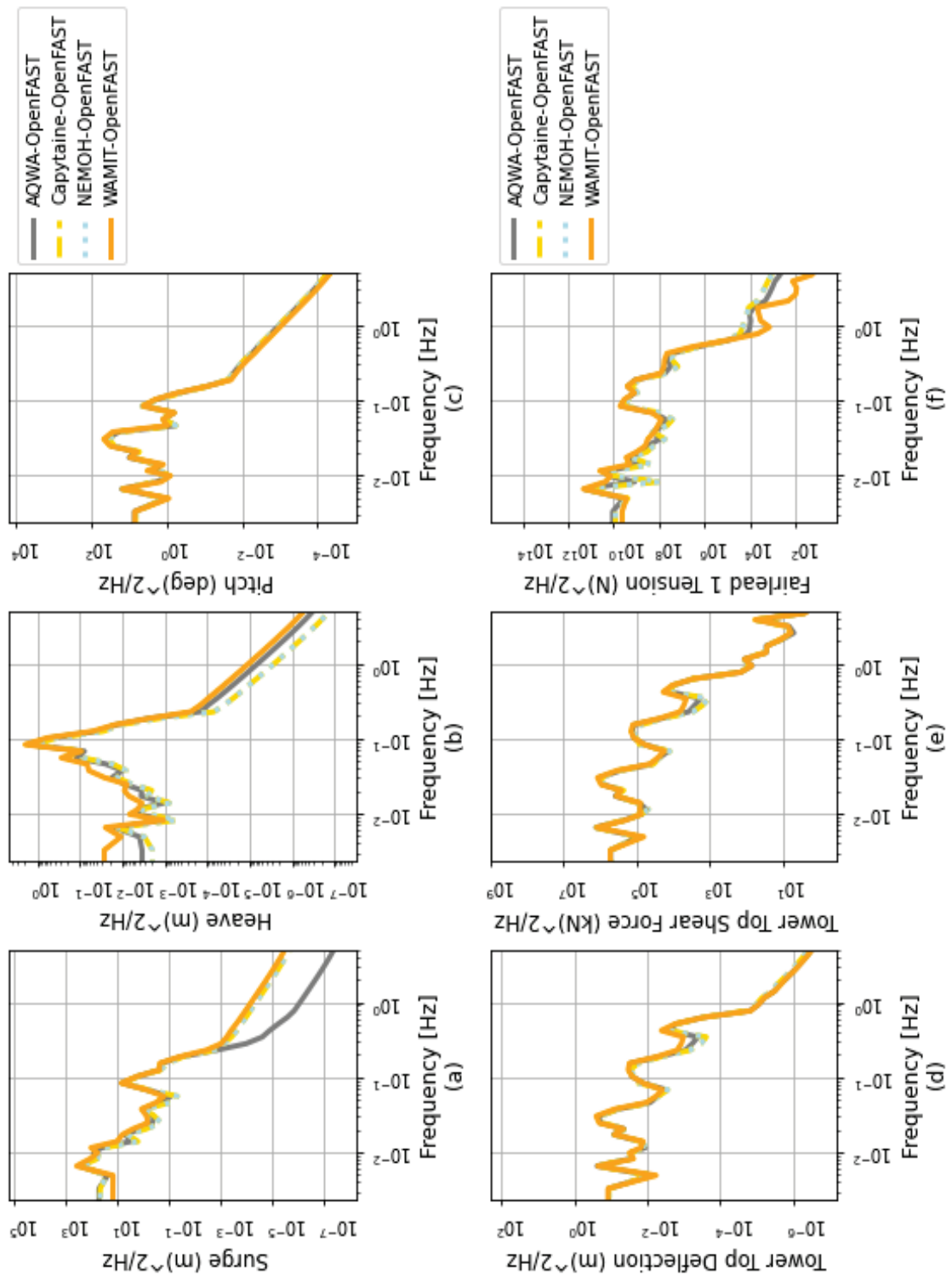


Figure 6.13. Semi-submersible platform PSD graphs for load case 5.2:

- a) Surge, b) Heave, c) Pitch, d) Tower Top Deflection, e) Tower Top Shear Force
- f) Fairlead 1 Tension

In Figure 6.13, PSD measured at various frequencies (Hz) using different simulation tools show highly similar results. However, in AQWA-OF, especially when using the boundary-integral formulation, the emergence of irregular frequencies can cause errors, especially in a wide frequency band and at high frequencies. Due to these errors, sudden changes in the calculated hydrodynamic coefficients and surge value were observed. The percentage rates for mean values on the semi-submersible platform for load case 5.2 conditions are as follows: AQWA-OF results compared to WAMIT-OF, 90.94% for surge (m), 99.36% for pitch (deg), 100.28% for tower top deflection (m). is 100.00% close for tower top shear (kN) and 100.74% for fairlead 1 tension (kN). When Capytaine-OF and NEMOH-OF results are compared to WAMIT-OF, 91.19% for surge (m), 95.86% for pitch (deg), 99.44% for tower top deflection (m), 99.38% for tower top shear (kN) and 100.74%, for fairlead 1 tension (kN). The results from AQWA-OF closely match those from WAMIT-OF, while NEMOH-OF and Capytaine-OF differ starting from the third decimal place, resulting in the same percentage values.

Table 6.7. Load Case 5.2 statistical results for semi-submersible platform

Load Case 5.2 (min)	AQWA OpenFAST	Capytaine OpenFAST	NEMOH OpenFAST	WAMIT OpenFAST
Surge (m)	3.80E+00	4.28E+00	4.28E+00	4.28E+00
Heave (m)	-5.74E-01	-5.09E-01	-5.09E-01	-6.20E-01
Pitch (deg)	-4.77E-01	-3.26E-01	-3.26E-01	-5.16E-01
Tower Top Def. (m)	-3.31E-02	-2.42E-02	-2.42E-02	-5.17E-02
Tower Top Shear (kN)	-3.68E+01	-1.83E+01	-1.83E+01	-7.83E+01
Fairlead 1 Tension (kN)	8.91E+05	8.94E+05	8.94E+05	8.68E+05
Load Case 5.2 (max)	AQWA OpenFAST	Capytaine OpenFAST	NEMOH OpenFAST	WAMIT OpenFAST
Surge (m)	1.02E+01	9.88E+00	9.88E+00	1.11E+01
Heave (m)	5.63E-01	4.73E-01	4.73E-01	6.20E-01
Pitch (deg)	5.83E+00	5.61E+00	5.61E+00	6.23E+00
Tower Top Def. (m)	6.95E-01	6.84E-01	6.84E-01	7.02E-01
Tower Top Shear (kN)	1.56E+03	1.54E+03	1.54E+03	1.63E+03
Fairlead 1 Tension (kN)	1.05E+06	1.03E+06	1.03E+06	1.04E+06
Load Case 5.2 (mean)	AQWA OpenFAST	Capytaine OpenFAST	NEMOH OpenFAST	WAMIT OpenFAST
Surge (m)	7.43E+00	7.45E+00	7.45E+00	8.17E+00
Heave (m)	-3.87E-02	-3.95E-02	-3.95E-02	-2.04E-02
Pitch (deg)	3.12E+00	3.01E+00	3.01E+00	3.14E+00
Tower Top Def. (m)	3.61E-01	3.58E-01	3.58E-01	3.60E-01
Tower Top Shear (kN)	8.04E+02	7.99E+02	7.99E+02	8.04E+02
Fairlead 1 Tension (kN)	9.54E+05	9.54E+05	9.54E+05	9.47E+05

6.1.2.8. Load Case 5.3 on Semi-Submersible Platform

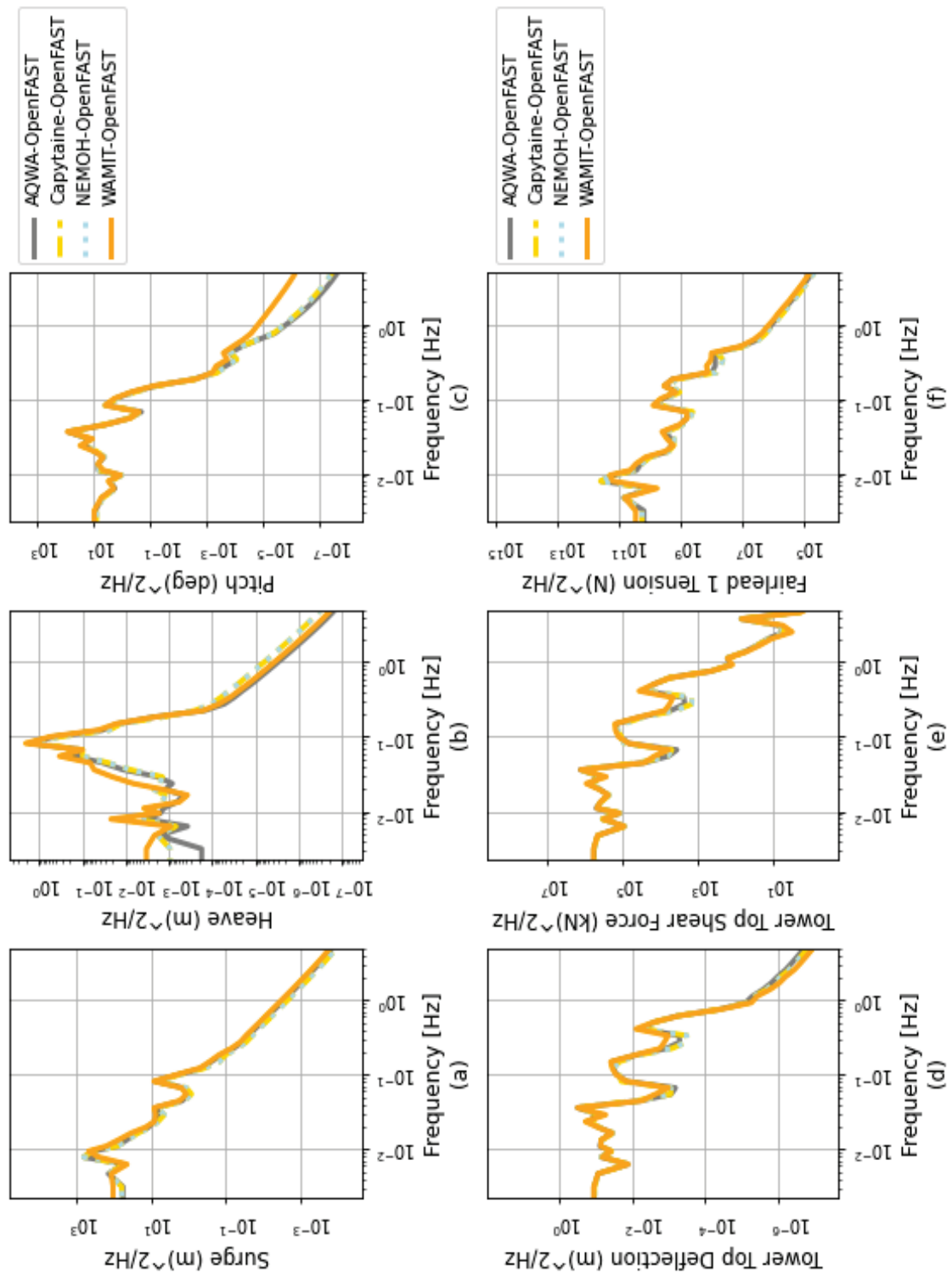


Figure 6.14. Semi-submersible platform PSD graphs for load case 5.3:

- a) Surge, b) Heave, c) Pitch, d) Tower Top Deflection, e) Tower Top Shear Force
- f) Fairlead 1 Tension

In Figure 6.14 and Table 6.8, PSD and statistical values for Load case 5.3's wind and wave conditions are shown, similar to those in Figure 6.13 and Table 6.7. When the mean values are compared to WAMIT-OpenFAST values as a percentage, AQWA-OpenFAST to WAMIT-OpenFAST results compare as 86.74% for surge (m), 99.04% for pitch (deg), 100.00% for tower top deflection (m), 99.80% for tower top shear (kN), and fairlead 1 tension (kN) it is calculated as 102.02%. Capytaine-OpenFAST and NEMOH-OpenFAST compare as 86.91% for surge (m), 95.67% for pitch (deg), 98.74% for tower top deflection (m), 98.79% for tower top shear (kN), and 102.02% for fairlead 1 tension (kN).

Table 6.8. Load case 5.3 statistical results for semi-submersible platform

Load Case 5.3 (min)	AQWA OpenFAST	Capytaine OpenFAST	NEMOH OpenFAST	WAMIT OpenFAST
Surge (m)	2.02E-01	5.39E-01	5.39E-01	9.14E-01
Heave (m)	-6.24E-01	-5.51E-01	-5.51E-01	-6.42E-01
Pitch (deg)	-1.60E+00	-1.54E+00	-1.54E+00	-1.37E+00
Tower Top Def. (m)	-5.30E-02	-4.93E-02	-4.93E-02	-2.83E-02
Tower Top Shear (kN)	-1.60E+02	-1.45E+02	-1.45E+02	-1.04E+02
Fairlead 1 Tension (kN)	8.43E+05	8.52E+05	8.52E+05	8.27E+05
Load Case 5.3 (max)	AQWA OpenFAST	Capytaine OpenFAST	NEMOH OpenFAST	WAMIT OpenFAST
Surge (m)	1.24E+01	1.19E+01	1.19E+01	1.32E+01
Heave (m)	5.40E-01	4.36E-01	4.36E-01	6.53E-01
Pitch (deg)	7.30E+00	7.09E+00	7.09E+00	7.08E+00
Tower Top Def. (m)	6.46E-01	6.42E-01	6.42E-01	6.18E-01
Tower Top Shear (kN)	1.43E+03	1.42E+03	1.42E+03	1.36E+03
Fairlead 1 Tension (kN)	1.16E+06	1.14E+06	1.14E+06	1.14E+06
Load Case 5.3 (mean)	AQWA OpenFAST	Capytaine OpenFAST	NEMOH OpenFAST	WAMIT OpenFAST
Surge (m)	5.30E+00	5.31E+00	5.31E+00	6.11E+00
Heave (m)	-2.36E-02	-2.43E-02	-2.43E-02	-5.40E-03
Pitch (deg)	2.06E+00	1.99E+00	1.99E+00	2.08E+00
Tower Top Def. (m)	2.38E-01	2.35E-01	2.35E-01	2.38E-01
Tower Top Shear (kN)	4.93E+02	4.88E+02	4.88E+02	4.94E+02
Fairlead 1 Tension (kN)	1.01E+06	1.01E+06	1.01E+06	9.90E+05

6.1.3. FloaTolia Platform

The FloaTolia platform was analyzed by AQWA and Capytaine potential flow solvers with the approach of using hydrodynamic coefficients as input to OpenFAST. In

addition, in the coupled approach, the platform is modeled as both rigid and flexible. The platform contains twelve heave plates, three buoyant legs, and buoyant floaters and is connected to a ballast with chain bundles. For this reason, there were some mesh quality problems related to the very complex platform and difficulties in designing platform members for OpenFAST.

6.1.3.1. Load Case 1.2 on FloaTolia Platform

In the graph, natural periods calculated with four different approaches (AQWA-OpenFAST, Capytaine-OpenFAST, F2A (rigid), F2A (flexible)) for six different movements of the FloaTolia platform (surge, sway, heave, roll, pitch, yaw) are compared. Since Capytaine-OpenFAST and NEMOH-OpenFAST values gave remarkably similar values on other platforms, AQWA-OpenFAST, Capytaine-OpenFAST, and F2A were used as rigid and flexible on the FloaTolia platform. Except for F2A (flexible) for platform surge and sway movements, natural periods differ among all approaches. It was approximately 89.5 seconds, showing no variation, and the F2A (flexible) was calculated as a value with no seconds. Despite this situation, there is a high consistency and correlation in modeling these movements. Natural periods for the heave movement vary around 34 seconds for F2A(flexible) and others. There is a difference of 0.7 seconds between rigid models. The natural periods for roll and pitch were approximately 2 seconds lower in F2A compared to AQWA-OpenFAST and NEMOH-OpenFAST results. This may be due to calculation differences between the programs. While the natural periods for yaw are between 53-54 seconds, the F2A (rigid) model is approximately one second longer than the others. Natural period rates are based on the F2A (rigid) platform. As a percentage, it is seen that AQWA-OPENFAST and Capytaine-OPENFAST platforms have 0.14%-0.45% higher values in surge, sway, and heave modes. In roll and pitch modes, both platforms have 6.11%-6.22% higher values. It is thought that the reason for the relatively high difference in pitch mode is the difficulty of modeling mooring line design and heave plates in OpenFAST. In yaw mode, AQWA-OPENFAST and Capytaine-OPENFAST have 1.51%-1.52% lower values. The F2A (flexible) platform has lower values than the F2A (rigid) platform in all modes, and the highest difference is seen in the heave mode, with 1.75%. It is thought that the reason for this is the platform's flexible feature. This comparative analysis shows that the different simulation approaches

are quite consistent with the natural period values of the FloaTolia platform.

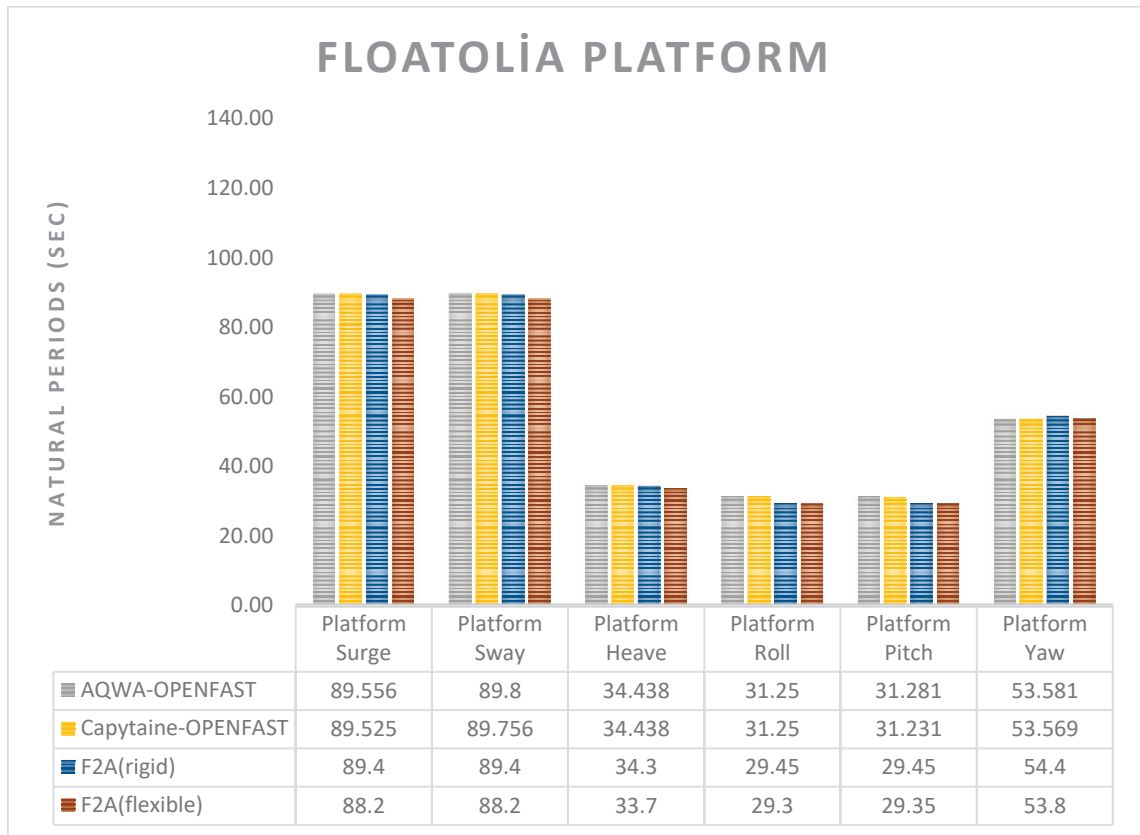


Figure 6.15. FloaTolia platform natural periods for each method

6.1.3.2. Load Case 1.3 on FloaTolia Platform

Six degrees of freedom mean values for each method in the static test converge to zero, and especially the heave value is expected to converge to zero. These results indicate that the turbine is in balance.

