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Numerical Analysis and Modeling of a Semi-Submersible Floating Wind Turbine Platform with Large Amplitude Motions Subjected to Extreme Wind and Wave Loads

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Abstract: The objective of this study is to predict the large amplitude motions of floating wind turbine platforms and to emphasize the significance of nonlinear forces when these platforms are subjected to combined wind and wave loads. The analysis utilizes the 5 MW OC4 semi-submersible model. First, we couple the OpenFAST v3.1.0 with SIMDYN, validate the effectiveness of the coupled program, and highlight the considerable impact of nonlinearity on the results, particularly in relation to the heave and pitch motions of offshore wind platforms under extreme environmental conditions. We then discuss the primary reasons for this phenomenon. Ultimately, this study proposes an optimized model aimed at mitigating the nonlinear effects associated with such conditions.

Keywords: large amplitude motion; semi-submersible floating wind turbine; blended time-domain method; nonlinearity; optimization

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1. Introduction

Wind power is an endlessly renewable energy source that can be harnessed both onshore and offshore. Fixed wind and floating wind are two distinct types of offshore wind energy systems that harness the power of wind at sea to generate electricity. Fixed wind refers to traditional offshore wind turbines that are directly anchored to the seabed. These turbines are generally installed in shallower waters, typically less than 50–60 m deep. Fixed wind technology is the more established and widely deployed method of offshore wind generation, with numerous operational offshore wind farms, particularly in Europe, such as those located in the North Sea. However, its application is constrained by the depth of the water. Floating wind technology refers to offshore wind turbines that are not anchored directly to the seabed but are instead mounted on floating platforms tethered to the ocean floor. This innovative approach allows for deployment in much deeper waters than traditional fixed turbines, thus unlocking vast new areas for offshore wind development. Typically, they are utilized in waters deeper than 60 m and can be positioned further offshore. Common types of floating wind platforms include spar and semi-submersible designs, and one of the popular models is OC4 semi-submersible [1]. Floating platforms can be arranged in larger and more expansive wind farms, enhancing overall energy production capacity. However, it is important to note that floating wind technology is still in the early stages of development compared to its fixed counterparts. Currently, offshore wind platforms are receiving increasing attention due to the stronger and more predictable wind conditions. The number of floating offshore wind turbines (FOWTs) has grown rapidly in recent years, highlighting the increasingly critical role of offshore wind energy in global energy systems. Despite the commercialization of FOWT technology, there are still numerous technical challenges to be addressed. As offshore wind farms are installed in deeper water depths, wind velocity increases, necessitating longer wind blades and leading to stronger wind loads, potentially causing significant platform motion. This motion, in turn, may exert higher forces on the blades and tower, creating complex and fluctuating aerodynamic conditions [2]. Therefore, ensuring the stability of the platform is of the utmost importance.

Researchers have employed various methods to investigate the response of floating platforms. Vorpahl [3] demonstrated the environmental loads, the relevant tools, and the standards used on offshore wind turbines. Ferrandis investigated the influence of the viscosity and the nonlinearities for FOWTs in regular waves through the CFD method [4]. Wang and Chen used computational fluid dynamics (CFD) to study the hydrodynamic response of FOWT semi-submersibles and the influence of viscosity and nonlinearities in regular waves [5], respectively. They also validated the responses of a semi-submersible under random waves via the CFD method at the same time [6]. Wan and Xia used the viscous flow solver naoe-FOAM-SJTU based on OpenFOAM to analyze semi-submersible platform motions [7]. Teng proposed a method to simulate the nonlinear response of moored floating platforms by dividing Quasi-Static Transfer Functions (QTFs) into different components [8]. Additionally, Katarzyna studied the dynamic response of the spar model by analyzing the instantaneous center of rotation of FOWTs [9]. Meanwhile, Jameel conducted a dynamic analysis of coupled spar platforms in deep water [10]. It is evident that researchers employ diverse approaches to study the predictions of floating platform motions. Wang and Roberston enhanced OpenFAST to predict the nonlinear, low-frequency responses of the semi-submersible model [11]. Wind loads often do not receive adequate attention in research, which typically emphasizes wave loads instead. FOWT systems are complex, requiring a holistic approach to analysis. To effectively evaluate FOWT systems, it is essential to consider aerodynamic and hydrodynamic calculations and mooring design, as each component interacts with the others. However, many studies overlook the critical importance of examining the system as a whole.

Considering the above issues, the most popular software is FAST v8.16, updated as OpenFAST and with more functions, which the National Renewable Energy Laboratory developed [12] (Golden, CO, USA). This multi-physics solver can simulate the coupled dynamic responses of FOWTs. Many researchers coupled OpenFAST or FAST with their own programs. Bae and Kim coupled Charm3D-FAST [13,14] to study the performance of the floating wind platform. Yang coupled FAST with AQWA to examine the interaction between the floaters of the multi-body platform [15]. However, the above works are based on normal conditions and do not account for extreme conditions. Due to the stable motions observed, nonlinearity was not considered in these studies.