Table 6.9. FloaTolia platform static test results

Load Case 1.3 (mean)	AQWA OpenFAST	Capytaine OpenFAST	F2A(Rigid)	F2A(Flexible)
Surge (m)	3.00E-03	3.00E-03	3.10E-03	2.80E-03
Sway (m)	-3.67E-08	-2.52E-07	6.00E-04	-9.00E-04
Heave (m)	-2.71E-02	-2.71E-02	5.20E-03	5.60E-03
Roll (deg)	3.20E-08	3.38E-08	9.00E-04	9.00E-04
Pitch (deg)	-3.09E-02	-3.09E-02	-3.14E-02	-3.20E-02
Yaw (deg)	-6.77E-08	-1.26E-07	-1.13E-05	-6.00E-04

6.1.3.3. Load Case 1.4 on FloaTolia Platform

In Figure 6.16, all methods give close values to each other. The main difference here is that F2A has different dumping and natural frequency values in the pitch free decay test. It is thought that this is due to differences between the versions and approaches of the programs, the placement of heave plates, and the calculation difference in the mooring line's structure. The natural period values obtained as a result of the test results obtained for the 300-kW model are 64 seconds for surge, 23 seconds for heave, and 38 seconds for pitch¹⁰⁷.

The natural periods of a 5 MW floating wind turbine and a 300-kW experimental turbine differ due to variations in their dimensions, overall mass, mooring systems, and size-dependent aerodynamic and hydrodynamic properties.

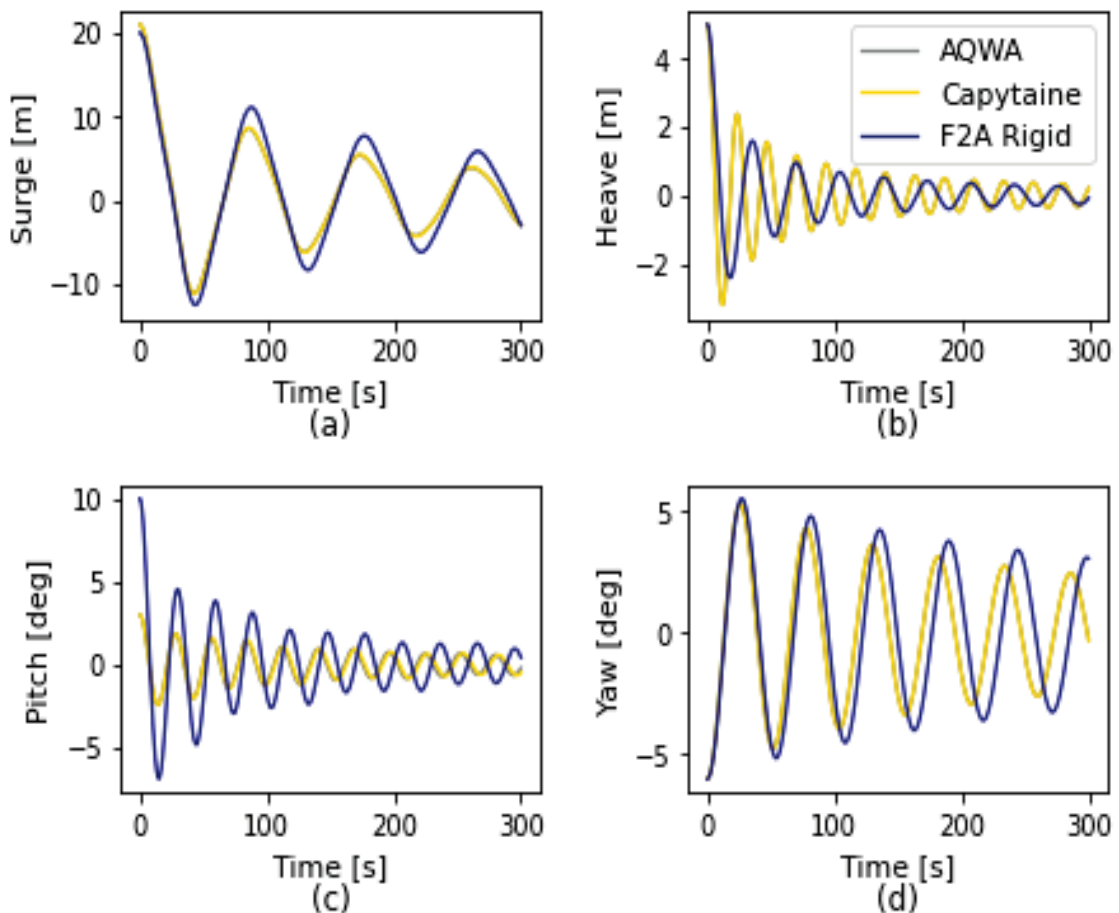


Figure 6.16. FloaTolia platform free decay test results:

a) Surge, b) Heave, c) Pitch, d) Yaw

6.1.3.4. Load Case 4.1 on FloaTolia Platform

In load case 4.1, surge, heave, pitch, and fairlead tension values are shown between 400 and 520 seconds. Related results and magnitudes were obtained in the surge and pitch graphs. However, the F2A (rigid) model was not entirely stable for surge and pitch, becoming stable only when the analysis duration was extended. Longer analysis durations were not conducted due to the high computational costs involved. In the heave graph, F2A (rigid) shows an offset compared to the others. The differences here are thought to be due to heave plate modeling and design differences between OpenFAST and AQWA. Additionally, the AQWA-OpenFAST value has a higher magnitude than the others, which is believed to be due to design and modeling differences in AQWA and Capytaine, as well as HydroDyn and MoorDyn.

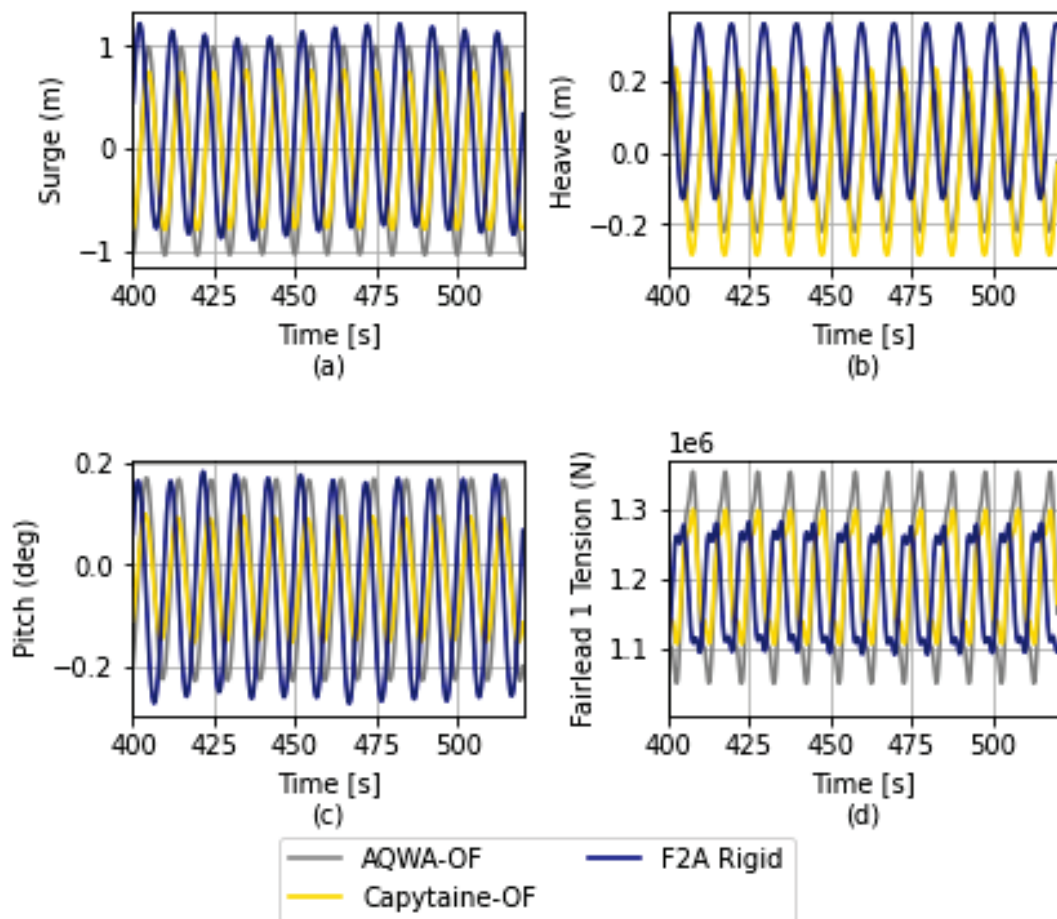


Figure 6.17. FloaTolia platform periodic time series for load case 4.1:

a) Surge, b) Heave, c) Pitch, d) Fairlead 1 Tension

6.1.3.5. Load Case 4.2 on FloaTolia Platform

Figure 6.18 shows the FloaTolia platform power spectra density outputs obtained from load case 4.2, a condition with irregular waves. PSD graphics were drawn for surge heave, pitch, and fairlead tension 1. Here, the graphs are correlated and consistent with each other. Here, the wind speed was not evaluated; only the movement of the platform was evaluated in irregular wave conditions. The most crucial point is that the random sea condition provided by the number of seeds in the Irregular wave condition in OpenFAST HydroDyn is the same as the condition in AQWA because the values here are obtained randomly according to the assigned seed number. This situation caused a slight difference in the graph.

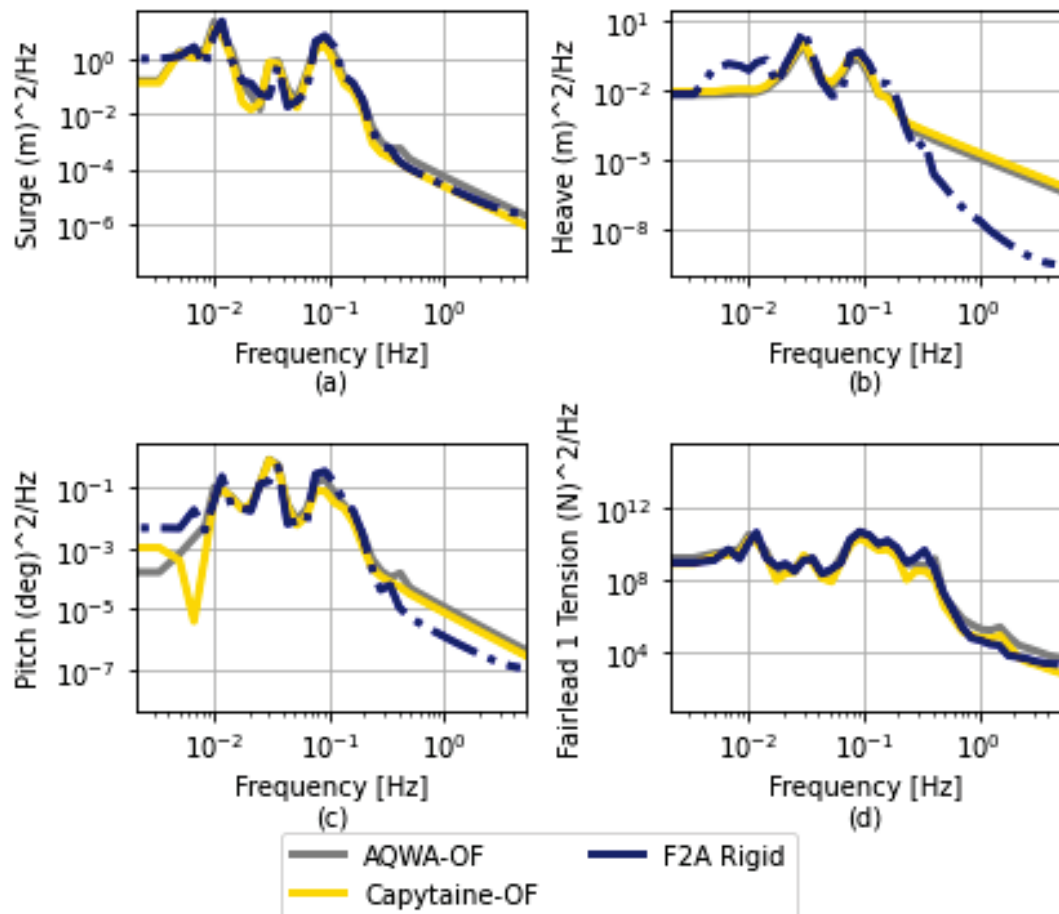


Figure 6.18. FloaTolia platform PSD graphs for load case 4.2:

a) Surge, b) Heave, c) Pitch, d) Fairlead 1 Tension

A comparison of the statistical values for load case 4.2 of the FloaTolia platform is examined. The fairlead 1 tension values are significantly similar, and despite the small values for surge, heave, and pitch, each method and approach are correlated with one another. If the maximum values are examined: The maximum surge value of the FloaTolia (F2A Rigid) platform in load case 4.2 is 2.24% higher than AQWA-OpenFAST and 9.65% higher than Capytaine-OpenFAST. The maximum heave value is 31.57% higher than AQWA-OpenFAST and 33.98% higher than Capytaine-OpenFAST. The maximum pitch value is 11.23% higher than AQWA-OpenFAST and 27.32% higher than Capytaine-OpenFAST. The maximum fairlead 1 tension value is 2.99% higher than AQWA-OpenFAST and 7.28% higher than Capytaine-OpenFAST.

Table 6.10. Load case 4.2 statistical results for the FloaTolia platform

Load Case 4.2 (min)	AQWA- OpenFAST	Capytaine- OpenFAST	F2A(Rigid)
Surge (m)	-1.27E+00	-9.74E-01	-1.74E+00
Heave (m)	-4.77E-01	-5.94E-01	-3.60E-01
Pitch (deg)	-4.48E-01	-3.74E-01	-5.04E-01
Fairlead 1 Tension (kN)	1.01E+06	1.08E+06	9.97E+05
Load Case 4.2 (max)	AQWA- OpenFAST	Capytaine- OpenFAST	F2A(Rigid)
Surge (m)	1.86E+00	1.45E+00	1.75E+00
Heave (m)	4.23E-01	5.58E-01	7.80E-01
Pitch (deg)	5.24E-01	4.48E-01	3.56E-01
Fairlead 1 Tension (kN)	1.36E+06	1.30E+06	1.40E+06
Load Case 4.2 (mean)	AQWA- OpenFAST	Capytaine- OpenFAST	F2A(Rigid)
Surge (m)	-1.91E-02	-1.32E-02	1.85E-01
Heave (m)	-2.86E-02	-2.89E-02	1.28E-01
Pitch (deg)	-3.16E-02	-3.21E-02	-4.35E-02
Fairlead 1 Tension (kN)	1.20E+06	1.20E+06	1.18E+06

6.1.3.6. Load Case 5.1 on FloaTolia Platform

In load case 5.1, surge heave pitch and fairlead tension values between 400 and 520 seconds are shown. Here, unlike 4.1, there is a steady wind. The values are similar to case 4.1, and the differences are due to mesh difficulty, complex platform geometry, and mooring lines. It is thought to be due to design differences. However, solution approaches are correlated with each other.

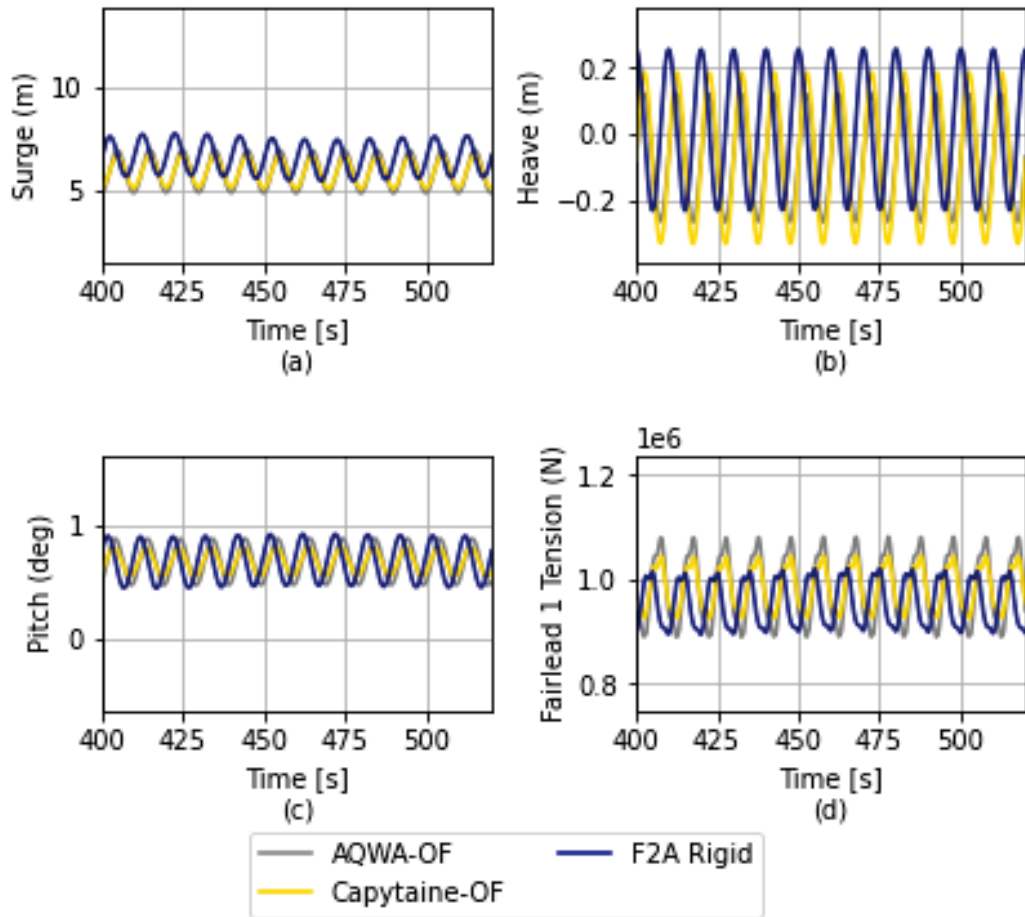


Figure 6.19: FloaTolia platform periodic time series for load case 5.1:
a) Surge, b) Heave, c) Pitch, d) Fairlead 1 Tension

6.1.3.7. Load Case 5.2 on FloaTolia Platform

Figure 6.20 contains the aero-hydro-servo-elastic power spectra obtained for irregular waves and turbulent wind at rated speed under load case 5.3. Statistical results are shown in Table 6.11. Considering the possibility that the behavior and seed values of the irregular waves obtained from the AQWA diffraction module and HydroDyn may be different, the focus is on the mean values sections.

This is because the same wave behavior, which is valid for all conditions with irregular waves, cannot be obtained in two different programs. Additionally, it can be observed that the peak values for each of the six different output variables are consistent with each other.

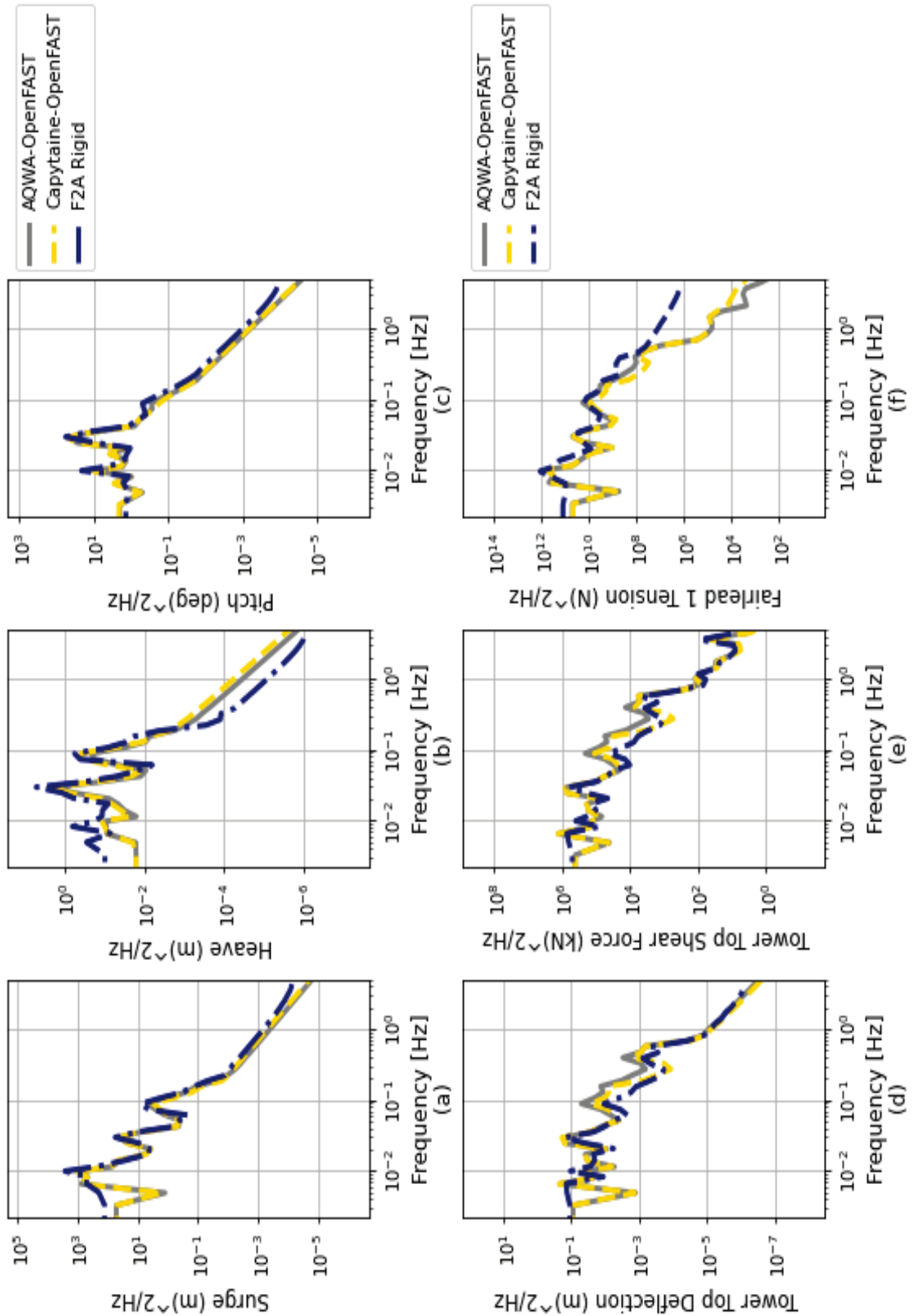


Figure 6.20. FloaTolia platform PSD graphs for load case 5.2:a) Surge, b) Heave, c) Pitch, d) Tower Top Deflection, e) Tower Top Shear Force f) Fairlead 1 Tension

Table 6.11 presents statistical values related to load case 5.2 of the FloaTolia platform. According to AQWA-OpenFAST in the mean values of load case 5.2, Capytaine-OpenFAST results are surge (m), heave (m), pitch (deg), tower Top Def. (m), tower top shear (kN) and fairlead 1 tension (kN) have rates of 100.00%, 100.00%, 100.00%, 100.03%, 100.00% and 100.00%. F2A (Rigid) results are 105.94% for surge (m), 68.59% for heave (m), 100.00% for pitch (deg), tower top def. It has 103.56% for (m), 105.56% for tower top shear (kN), and 98.28% for fairlead 1 tension (kN).

Table 6.11. Load Case 5.2 statistical results for the FloaTolia platform

Load Case 5.2 (min)	AQWA OpenFAST	Capytaine OpenFAST	F2A(Rigid)
Surge (m)	3.67E+00	3.67E+00	1.57E+00
Heave (m)	-6.63E-01	-7.77E-01	-6.73E-01
Pitch (deg)	-1.59E+00	-1.68E+00	-1.90E+00
Tower Top Def. (m)	0.0481	0.0624	0.0872
Tower Top Shear (kN)	1.28E+02	1.49E+02	2.23E+02
Fairlead 1 Tension (kN)	7.08E+05	7.08E+05	6.74E+05
Load Case 5.2 (max)	AQWA OpenFAST	Capytaine OpenFAST	F2A(Rigid)
Surge (m)	1.55E+01	1.56E+01	1.78E+01
Heave (m)	3.60E-01	4.92E-01	5.71E-01
Pitch (deg)	3.00E+00	3.03E+00	2.99E+00
Tower Top Def. (m)	0.5288	0.5005	0.4335
Tower Top Shear (kN)	1.21E+03	1.15E+03	9.99E+02
Fairlead 1 Tension (kN)	1.15E+06	1.11E+06	1.20E+06
Load Case 5.2 (mean)	AQWA OpenFAST	Capytaine OpenFAST	F2A(Rigid)
Surge (m)	1.01E+01	1.01E+01	1.07E+01
Heave (m)	-1.35E-01	-1.35E-01	-9.26E-02
Pitch (deg)	1.15E+00	1.15E+00	1.15E+00
Tower Top Def. (m)	0.3005	0.3006	0.3112
Tower Top Shear (kN)	6.83E+02	6.83E+02	7.21E+02
Fairlead 1 Tension (kN)	8.72E+05	8.72E+05	8.57E+05

6.1.3.8. Load Case 5.3 on the FloaTolia Platform

In load case 5.3, PSDs for six outputs under extreme speed and irregular waves, as in 5.2, showed closely correlated results. This shows that different methods produce similar results. especially in turbulent and irregular conditions.

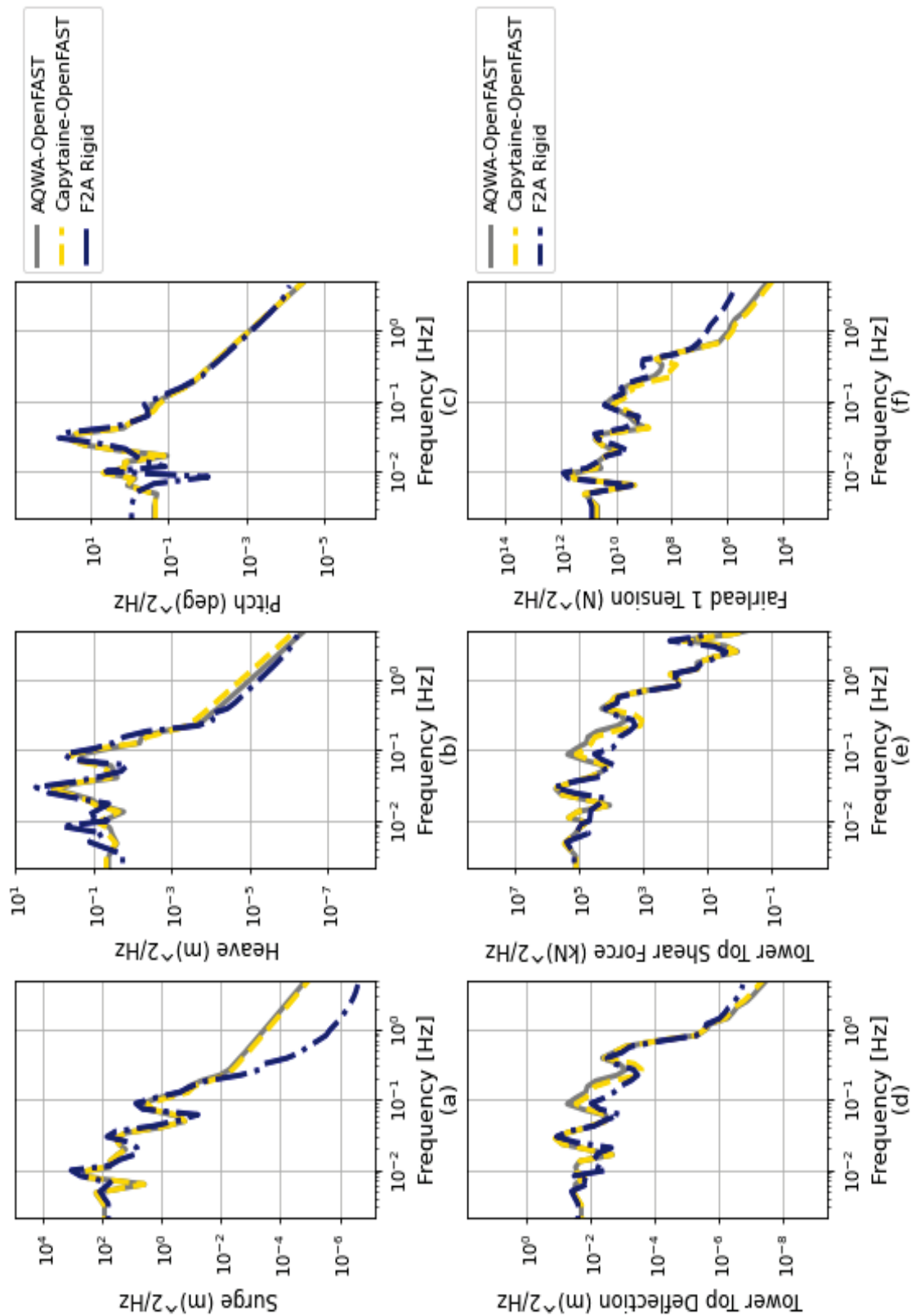


Figure 6.21. FloaTolia platform PSD graphs for load case 5.3: a) Surge, b) Heave, c) Pitch, d) Tower Top Deflection, e) Tower Top Shear Force f) Fairlead 1 Tension

Table 6.12 shows the statistical values for load case 5.3 of the FloaTolia platform, focusing on the mean values. When Capytaine-OpenFAST and F2A (Rigid) programs are compared according to AQWA-OpenFAST in the mean values of load case 5.3, Capytaine results are 100.15% for surge (m), 100.00% for pitch (deg), tower top def. There is a rate of 100.05% for (m), 100.00% for tower top shear (kN), and 99.90% for fairlead 1 tension (kN). F2A (Rigid) results are 92.46% for surge (m), 91.60% for pitch (deg), and tower top def. It has rates of 96.72% for (m), 101.49% for tower top shear (kN), and 100.93% for fairlead 1 tension (kN). For a better understanding of the results, time series outputs are shown for load case 5.3 in Appendix B.

Table 6.12. Load Case 5.3 statistical results for the FloaTolia platform

Load Case 5.3 (min)	AQWA- OpenFAST	Capytaine- OpenFAST	F2A(Rigid)
Surge (m)	1.63E+00	1.64E+00	-2.11E-01
Heave (m)	-6.67E-01	-7.72E-01	-5.01E-01
Pitch (deg)	-2.07E+00	-2.11E+00	-2.44E+00
Tower Top Def. (m)	-0.0551	-0.0199	0.0144
Tower Top Shear (kN)	-1.58E+02	-6.51E+01	1.41E+01
Fairlead 1 Tension (kN)	7.50E+05	7.47E+05	7.44E+05
Load Case 5.3 (max)	AQWA- OpenFAST	Capytaine- OpenFAST	F2A(Rigid)
Surge (m)	1.30E+01	1.30E+01	1.39E+01
Heave (m)	3.55E-01	4.79E-01	6.93E-01
Pitch (deg)	2.85E+00	2.85E+00	3.21E+00
Tower Top Def. (m)	0.4424	0.4146	0.3379
Tower Top Shear (kN)	9.28E+02	8.55E+02	8.10E+02
Fairlead 1 Tension (kN)	1.25E+06	1.20E+06	1.27E+06
Load Case 5.3 (mean)	AQWA- OpenFAST	Capytaine- OpenFAST	F2A(Rigid)
Surge (m)	6.50E+00	6.51E+00	6.01E+00
Heave (m)	-8.01E-02	-8.05E-02	3.50E-02
Pitch (deg)	7.38E-01	7.38E-01	6.76E-01
Tower Top Def. (m)	0.1921	0.1922	0.1858
Tower Top Shear (kN)	4.02E+02	4.02E+02	4.08E+02
Fairlead 1 Tension (kN)	9.69E+05	9.68E+05	9.78E+05

6.2. Examination of Innovative Platforms as Rigid and Flexible.

The FloaTolia platform is modeled under the F2A approach as rigid and flexible, as described in Chapter 5.5. The primary output of these analyses is to observe the

differences between platforms modeled as rigid and flexible. Two different models of the same platform have been compared using the free decay test and other load cases that include wind and wave conditions.

6.2.1. Load Case 1.4 on Flexible FloaTolia platforms

The rigid and flexible free decay tests for the FloaTolia platform are similar. The principal distinction between these analyses is in the platform's 2nd harmonic pitch and 2nd harmonic heave frequencies. The design allows for pitch and heave movements as if the ballast and upper platform are connected by chain bundles, functioning like a separate platform. The period of the pitch movement is approximately 2.2 seconds, while the period of the heave movement is around 1.2 seconds.

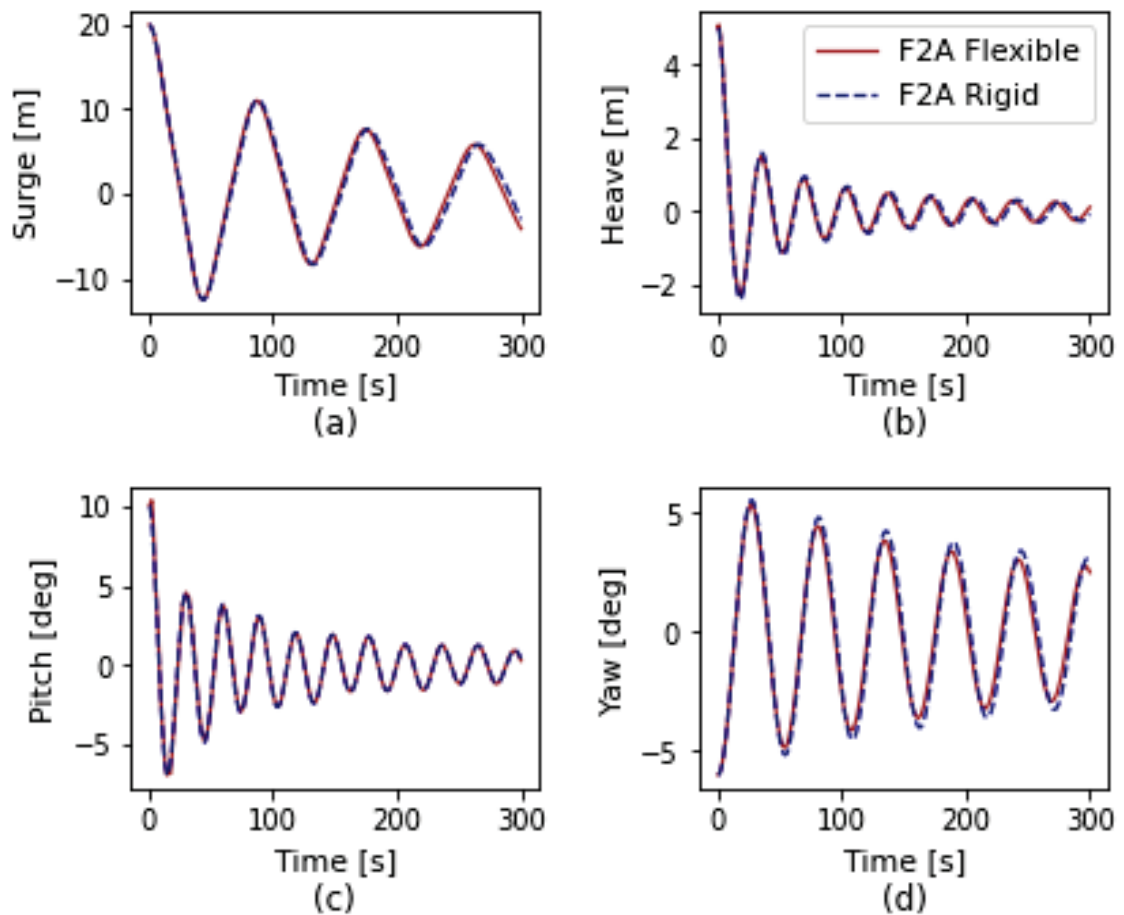


Figure 6.22. Comparison of free decay test results for the FloaTolia platform as rigid and flexible configuration: a) Surge, b) Heave, c) Pitch, d) Yaw