In recent years, extreme conditions have become more frequent due to climate change. Rising temperatures are causing more intense weather events such as storms, heatwaves, and large waves. Additionally, melting glaciers and the expansion of seawater are raising sea levels, increasing the risk of coastal flooding and storm surges, which is posing a serious threat to the safety of coasts and marine structures. In this paper, we mainly focus on the high waves and storms in the ocean. These extreme conditions are typically driven by severe weather events, including hurricanes, typhoons, and cyclones, and are characterized by powerful winds and large waves. In Journee and Massie's book, they define the extreme sea state [16]. Understanding the response of FOWTs in extreme environments has posed a significant challenge in recent years. When external loads are substantial, it is inadequate to consider only linear forces. Jang and Kim emphasized the importance of nonlinear Froude–Krylov forces and nonlinear hydrostatic restoring forces in the motions of arctic spars [17]. Similarly, Bandyk, Rodríguez, and Rajendran conducted comparable analyses on ship performance by incorporating nonlinear forces [18–20]. However, there remains a limited amount of research focused on predicting platform motions under the combined impacts of wind and wave loads while considering these nonlinear forces. Further investigation is necessary to thoroughly explore the effects of nonlinear forces on FOWTs.

Floating structures interact with waves, currents, and winds in complex ways. When it comes to extreme conditions, nonlinear forces offer a more precise representation of these interactions than linear models. The dynamics of these nonlinear forces can impact the stability of the structure. In cases where structures respond nonlinearly to hydrodynamic forces, they may exhibit behaviors not accounted for in linear models, such as increased response amplitudes. Nonlinear interactions can result in resonant phenomena, where the structure's natural frequencies align with wave frequencies, leading to amplified responses. This is a crucial consideration when designing systems to mitigate such effects. Accurately predicting nonlinear forces is vital for assessing structural integrity and ensuring safety, as well as for optimizing design and reducing the risk of catastrophic failures. The novelty of this study is to analyze the nonlinear response of motions under extreme wind and wave loads in floating offshore wind turbine systems, which is seldom considered currently.

Based on previous research conducted at the Texas A&M University Marine Dynamic Lab, we utilized the SIMDYN program, which was developed by the lab (College Station, TX, USA). This program operates in the time domain and is used in solving both linear and nonlinear governing equations. Its nonlinear capabilities account for the nonlinearity of Froude–Krylov and hydrostatic forces. A notable distinction of SIMDYN is the derivation of nonlinear forces, specifically the Froude–Krylov force and restoring force, which are obtained from the platform's instantaneous position and orientation. In contrast, other numerical methods derive the Froude–Krylov force and the restoring force from the averaged positions of the platform.

Therefore, this paper begins by demonstrating the trend and background of FOWTs and illustrating the current numerical methods used in this field and then pointing out the inadequate parts of the current study and briefly introducing the importance and breakthrough of our work. Then, it explains how to integrate SIMDYN with OpenFAST and details the evaluation of linear and nonlinear hydrodynamic loads. Following this, the program's accuracy will be established, and several cases under varying conditions will be presented and discussed. Ultimately, the paper will propose an optimized platform shape model based on the preceding calculations. The conclusions and implications of this work are discussed last.

2. SIMDYN-OpenFAST Program

There are various tools available for evaluating the performance of FOWTs, with OpenFAST being the most widely used. OpenFAST is a multi-physics solver capable of simulating the coupled dynamic responses of FOWTs. It effectively models the interactions between wind turbines, wind, their supporting structures, and control systems. The OpenFAST framework encompasses several modules, each tailored to simulate different aspects of a wind turbine system. As a comprehensive toolset, OpenFAST enables users to investigate wind turbine performance across a range of scenarios. Its modular design allows for a focused analysis of specific subsystems, which can then be integrated for full-system simulations.

OpenFAST is comparable to other simulation tools such as FAST (its predecessor), ANSYS, Bladed, and OpenWind. However, it distinguishes itself by being open source, which fosters greater transparency and customization. Additionally, OpenFAST supports both land-based and offshore wind turbine systems, providing flexibility in the models it can integrate. Therefore, OpenFAST is an advanced tool designed for simulating the performance of wind turbines across a diverse array of conditions. With its flexibility, comprehensive capabilities, and high accuracy, OpenFAST has become an indispensable resource in the wind turbine industry.

Our research group extensively studied different model types using SIMDYN and verified its accuracy across various fields. Somayajula and Falzarano demonstrated the effectiveness of SIMDYN through an example of parametric roll simulation of a container ship [21], showcasing its ability to accurately analyze nonlinear time-varying phenomena. In a separate study, Jose coupled FAST with SIMDYN to study the classic instability of negative damping that occurs in FOWTs [22]. Additionally, Wang and Falzarano integrated SIMDYN with MAP to predict the motions of a wave energy converter with mooring lines [23].