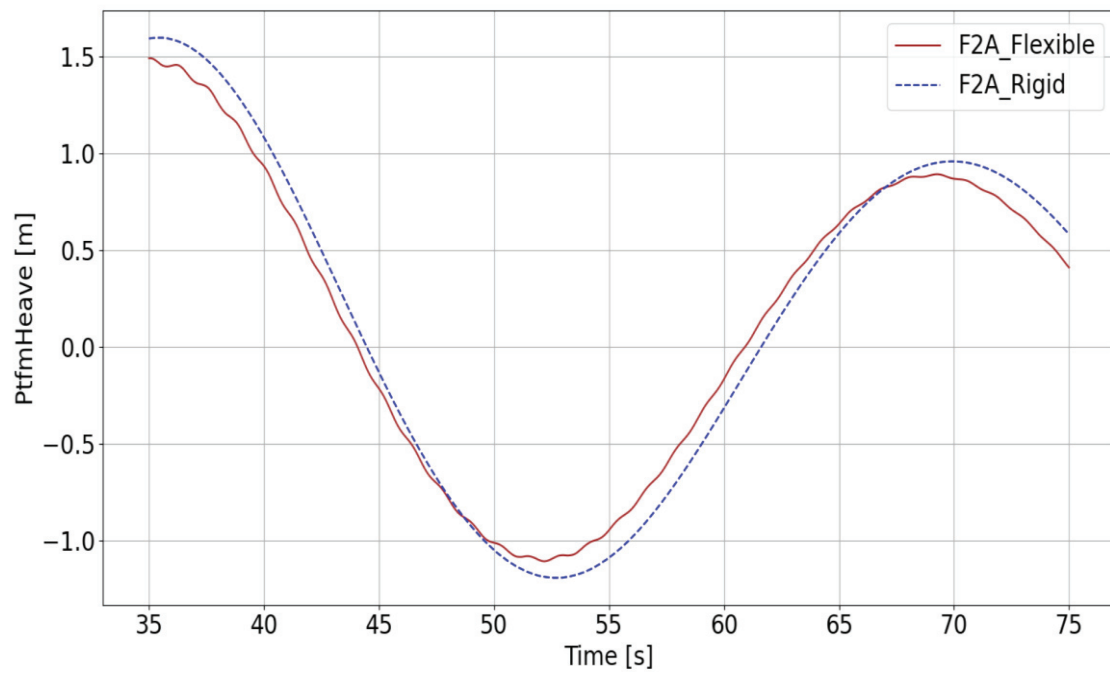


Figure 6.23. Comparison of heave motion for the FloaTolia platform as rigid and flexible configuration

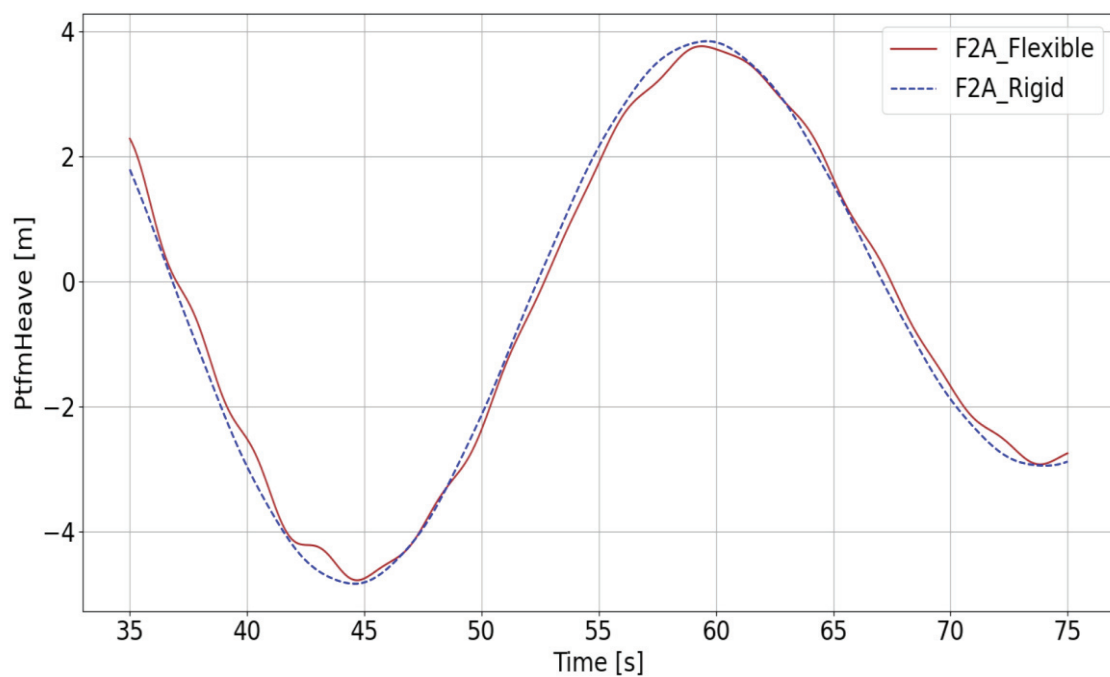


Figure 6.24. Comparison of pitch motion for the FloaTolia Platform as rigid and flexible configuration

6.2.2. Load Case 4.1 on Flexible FloaTolia platforms

In load case 4.1, similar graphics are obtained as in the free decay tests. The only main difference here is that the pitch values have higher flexible values, the main reason for this is that the pitch angle caused by the flexible connection of the ballast is higher.

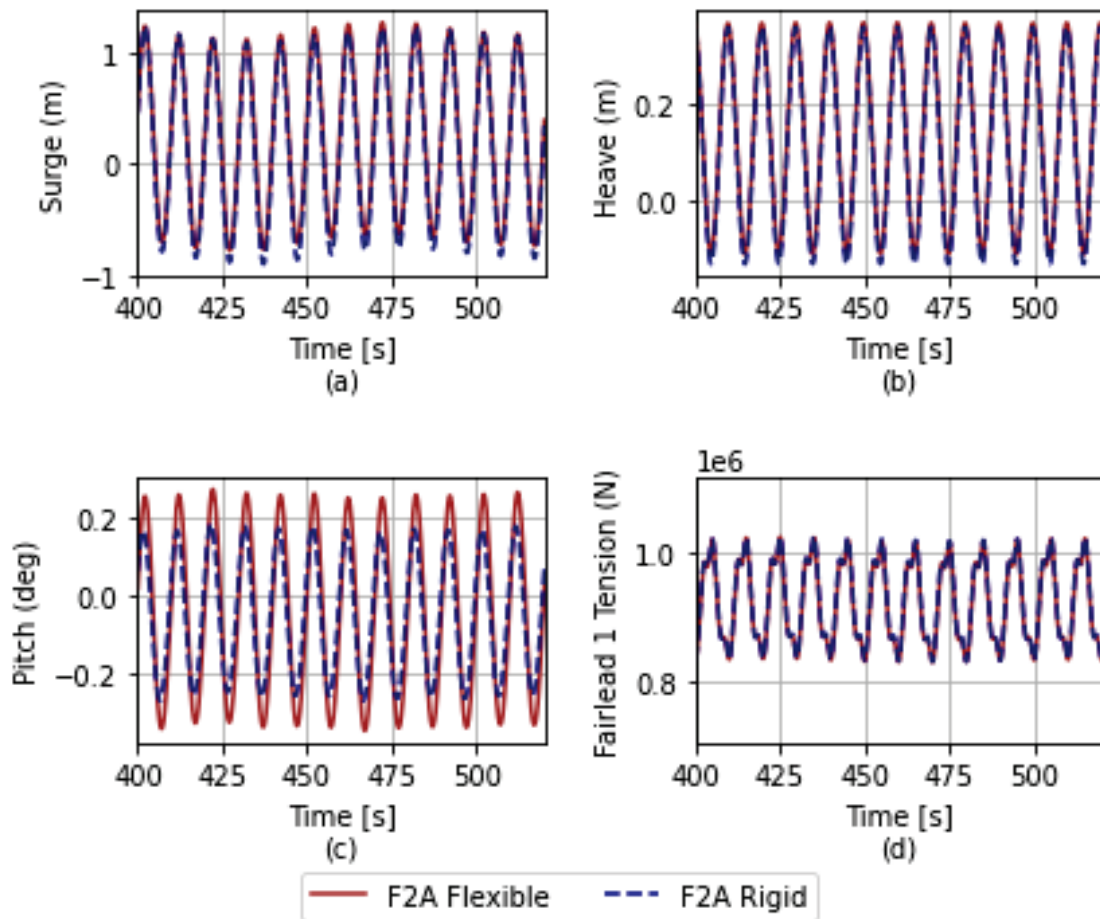


Figure 6.25. Comparison of load case 4.1 results for the FloaTolia platform as rigid and flexible configuration: a) Surge, b) Heave, c) Pitch, d) Fairlead 1 Tension

6.2.3. Load Case 4.2 on Flexible FloaTolia platforms

In Figure 6.26, related results were obtained for the flexible and rigid models in load case 4.2, which contained only irregular waves, as seen in Figure 6.26. The turbine did not experience any resonance. The energy peak levels captured are correlated with each other.

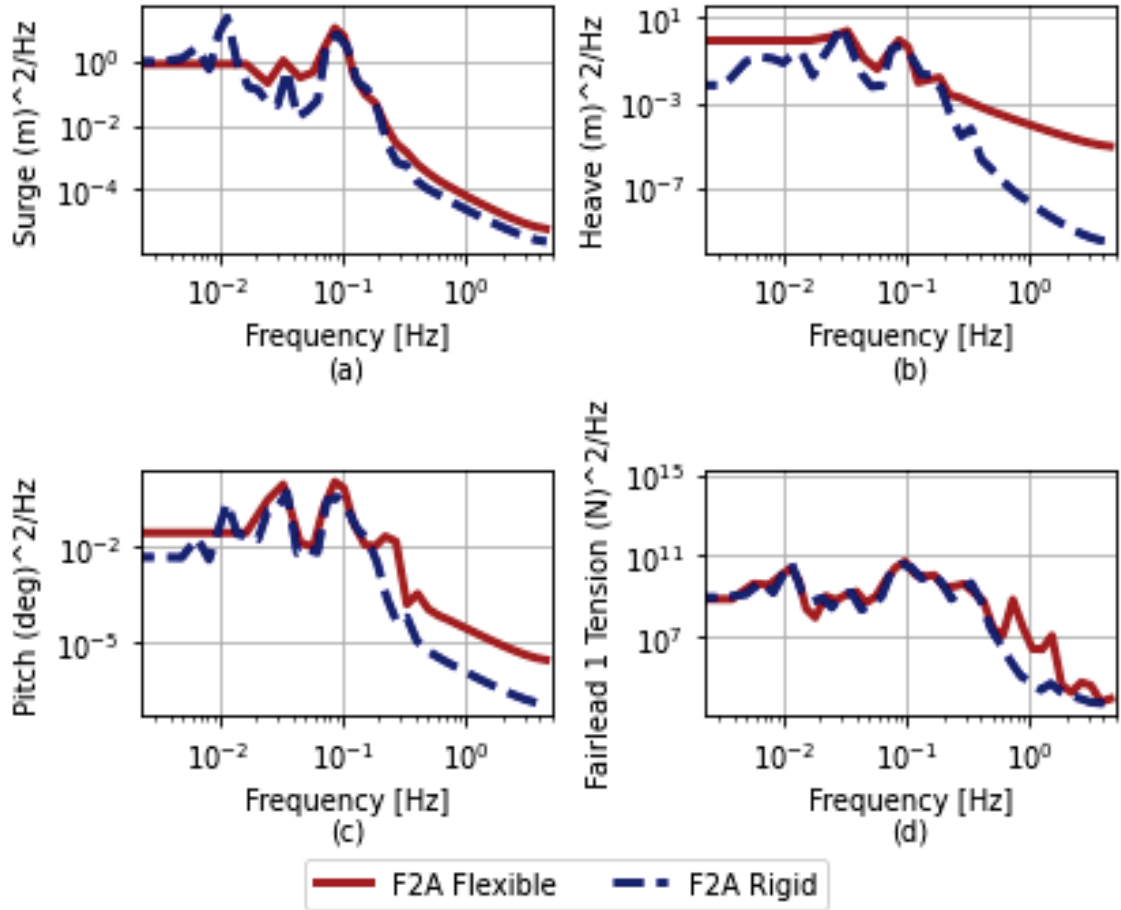


Figure 6.26. Comparison of load case 4.2 results for the FloaTolia platform as rigid and flexible configuration: a) Surge, b) Heave, c) Pitch, d) Fairlead 1 Tension

6.2.4. Load Case 5.1 on Flexible FloaTolia Platforms

In load case 5.1, in the analysis of the wind turbine under steady wind and regular wave conditions, the turbine enters resonance with the effect of the wind. This is because the ballast is flexible and connected with chains and makes movements such as pitch and heave. As seen in Figure 6.27, results were obtained in terms of pitch motion, which was quite high in the flexible model and different from the rigid value.

The other three outputs, heave, pitch, and fairlead tension gave very similar results. The differing pitch behavior of the flexible FloaTolia platform under wind load is thought to arise because the platform members, which are interconnected by chains, respond differently to these conditions.

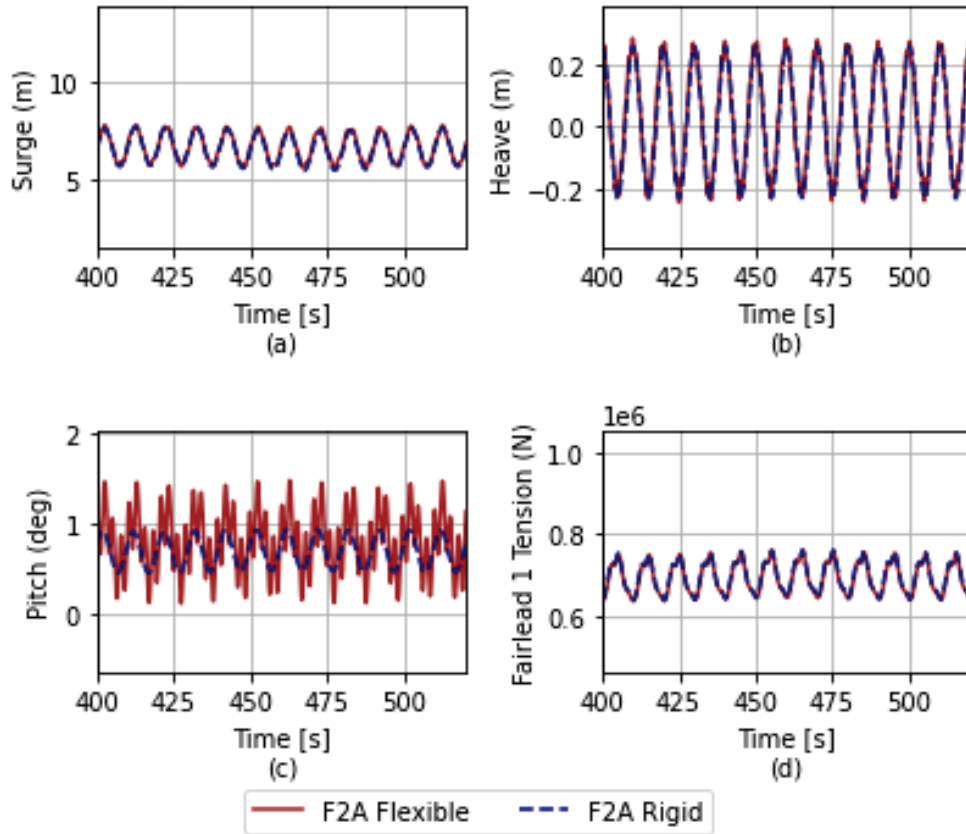


Figure 6.27. Comparison of load case 5.1 results for the FloaTolia Platform as rigid and flexible configuration: a) Surge, b) Heave, c) Pitch, d) Fairlead 1 Tension

6.2.5. Load Case 5.2 on Flexible FloaTolia platforms

A comparison of the graphs in Figure 6.28 shows that the flexible model shows greater dynamic response, with higher peaks observed at certain frequencies than the rigid model. Only the PSD graphs for the 5.2 load case are compared. This is because similar graphs are obtained for the 5.3 and 5.2 load cases. The sharp peaks seen for the flexible model in Figure 6.28 indicate the presence of resonance. To further determine at what frequency the sharp peaks occur, the natural frequency values in Table 6.13 are added to the Figure 6.28 graph and plotted.

The graphs for the surge, pitch, heave, and fairlead 1 tension values are plotted, and the remaining parts are shown in Appendix B. In Table 6.13, the natural frequency values were found with the help of free decay tests by entering initial conditions in the OpenFAST ElastoDyn module.

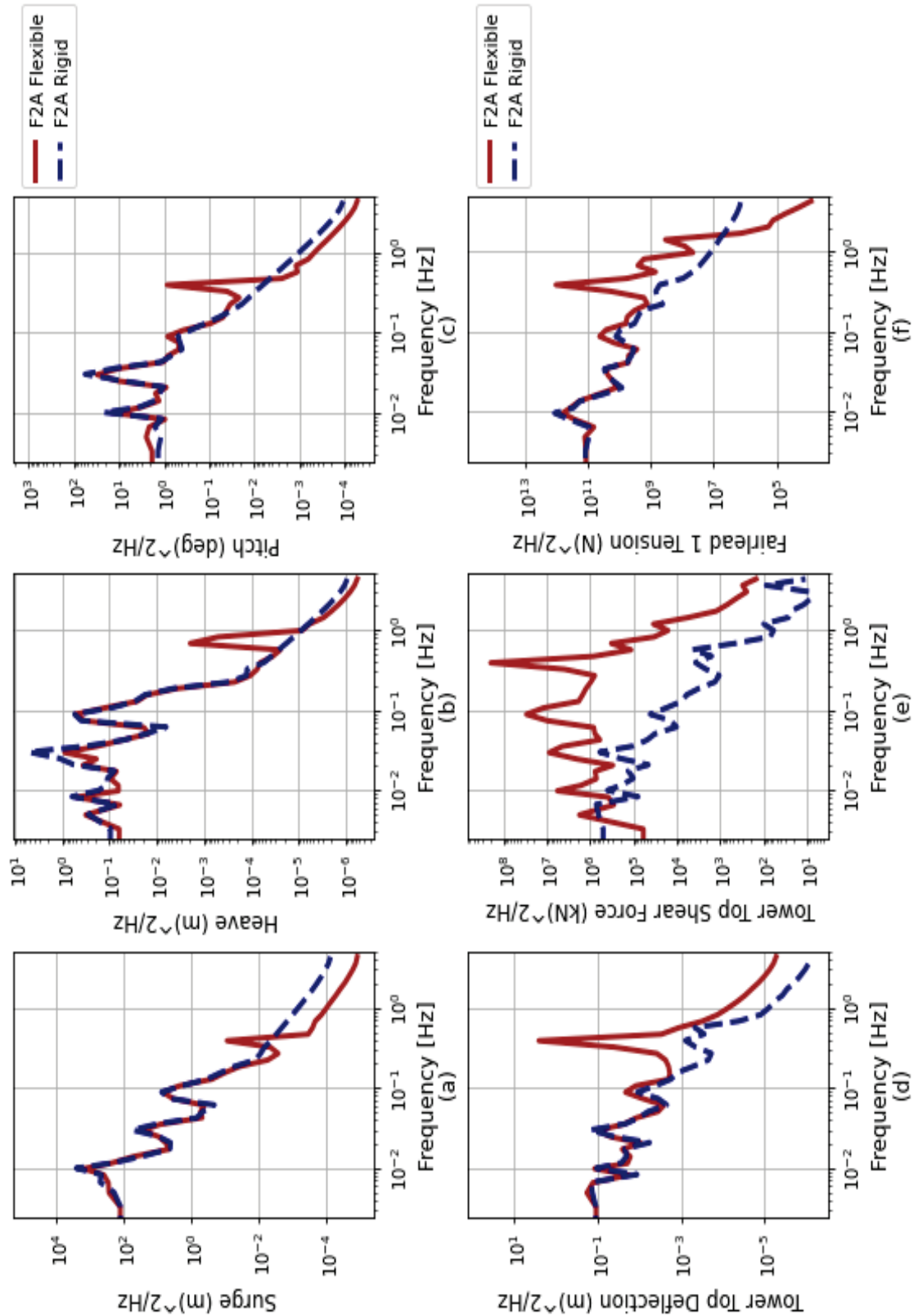


Figure 6.28. Comparison of load case 5.2 results for the FloaTolia platform as rigid and flexible configuration: a) Surge, b) Heave, c) Pitch, d) Tower Top Deflection
e) Tower Top Shear Force f) Fairlead 1 Tension

Table 6.13. 5 MW NREL Wind Turbine with FloaTolia (Flexible) platform Full-System
Natural Frequencies in Hertz

Flexible FloaTolia System Natural Frequencies in Hertz	
Description	Hz
Surge	0.0113
Yaw	0.0185
Heave	0.0301
Pitch	0.0340
1st Tower Side-to-Side	0.3670
1st Tower Fore-Aft	0.3704
2nd Harmonic Pitch	0.4545
2nd Harmonic Heave	0.8333
2nd Tower Side-to-Side	2.0513
2nd Tower Fore-Aft	2.4200

The differences between the F2A flexible and rigid models are seen in the graphs of Figures 6.29 and 6.30 for surge, heave pitch, and fairlead tension values, with the flexible model showing higher response amplitudes at certain frequencies than the rigid model and varying over a wide range. The vertical lines represent various natural frequencies and modes (e.g., the 1st and 2nd tower fore-aft and side-by-side motion modes, surge, heave, pitch, and yaw modes).

The differences between the flexible structure (red) and the rigid structure (blue) can be seen in the responses at certain frequencies, particularly at higher frequencies for the 2nd harmonic heave and 2nd harmonic pitch frequencies. In subplot (b) of Figure 6.29, the main difference in heave motion occurred at the 2nd harmonic heave frequency, where higher values were also obtained. In Figure 6.29 subplot (a) and Figure 6.30, it is observed that the 2nd pitch harmonics frequency is higher in the flexible model. Furthermore, the natural frequency values such as wave and the pitch and heave natural frequencies also showed similar behavior. Both models. The graphs of the values of tower top deflection and shear force are shown in Appendix B.

This thesis does not include a study aimed at preventing resonance. The focus is on comparing the different PSD (Power Spectral Density) graphs of the FloaTolia platform, which is designed to be flexible and rigid. Because the platform is flexible, the connection between the ballast and the floater causes pitch and heave movements, which consequently result in higher responses.

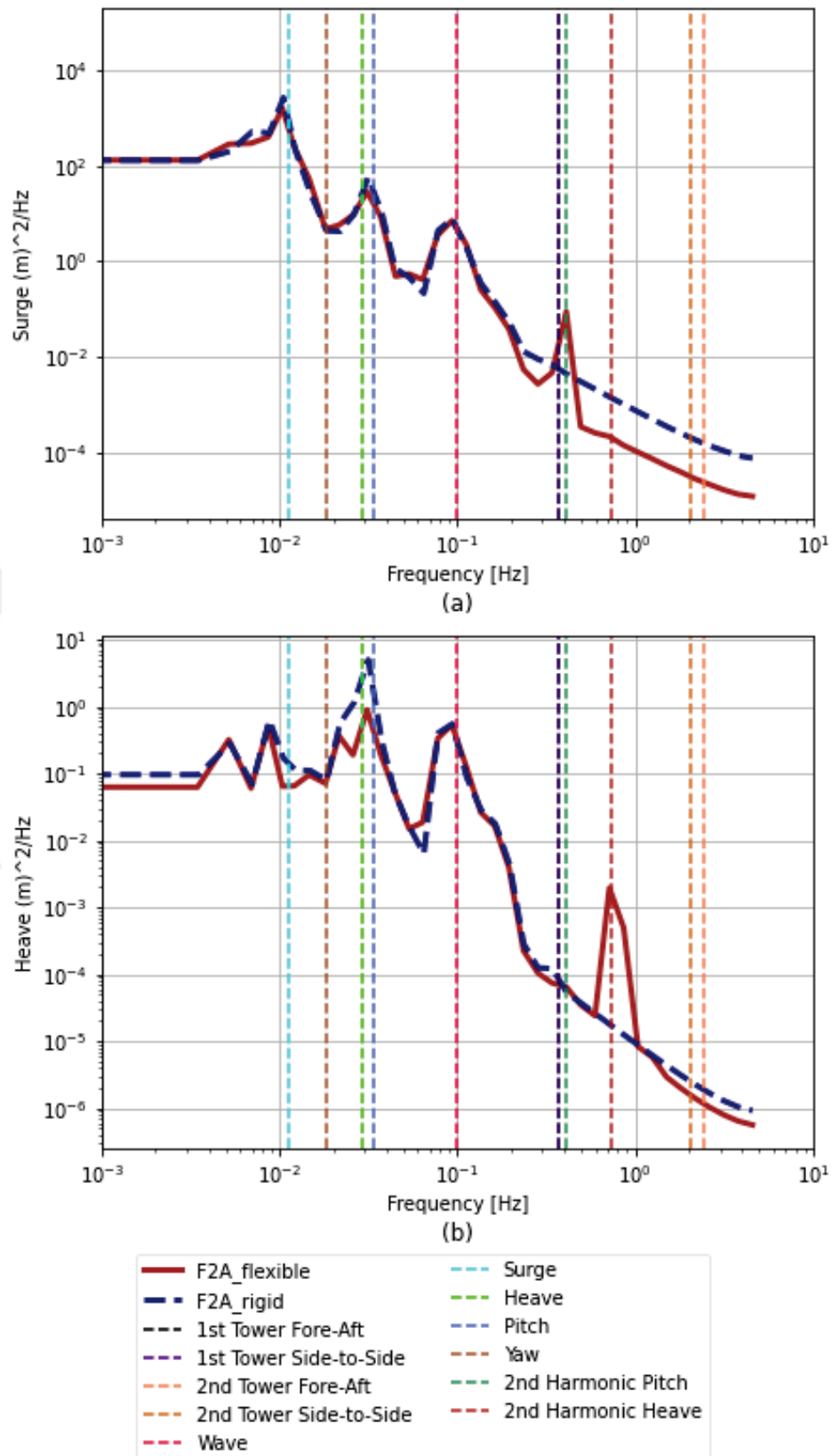


Figure 6.29. Comparison of load case 5.2 PSD graphs with natural frequencies of the wind turbine a) Surge b) Heave

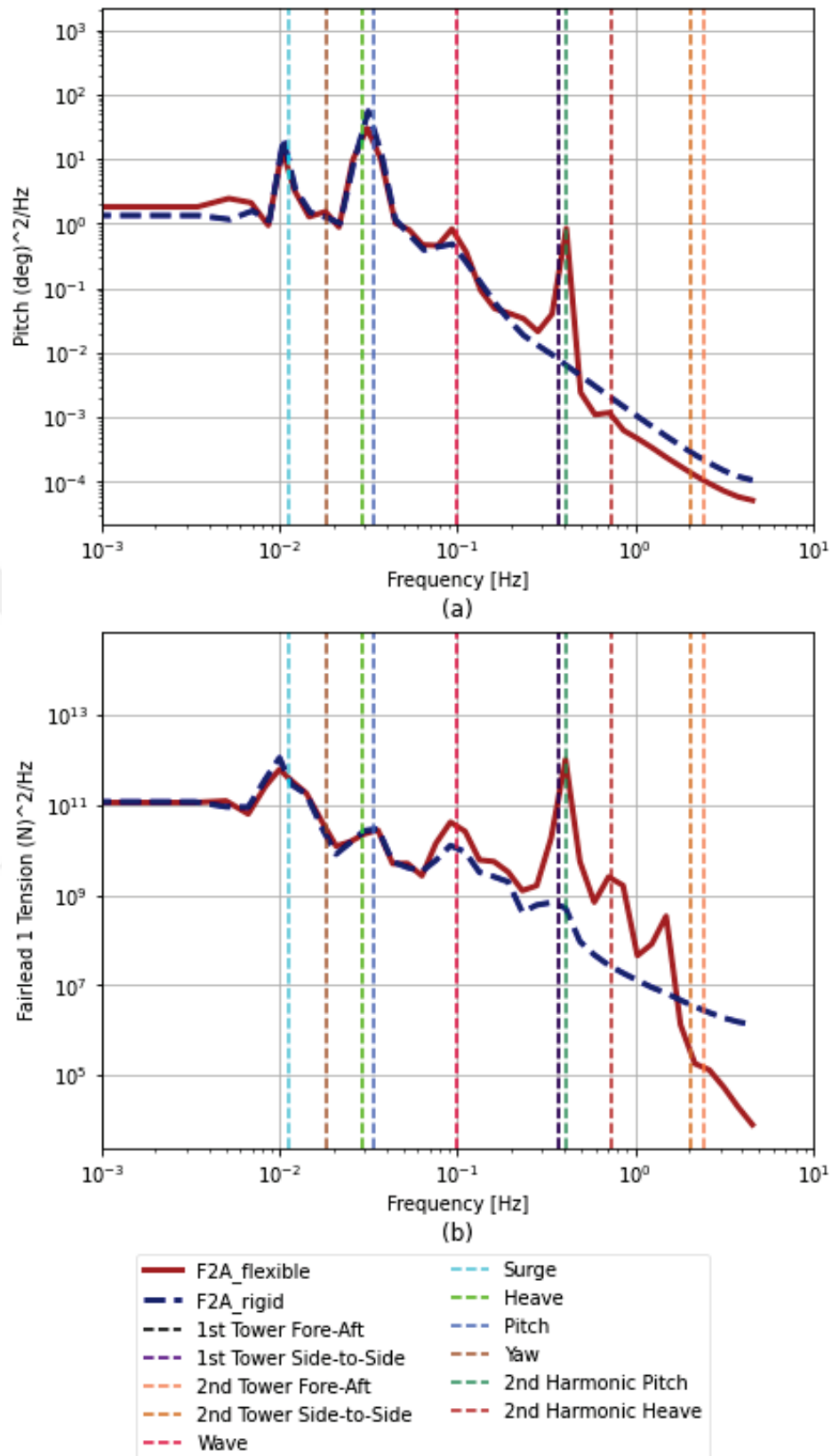


Figure 6.30. Comparison of load case 5.2 PSD graphs with natural frequencies of the wind turbine a) Pitch b) Fairlead 1 tension

6.3. Comparison of Platforms

In this section, three different platforms were compared with the results from AQWA-OpenFAST, which are considered the most accurate, as they provided the closest results to the WAMIT-OpenFAST outputs during the load cases.

6.3.1. Load Case 1.2 for Comparison of Platforms

Figure 6.31 compares the natural periods of surge, sway, heave, roll, pitch, and yaw movements for the spar, semi-submersible, and FloaTolia platforms. The spar and semi-submersible platforms have longer natural periods in surge and sway movements, while FloaTolia has the longest natural period in heave, around 35 seconds. While all platforms have similar natural periods (20-25 seconds) in roll and pitch movements, in yaw movement, the FloaTolia platform is between the spar and semi-submersible platforms and has a value of approximately 54 seconds. Based on these results, the FloaTolia platform is structurally less flexible in surge and sway movements and performed second best after the semi-submersible in yaw. Each platform has similar values in pitch and roll movements.

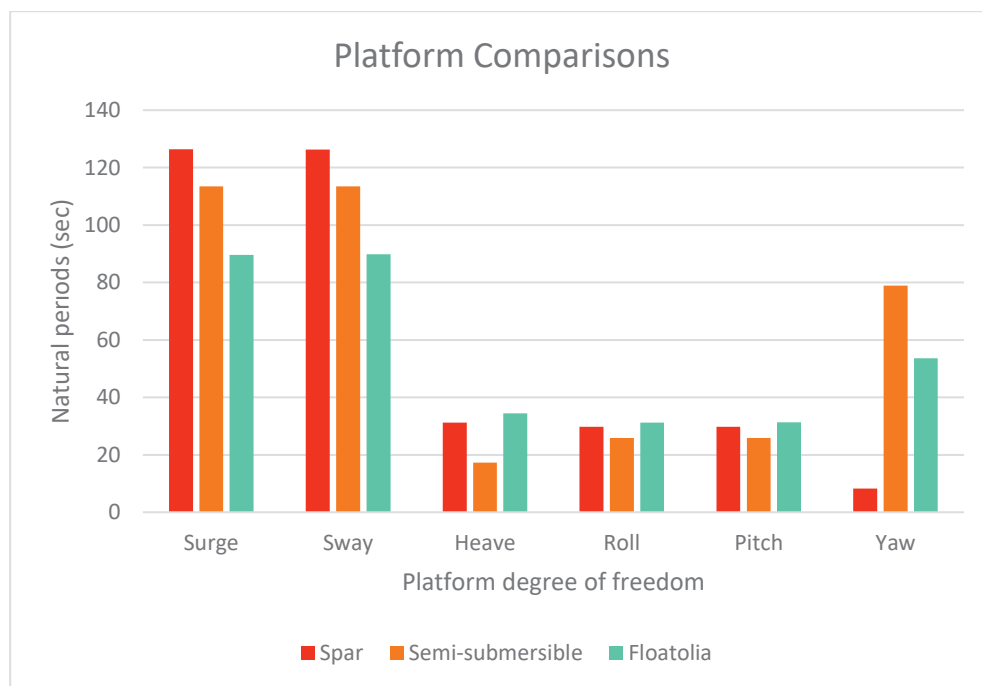


Figure 6.31. Comparisons of three platforms for natural periods

6.3.2. Load Case 1.4 for Comparison of Platforms

Figure 6.32 shows the free decay test results of surge, heave, and pitch movements of three different floating platforms, respectively, as a result of the simulation data obtained under load case 1.4. As stated in load case 1.2, graphics of surge heave pitch and yaw natural periods are shown. In addition, damping ratios are listed in Table 6.14 for a better understanding of the free decay test.

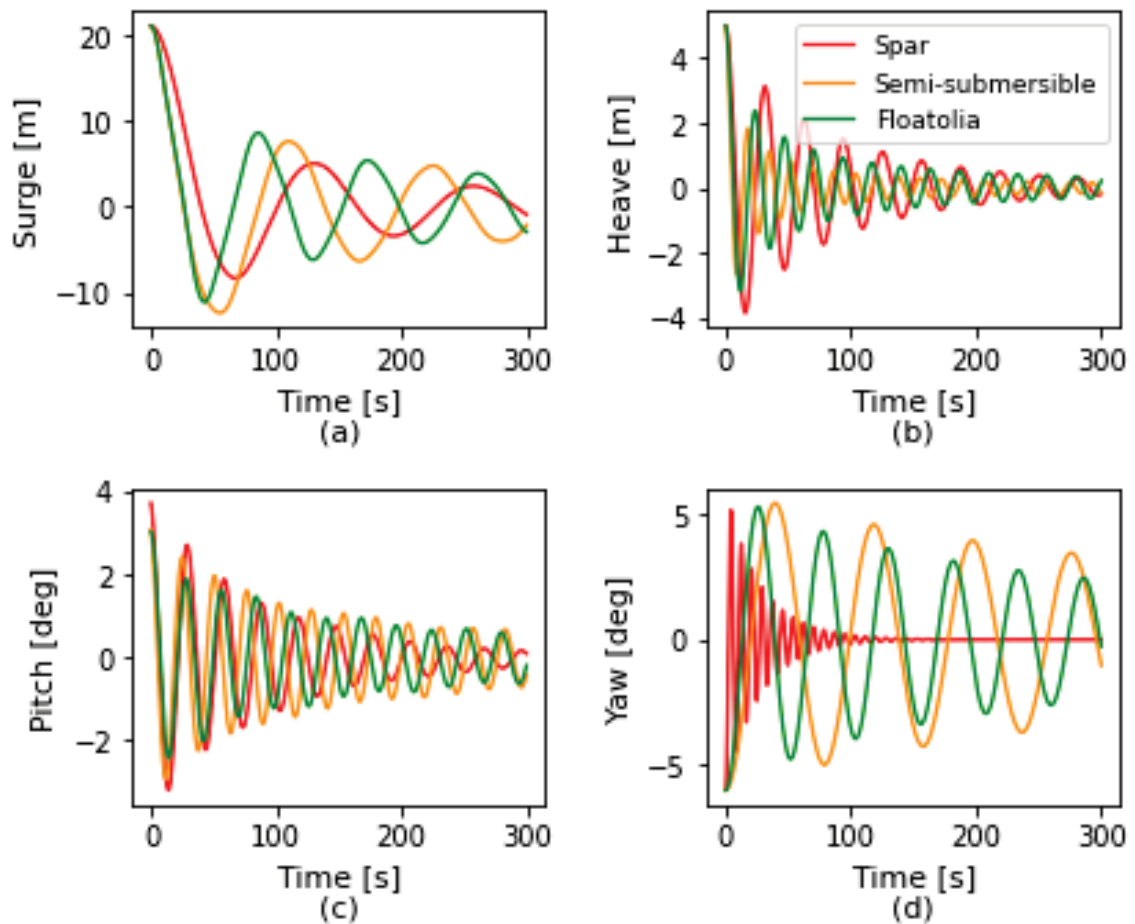


Figure 6.32. Comparisons of three platforms for free decay test:

a) Surge, b) Heave, c) Pitch, d) Yaw

Also, damping ratio values are shown in Table 6.14. According to the data presented in Table 6.14, damping ratios in different degrees of freedom platforms (surge, heave, pitch, yaw).

For surge values, the damping rate of the spar platform is 189.97% higher than the FloaTolia platform, and the semi-submersible platform is 117.64% higher. For heave

values, the spar is 118.75% higher; the semi-submersible is 100.45% higher. The spar is 274.88% higher for pitch values, and the semi-submersible is 158.77% higher. The spar is 203.52% higher in yaw values, and the semi-submersible is 100.44% higher. These results show that spar and semi-submersible platforms generally have a higher damping ratio than FloaTolia. In summary, the spar platform has the highest damping ratios of all values, and FloaTolia has the lowest damping ratios. However, damping ratios are similar to the semi-submersible platform at yaw and heave values.

Table 6.14. Damping ratios for three platforms

Damping Ratio	Spar	Semi-Submersible	FloaTolia
Surge	0.1174	0.0727	0.0618
Heave	0.0532	0.045	0.0448
Pitch	0.058	0.0335	0.0211
Yaw	0.0462	0.0228	0.0227

6.3.3. Comprehensive Analysis of Load Cases from 4.1 to 5.3

In this section, platforms are evaluated for five different load cases from the Load case table. The mean values of surge, heave, and pitch movements are shown in graphs, and the mean max and min values are also prepared in tables to better understand the platforms' behavior under load situations. In addition, fairlead tension values, wind direction blade root force, yaw bearing force, and thrust force values are plotted as graphs. In the results, mean values for surge, heave, and pitch motion are shown in graphics, and absolute maximum values are also considered for other wind turbine components.

Figure 6.33 is given graphically, and for better understanding, the maximum and minimum values are also given in Table 6.15. As seen in the chart, the spar platform is by far the platform that fluctuates the most. The FloaTolia platform is between the two platforms in terms of mean levels of volatility. In load Case 5.1, the maximum value of the spar platform reaches 208.46% of FloaTolia. In load case 5.2, the max value of the spar platform is 176.69% of FloaTolia. In load case 5.3, the max. value of the spar platform shows a high deviation, reaching up to 193.76% of FloaTolia. The semi-submersible platform shows lower percentage deviations; In load case 5.1, the max. value is 85.81% of FloaTolia, in load case 5.2, it is 65.45%, and in load case 5.3, it is 94.88%.

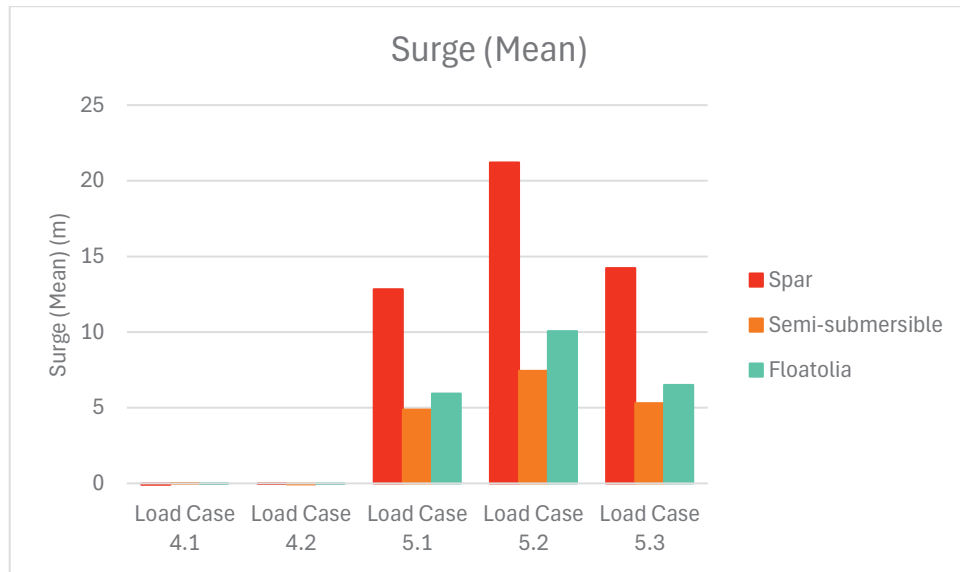


Figure 6.33. Comparisons of three platforms for surge

Table 6.15. Surge motion values for three platforms

Surge Load Case Name	Spar		Semi-submersible		FloaTolia	
	Min (m)	Max(m)	Min (m)	Max(m)	Min (m)	Max(m)
Load Case 4.1	-1.69	1.50	-1.11	1.15	-1.05	1.00
Load Case 4.2	-3.88	6.45	-5.90	6.99	-1.27	1.86
Load Case 5.1	11.19	14.53	3.76	5.98	4.91	6.98
Load Case 5.2	7.22	27.37	3.80	10.15	3.67	15.51
Load Case 5.3	7.42	25.23	0.20	12.35	1.63	13.02

The spar platform, as shown in Figure 6.34, has a higher mean value of the heave than the other two platforms in terms of magnitude, just like the surge motion. In addition, since the min and max values are higher, the standard deviation value is relatively high. The water depth for the FloaTolia and semi-submersible platforms is 200 meters, while for the spar platform, it is 320 meters.

In load case 4.1, the max value of the spar platform reaches 164.71% of FloaTolia, while the max value of the semi-submersible platform reaches 335.29%. In load case 5.1, the max value of the spar platform is 58.33% of FloaTolia, while the max value of the semi-submersible platform is 466.67%. In load case 5.2, the max value of the spar platform is 50.00% of FloaTolia, and the max value of the semi-submersible platform is 155.56%.

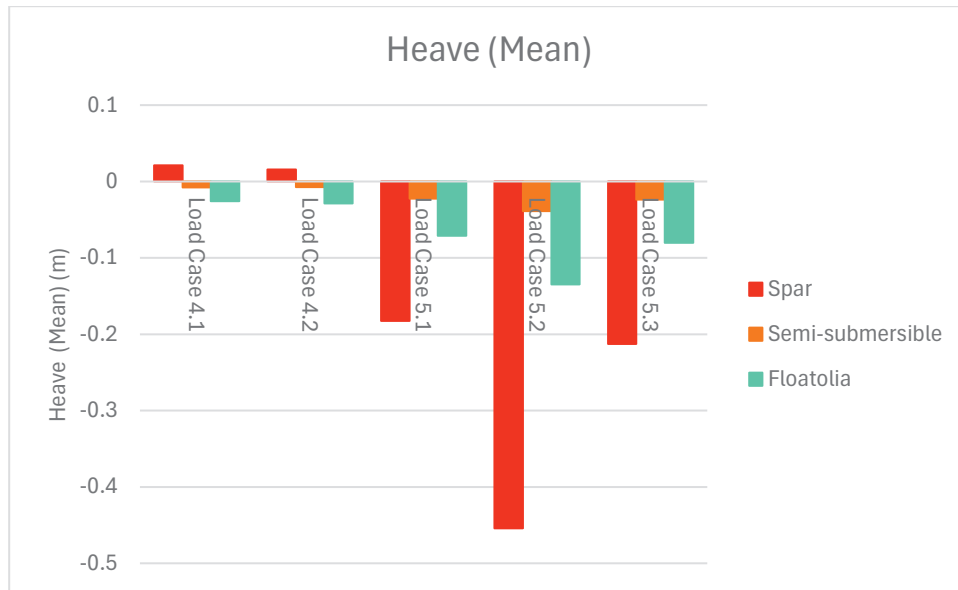


Figure 6.34. Comparisons of three platforms for heave

Table 6.16. Heave motion values for three platforms

Heave Load Case Name	Spar		Semi-submersible		FloaTolia	
	Min (m)	Max(m)	Min (m)	Max(m)	Min (m)	Max(m)
Load Case 4.1	-0.23	0.28	-0.59	0.57	-0.22	0.17
Load Case 4.2	-0.60	0.52	-0.53	0.59	-0.48	0.42
Load Case 5.1	-0.43	0.07	-0.60	0.56	-0.26	0.12
Load Case 5.2	-0.98	0.18	-0.57	0.56	-0.66	0.36
Load Case 5.3	-1.54	0.73	-0.62	0.54	-0.67	0.35

In Figure 6.35 and Table 6.17, as with the other movements, the spar platform has the highest pitch movement. Additionally, the FloaTolia platform has very low pitch values. This phenomenon is thought to be due to the design of the mooring lines. According to the analysis, the highest pitch angle of the FloaTolia platform was found to be 3 ° degrees. As a result of this design, mooring lines are exposed to higher loads, and the pitch angle has very low values. For example, in load case 5.2, the max value of the spar platform is 258.00% of FloaTolia, and the max value of the semi-submersible platform is 194.33%. When the pitch (max) values of load case 5.3 are evaluated according to FloaTolia, the max value of the spar platform is 293.33% of FloaTolia, and the max value of the semi-submersible platform is 256.14%. Having low pitch values of the FloaTolia platform reduces the forces and stress it is exposed to and contributes positively to structural durability.

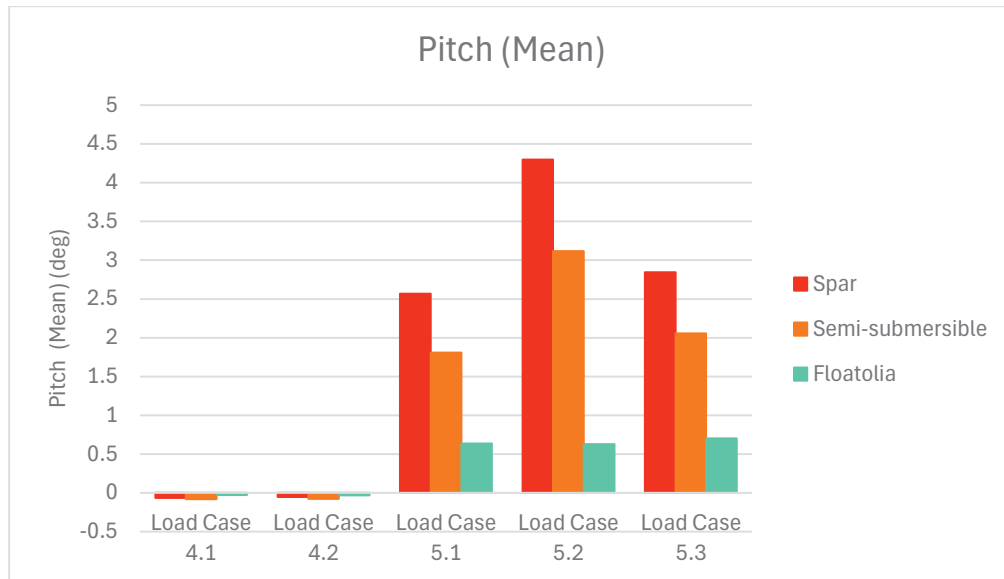


Figure 6.35. Comparisons of three platforms for pitch

Table 6-17: Pitch motion values for three platforms

Pitch	Spar		Semi-submersible		FloaTolia	
Load Case Name	Min (°)	Max (°)	Min (°)	Max (°)	Min (°)	Max (°)
Load Case 4.1	-0.89	0.77	-1.13	0.96	-0.23	0.17
Load Case 4.2	-1.85	1.92	-1.46	0.95	-0.45	0.52
Load Case 5.1	1.72	3.41	0.78	2.84	0.47	0.89
Load Case 5.2	0.59	7.74	-0.48	5.83	-1.59	3.00
Load Case 5.3	-1.71	8.36	-1.60	7.30	-2.07	2.85

In Figure 6.36, fairlead tension maximum values were selected. Regarding the forces acting on fairlead 1 tension, the three platforms are FloaTolia, semi-submersible, and spar platforms. In load case 5.2, the fairlead tension 1 (max) value of the semi-submersible platform is 149.47% higher than the spar platform and 64.35% higher than the FloaTolia platform. In load case 5.3, the fairlead tension 1 (max) value of the semi-submersible platform is 176.22% higher than the spar platform and 75.20% higher than the FloaTolia platform.

In addition, for the fairlead 1 tension value, the FloaTolia platform obtained values between the spar and semi-submersible platforms. Within the scope of this result, it is thought that if a more suitable design is made, the FloaTolia platform can also provide reasonable values regarding the mooring line.

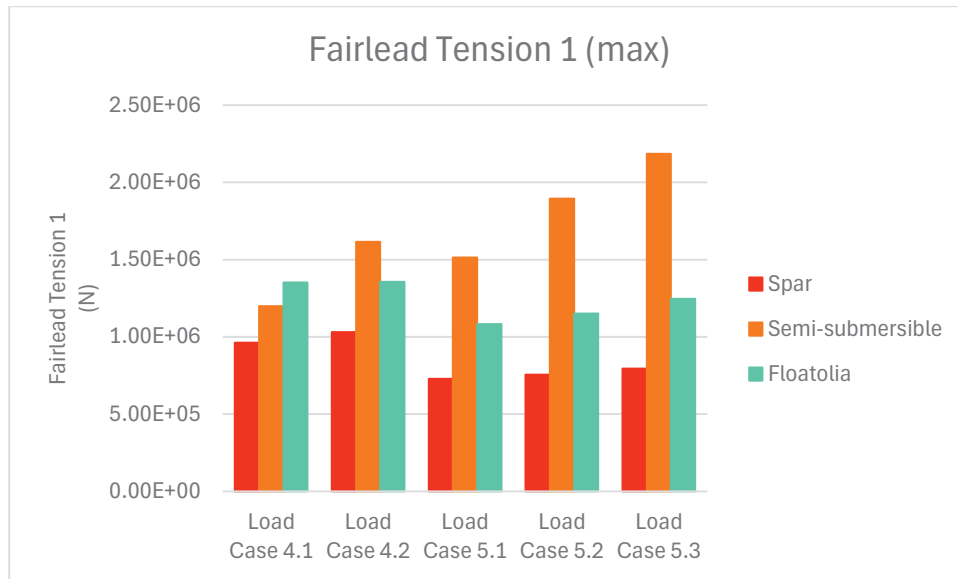


Figure 6.36. Comparisons of three platforms for fairlead tension 1

Fairlead tension 2 and 3 max values with symmetrical configurations are shown in Figures 6.39 and 6.39. In load case 5.1, the fairlead tensions max of the FloaTolia platform is 28.44% higher than the spar platform and 33.33% higher than the semi-submersible platform. In load case 5.2, it is 30.0% more than the spar platform and 60.95% more than the semi-submersible platform. Finally, in load case 5.3, the fairlead tensions max value of the FloaTolia platform is 24.41% higher than the spar platform and 36.21% higher than the semi-submersible platform. These results are attributed to the mooring line design and the pitch angle not exceeding 3 degrees, as previously shown.

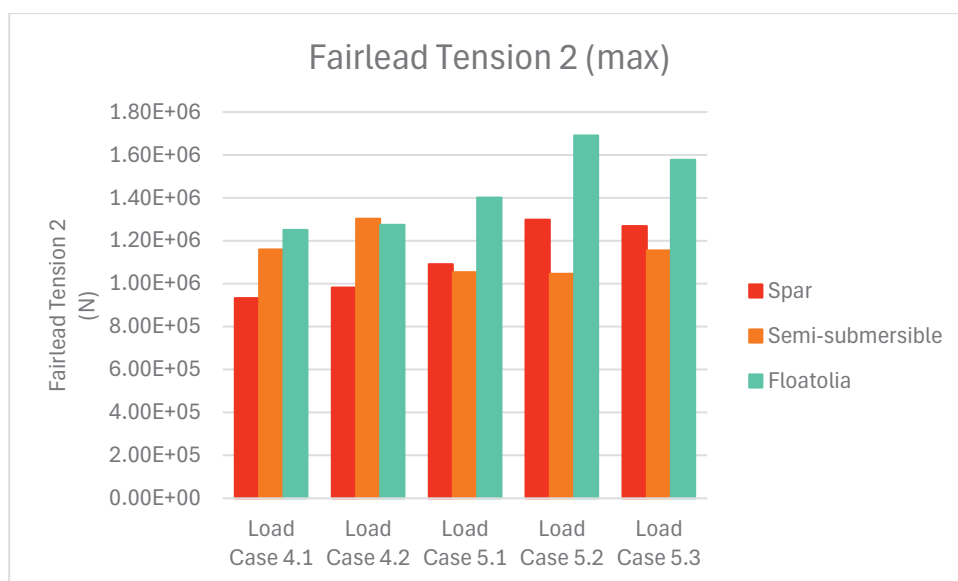


Figure 6.37. Comparisons of three platforms for fairlead tension 2

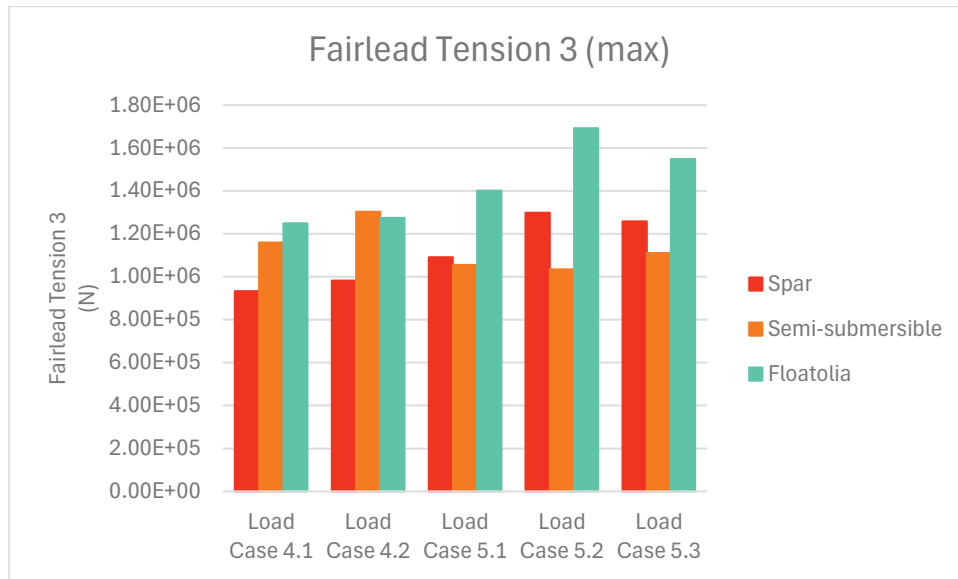


Figure 6.38. Comparisons of three Platforms for fairlead tension 3

In Figure 6.39, in load case 5.1, the tower top FA (max) value of the FloaTolia platform is proportionally 70.82% less than that of the spar platform and 5.84% less than that of the semi-submersible platform. In load case 5.2, the tower top FA max value of the FloaTolia platform is 32.62% less than the spar platform and 31.47% less than the semi-submersible platform. In load case 5.3, the tower top FA max value of the FloaTolia platform is 77.42% less than the spar platform and 46.09% less than the semi-submersible platform. These results indicate that the FloaTolia platform has lower tower top FA max values than other platforms. The lower tower top (FA) fore-aft deflection value shows that the platform's tower is quite resistant to back-and-forth movements and deformations.

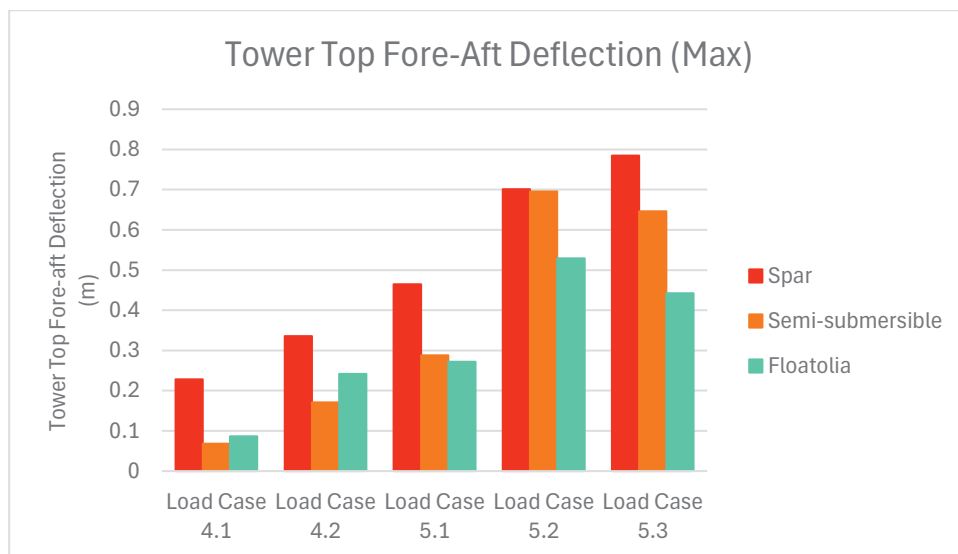


Figure 6.39. Comparisons of three platforms for tower top fore-aft deflection

When the blade root force (max) value in the wind direction is compared in Figure 6.41, it is seen that the FloaTolia platform has the lowest value. For example, FloaTolia, with the load case set to 5.2, has a max value of 8.80% less than the spar platform and a max value of 3.12% less than the semi-submersible platform. Especially in extreme wind conditions, the load that the FloaTolia platform is exposed to is reduced compared to other platforms.

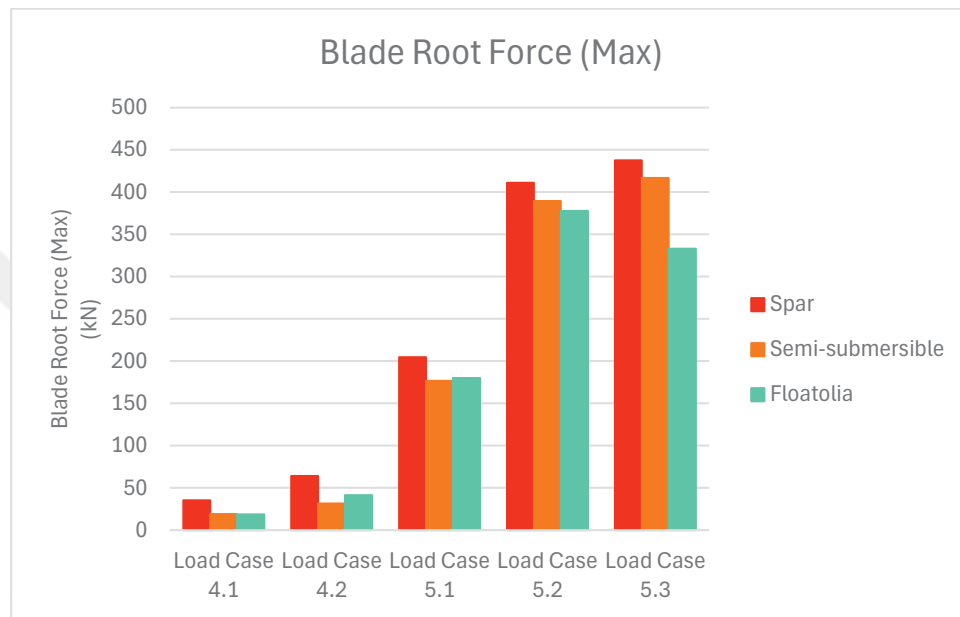


Figure 6.40. Comparisons of Three Platforms for Blade Root Force

In Figure 6.41, the maximum value of the yaw-bearing force is shown for different platforms. For example, if the load cases under the conditions of wind and wave are examined, in load case 5.1, the yaw bearing Fx max value of the FloaTolia platform is 63.00% less than the spar platform and 6.92% less than the semi-submersible platform. In load case 5.2, the yaw-bearing Fx (max) value of the FloaTolia platform is 24.79% less than the spar platform and 28.93% less than the semi-submersible platform. In load case 5.3, the yaw-bearing Fx (max) value of the FloaTolia platform is 90.83% less than the spar platform and 54.06% less than the semi-submersible platform.

As with other components, the FloaTolia platform has a lower value than the other platforms. With this result, the lifespan of floating wind turbines using the FloaTolia platform is expected to be longer.

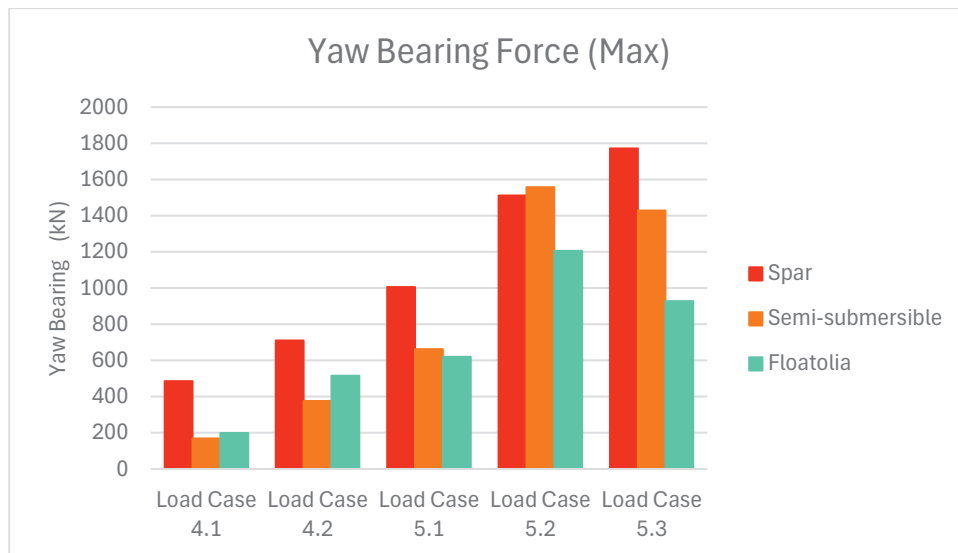


Figure 6.41. Comparisons of three platforms for yaw bearing force

In Figure 6.42, the lowest thrust force in wind conditions was obtained on the FloaTolia platform. It is thought that the main reason for this is the low pitch angle and performance of the FloaTolia platform. In percentage terms, in load case 5.1, the rotor thrust (max) value of the FloaTolia platform is 23.91% less than the spar platform and 1.28% less than the semi-submersible platform. In load case 5.2, the rotor thrust (max) value of the FloaTolia platform is 12.96% less than the spar platform and 10.19% less than the semi-submersible platform. Finally, in load case 5.3, the maximum rotor thrust value of the FloaTolia platform is 48.53% less than the semi-submersible platform and 50.92% less than the spar platform.

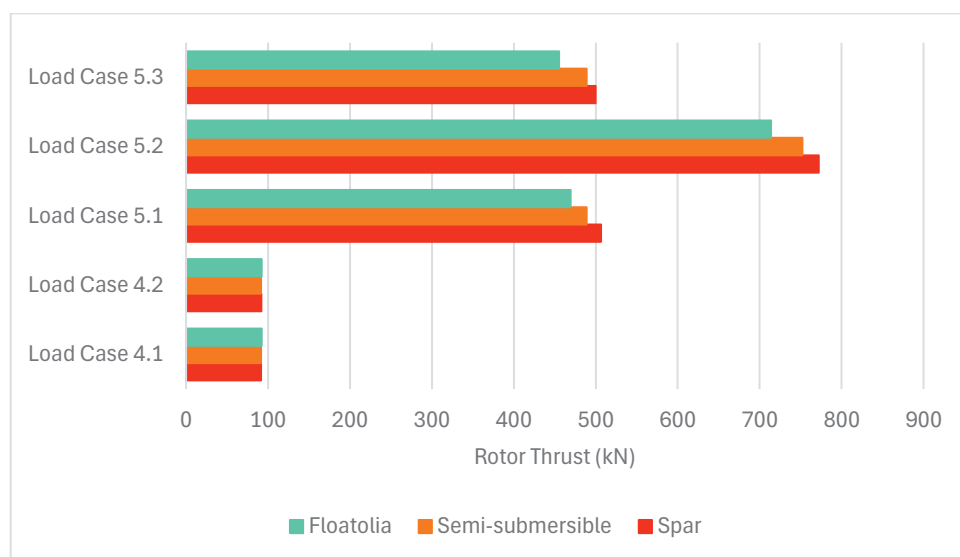


Figure 6.42. Comparisons of three platforms for thrust force

Regarding wind turbine components and parameters shown in the figures, the FloaTolia is the platform exposed to the least force, thanks to its low pitch angle value. On the other hand, the numbered fairlead tension has higher values for 2 and 3 max values than the other platforms. Among other platforms, the semi-submersible platform outputs are closer to the FloaTolia platform. When these results are evaluated, it can be concluded that using the FloaTolia platform instead of other known platforms will expose lower ultimate loads for wind components and higher ultimate loads for mooring line components.



CHAPTER 7

CONCLUSIONS

In this study, the numerical analysis of three distinctive designs, spar semi-submersible and FloaTolia, was conducted using different coupled methods. The FloaTolia platform, which was evaluated for 300 kW at IZTECH, is an innovative platform and has been modified to suit 5 MW. In addition, spar and semi-submersible platforms, which are frequently used in literature, were used to evaluate the methods. The first method is to enter hydrodynamic coefficients as input into OpenFAST. This chaptered method has been assessed using programs such as AQWA-OpenFAST, NEMOH-OpenFAST, Capytaine-OpenFAST, and WAMIT-OpenFAST for spar and semi-submersible platforms.

The first method in this thesis aims to perform a numerical analysis of platforms using three different hydrodynamic programs, such as ANSYS, AQWA Capytaine, and NEMOH, instead of the WAMIT tool used. For this reason, meshing 3D models were prepared using ANSYS AQWA software licensed by IZTECH, and the geometries were solved using different potential solvers with the help of BEMRosetta.

In the first method, AQWA-OpenFAST and Capytaine-OpenFAST programs, which were developed for spar and semi-submersible and provide more efficient and accurate results for use on the FloaTolia platform, were selected. Along with this approach, another alternative method called F2A is used by coupling AQWA-FAST v7. The most positive aspect of this method is that you can easily design overly complex platforms such as FloaTolia, which need to be flexible or rigid, with AQWA. In this way, it is possible to model flexible elements on the platform, and the FloaTolia program was designed as rigid and flexible and tested with the platform analyzed only as rigid, such as AQWA-OpenFAST and Capytaine-OpenFAST programs.

As a result, platforms exposed to various sea and wind conditions were analyzed, and their behavior was examined, as shown in Table 5.14. The FloaTolia platform was analyzed as rigid and flexible using the F2A method. Additionally, all platforms were compared with each other for different load cases with the AQWA-OPENFAST coupled in terms of loads on different turbine components. The results of this study and scientific

studies that can be focused on in future studies are as follows:

- 1) As a result of giving hydrodynamic coefficients for the spar platform as input to OpenFAST using potential solvers such as AQWA, NEMOH, and Capytaine, almost all programs gave the same results in all load cases due to the very simple geometry of the spar platform and the high mesh quality.
- 2) Hydrodynamic coefficients were provided as input to OpenFAST by using the above-mentioned programs on the semi-submersible platform. Due to the slightly more complexity of the geometry and the problems in the mesh that occurred, it gave very similar results to WAMIT in load cases, with acceptable differences.
- 3) First of all, the NEMOH-OpenFAST couple method is not used on the FloaTolia platform. The reason for this is that Capytaine and NEMOH have the same solvers, and Capytaine, which is Python-based, gives much faster results. In addition, the analyses of the FloaTolia platform, which were designed rigidly with the F2A approach, were compared with AQWA and Capytaine. In the FloaTolia platform, the geometry was especially complex and caused acceptable differences in the AQWA and Capytaine solutions. In addition, F2A, which has the same mesh structure as AQWA, produced negligibly different results. The reason for this may be that the values depending on the random seed number are different in OpenFAST HydroDyn and AQWA, especially in terms of Irregular wave, and the FAST version used is FAST v7, which is quite old compared to OpenFAST. In addition, the differences in the platform and mooring line during the design may have caused this difference. Despite these difficulties, the F2A method has given remarkably close results and correlated them with other approaches.
- 4) The FloaTolia platform was analyzed using the F2A approach as rigid and flexible. It was found that the second harmonic pitch and second harmonic heave oscillations of the platform caused resonance, especially. By preventing these oscillations, the platform will give very similar results to the rigid one. The FloaTolia platform, which is analyzed especially as rigid and flexible, has close free decay and natural period results. However, after load case 4.1, it resonates with the platform flexible due to the wave effect.
- 5) The AQWA-OpenFAST method, which gives the closest results to WAMIT-OpenFAST outputs, was chosen as the approach for the three platforms that were analyzed rigidly and compared with each other. The most important part that stands out here is that almost all wind turbine components are exposed to less load since the pitch angle of the FloaTolia platform is quite stable in the load cases with the mooring line designs. However, the load on the mooring lines is higher than on other platforms.

6) FloaTolia depends on higher periods and stability in terms of degree of freedom in heave motion than others because of heave plates. In addition, surge and sway period values are lower than other platforms and have weaker stability. It has features close to the spar platform in terms of pitch and roll.

7) For the FloaTolia platform, the flexible model is designed to be more like the rigid model to avoid resonance.

8) More realistic and professional studies and calculations for the FloaTolia platform, modeled rigidly on OpenFAST, are site-specific by standards such as IEC 61400-1, standard wind turbine class⁹⁷ or DNVGL-ST-0437 Loads and site conditions for wind turbines¹¹⁵. For more comprehensive floating offshore wind turbine components, can be made under the standards.



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APPENDIX A

In Chapter 5.3, mesh geometries for three different platforms are presented: the spar platform in Figure A.1, the semi-submersible platform in Figure A.2, and The FloaTolia platform in Figure A.3. Only the parts solved using the potential flow solver are shown, while the thinner members are defined in HydroDyn.

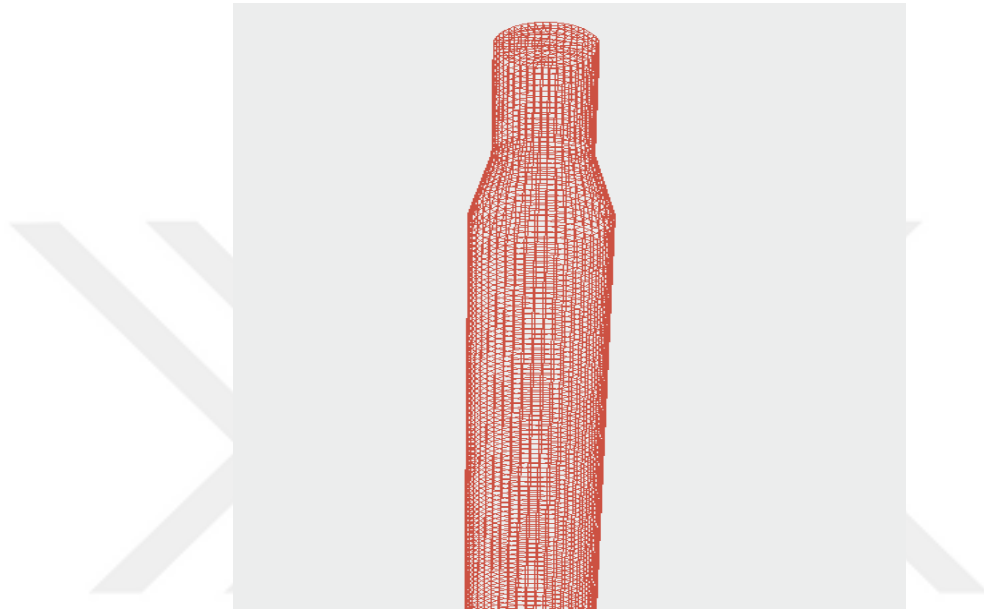


Figure A.1. Mesh representations of NREL Spar type platform

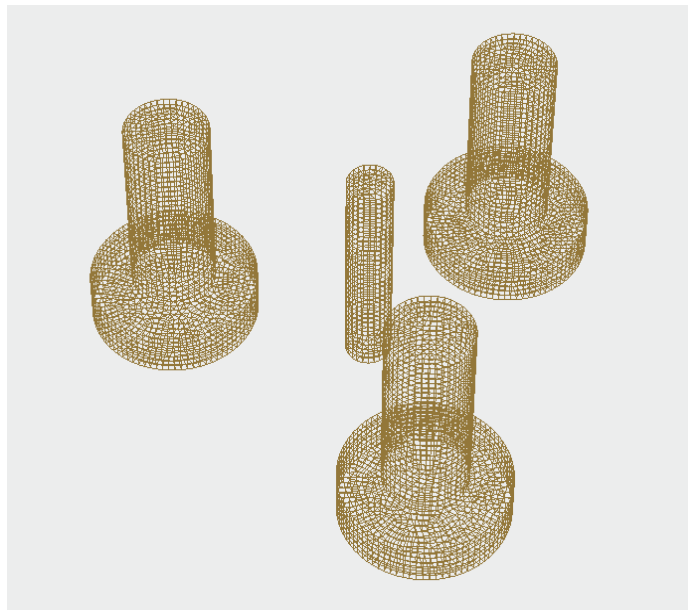


Figure A.2. Mesh representations of NREL semi-submersible type platform

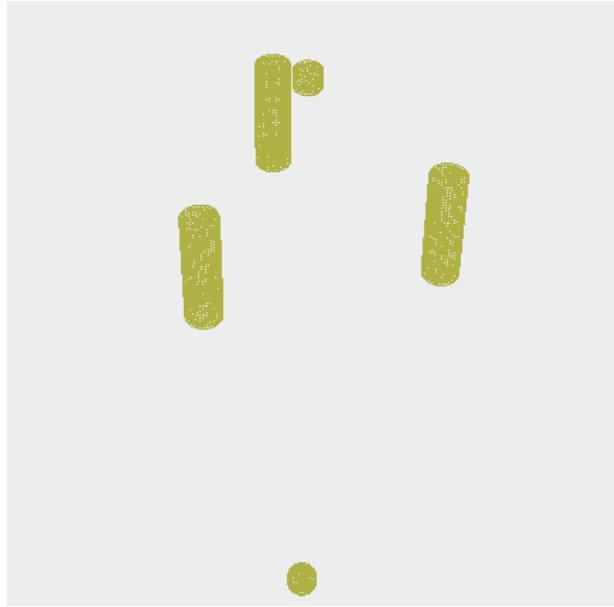
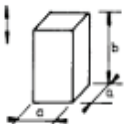
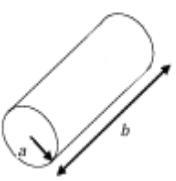


Figure A.3. Mesh representations of The FloaTolia platform

The procedures for obtaining drag and added mass coefficients for buoyant legs, to be used in Morison's equations, are outlined in this section as follows :

Table A.1 . Added mass coefficient for buoyant legs (source: DNV-RP-C205 ¹¹⁶)

Table D-2 Analytical added mass coefficient for three-dimensional bodies in infinite fluid (far from boundaries). Added mass is $m_A = \rho C_A V_R$ [kg] where V_R [m ³] is reference volume. (Continued)					
Body shape		Direction of motion	C_A		V_R
Square prisms		Vertical	b/a	C_A	$a^2 b$
			1.0	0.68	
			2.0	0.36	
			3.0	0.24	
			4.0	0.19	
			5.0	0.15	
			6.0	0.13	
			7.0	0.11	
			10.0	0.08	
Right circular cylinder		Vertical	$b/2a$	C_A	$\pi a^2 b$
			1.2	0.62	
			2.5	0.78	
			5.0	0.90	
			9.0	0.96	
			∞	1.00	

To determine the added mass coefficient (C_A) for the floating legs, the $b/2a$ ratio was calculated as 5.55 using Table A.1. Since this ratio was not among the table values, the C_A value was found by interpolation, resulting in a value of 0.908. This value is the added mass coefficient required for the floating legs to be used in the Morison equations.

Table A.3 . Surface roughness table for cylinders(source: DNV-RP-C205 ¹¹⁶)

Table 6-1 Surface roughness	
<i>Material</i>	<i>k (meters)</i>
Steel, new uncoated	5×10^{-5}
Steel, painted	5×10^{-6}
Steel, highly corroded	3×10^{-3}
Concrete	3×10^{-3}
Marine growth	5×10^{-3} to 5×10^{-2}

From Table A.3, 'Steel, new uncoated' was selected, and the surface roughness to diameter ratio k/D was calculated as 1.42×10^{-5} . Using this value and the average Reynolds number 5×10^6 obtained for the buoyant legs in a sea state with $H=6$ meters and $T=10$ seconds, the drag coefficient C_d was found to be 0.69 in Table A.4, which was marked in red.

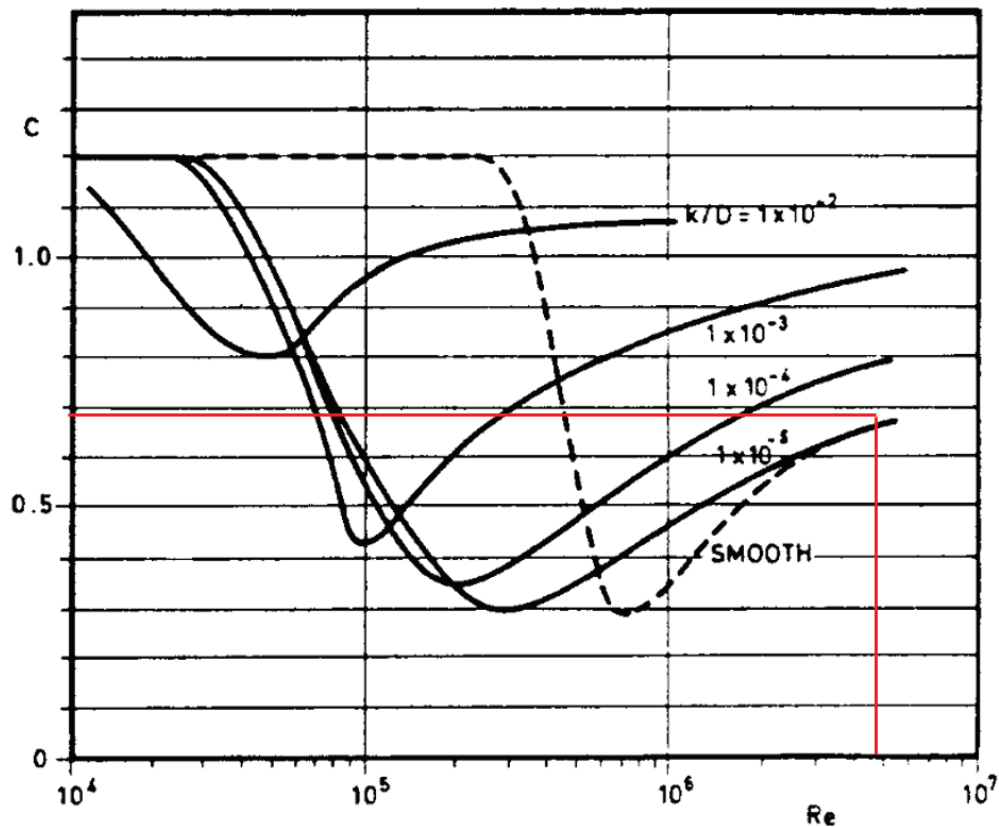


Figure A.4. Drag coefficient values for buoyant legs (source: DNV-RP-C205 ¹¹⁶)

APPENDIX B

Figures B.1 to B.5 are plotted to show the correlation and compatibility of the (F2A) couple method with other hydrodynamic coefficients for the FloaTolia platform in terms of time output. These figures utilize the F2A, Capytaine-OpenFAST, and AQWA-OpenFAST methods under load case 5.3 conditions, presenting basic outputs such as surge, pitch, yaw, thrust, and blade pitch angle respectively. In Figure B.6, the turning responses of the F2A flexible and rigid models are compared in terms of tower top deflection and shear force . The flexible model shows higher response amplitudes at certain frequencies, indicating greater susceptibility to resonance.

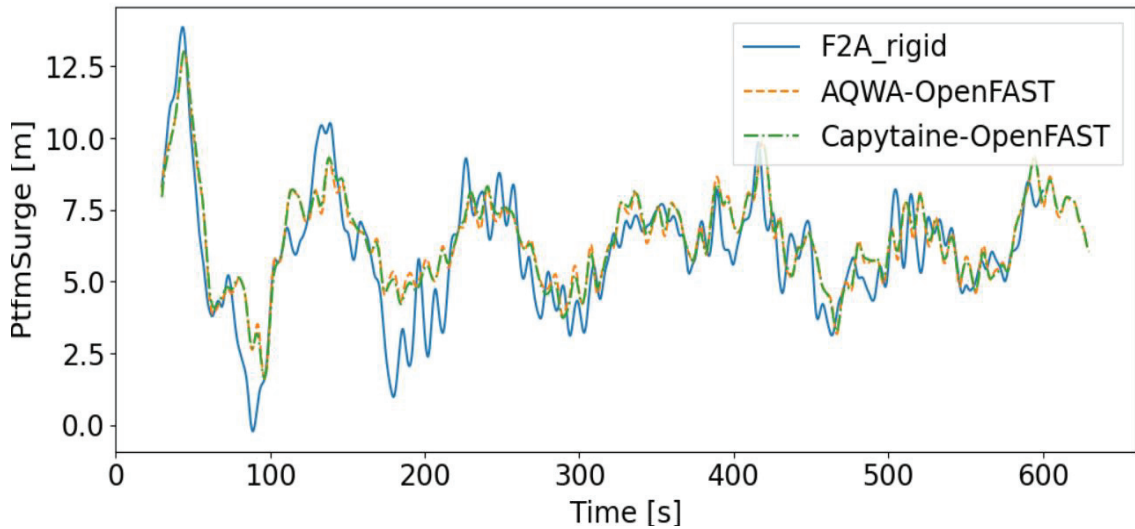


Figure B.1. Comparison of time series output for surge on FloaTolia

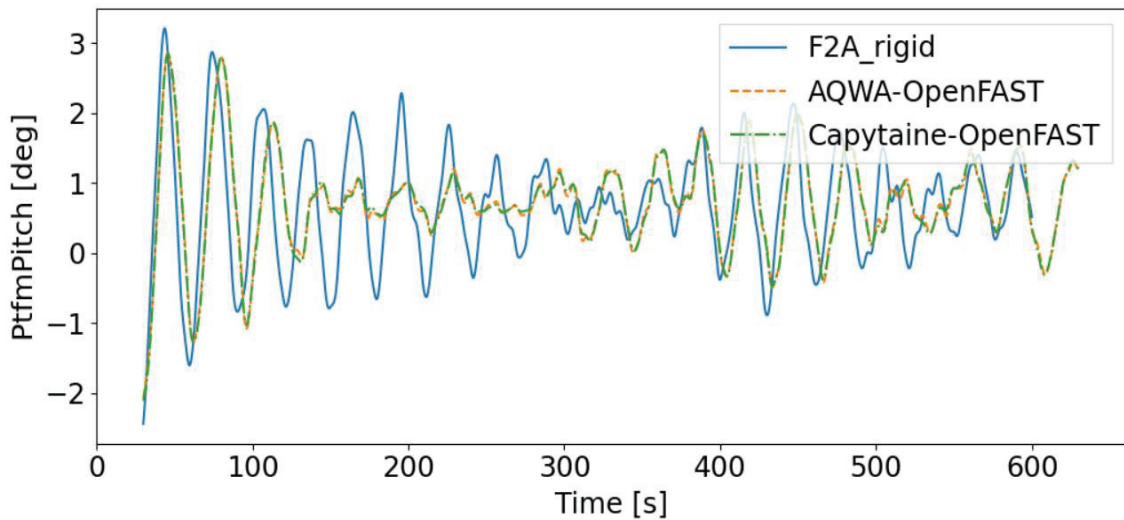


Figure B.2. Comparison of time series output for pitch on FloaTolia

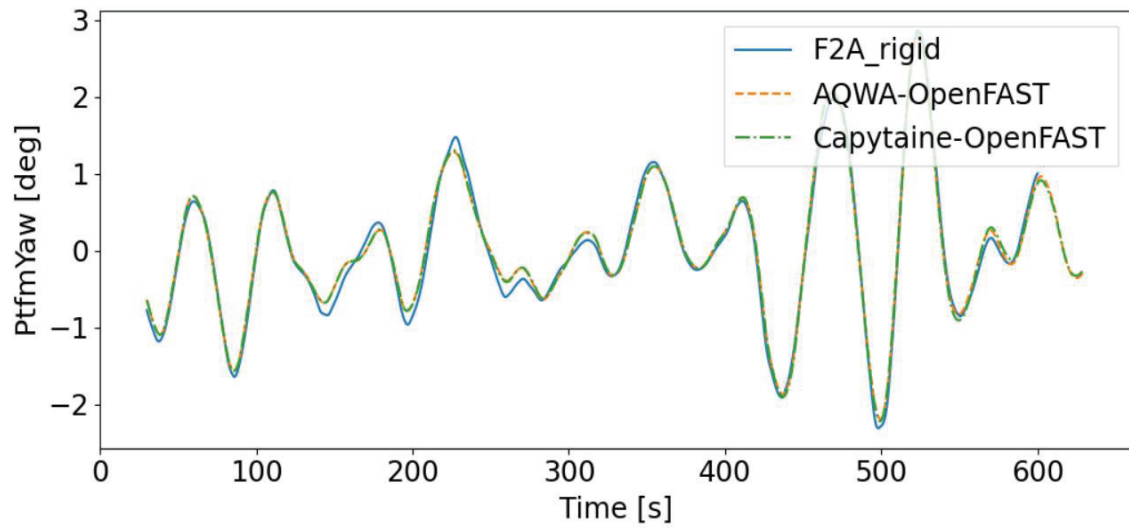


Figure B.3. Comparison of time series output for yaw on FloaTolia

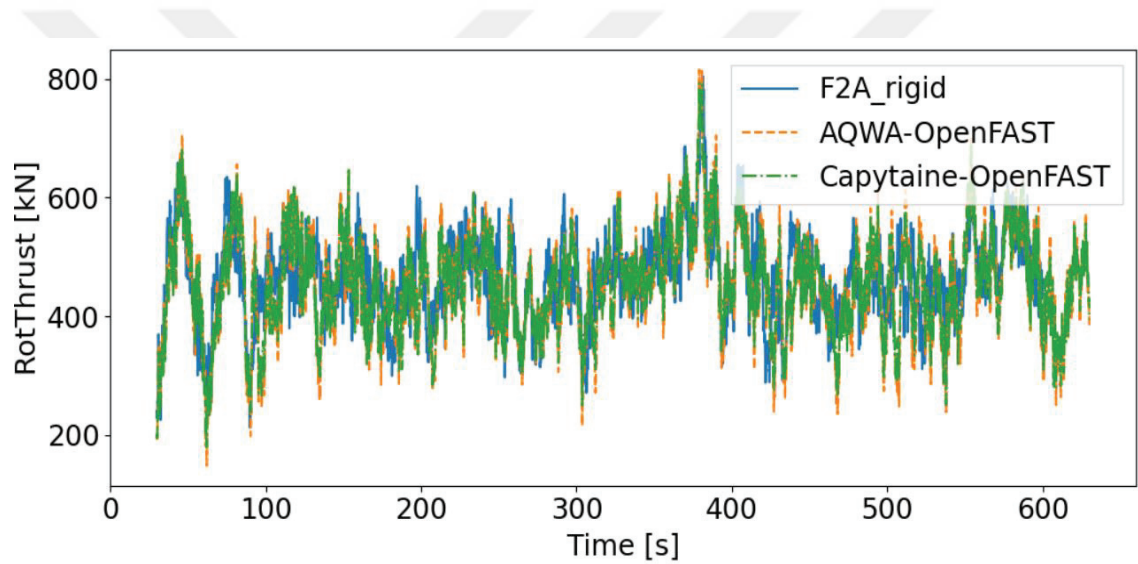


Figure B.4. Comparison of time series output for thrust on FloaTolia

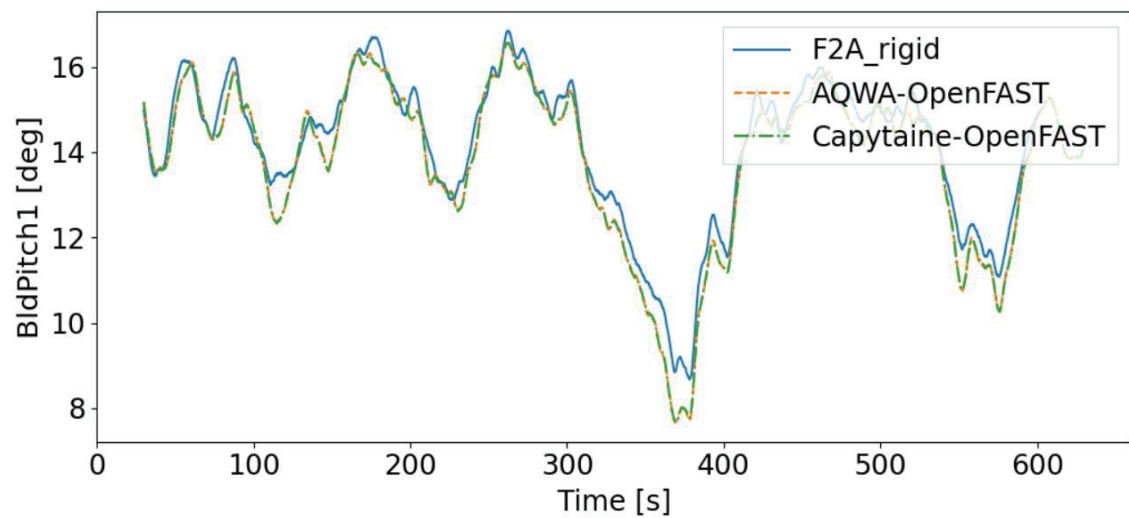


Figure B.5. Comparison of time series output for blade pitch angle on FloaTolia

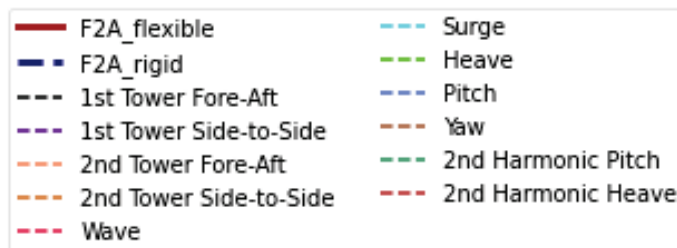
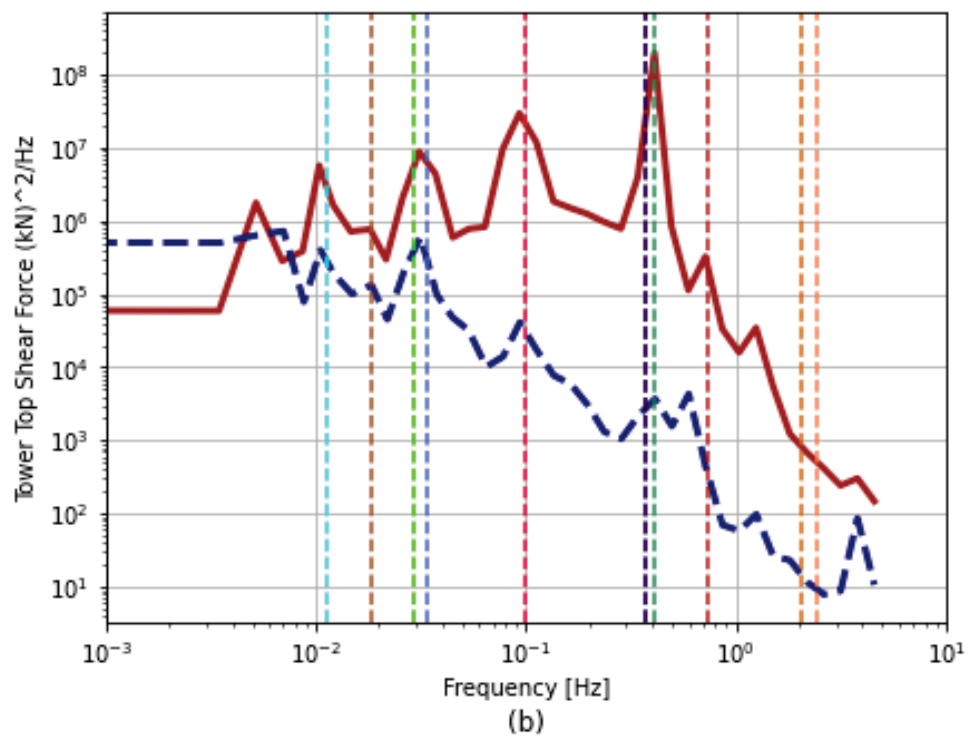
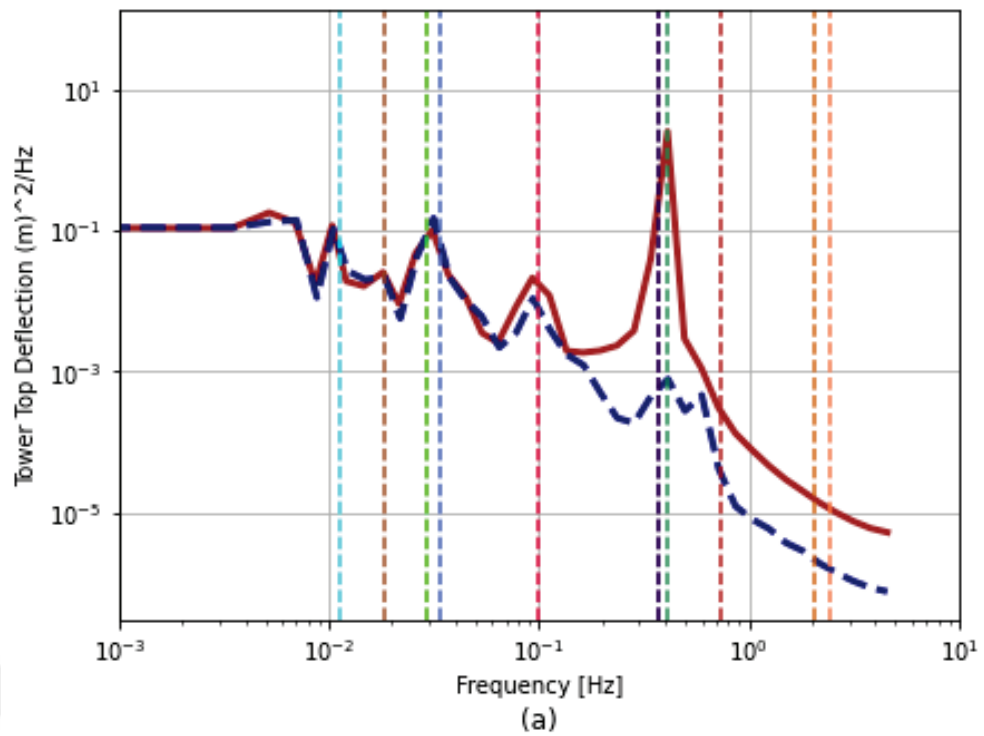


Figure B.6. Comparison of load case 5.2 PSD graphs with natural frequencies of the wind turbine a) Tower top deflection b) Tower top shear force