In our current work, we have coupled SIMDYN with OpenFAST to examine the large amplitude platform motions of a semi-submersible floating wind turbine under extreme wind and wave loads. This involved replacing HydroDyn, a time-domain hydrodynamics module in OpenFAST, which offers hydrodynamic simulations specifically for offshore wind turbines, modeling the interaction between turbine platforms (such as floating structures) and water and incorporates the effects of wave motion, currents, and the platform's movement in its analysis. The modules are illustrated in Figure 1.

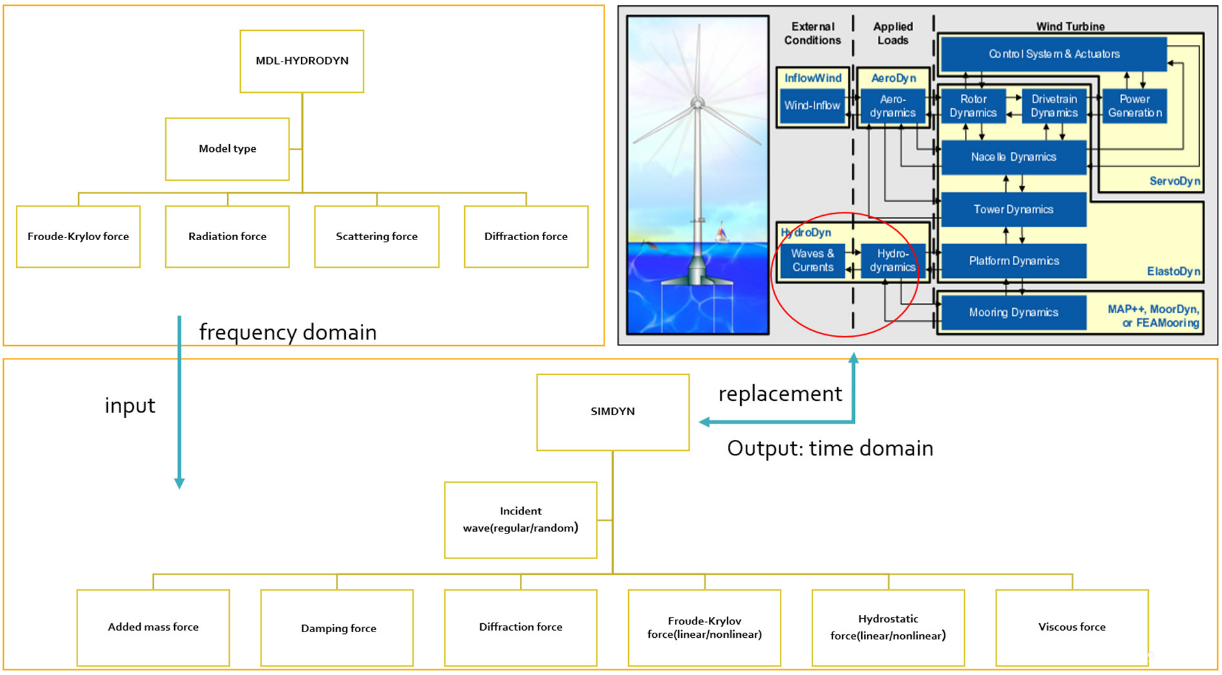


Figure 1. The modules of OpenFAST coupled with SIMDYN.

HydroDyn has the capability to calculate the linear hydrostatic force, added mass, and damping terms arising from linear wave radiation. The wave excitation term is derived from first- and second-order diffraction. In the context of SIMDYN, the real-time inertial force, damping force, hydrostatic force, and incident wave force can also be assessed. These forces are input into the SIMDYN-OpenFAST program, which then provides the acceleration at a subsequent time for the next calculation step. It is important to note that HydroDyn is based on the Wamit output, while SIMDYN relies on MDLHydroDyn [24], a research product developed by the Marine Dynamics Laboratory at Texas A&M University (College Station, TX, USA), and has been verified. SIMDYN-OpenFAST offers two calculation methods. The first is based on linear analysis, utilizing an algorithm similar to the HydroDyn module. This method will be used to verify the accuracy of our program against results from OpenFAST. The second method is based on nonlinear analysis, which will be the primary focus of this paper.

3. Theoretical Background

The general parameters of the semi-submersible platform are present in Table 1, and the model is shown in Figure 2.

Table 1. The semi-submersible platform general parameters.

Water Plane area (m^2)	368
Displacement (m^3)	13,464
Center of Buoyancy (z) (m)	−13
Center of Gravity (z) (m)	−5
Metacentric Height GM (m)	2
Water Depth (m)	320
Wave direction (deg)	180
Wave type	Regular/Random Wave
Depth of platform base below SWL (total draft) (m)	20
Elevation of main column (tower base) above SWL (m)	10
Diameter of main column (m)	6.5
Diameter of offset (upper) columns (m)	12
Diameter of base columns (m)	24

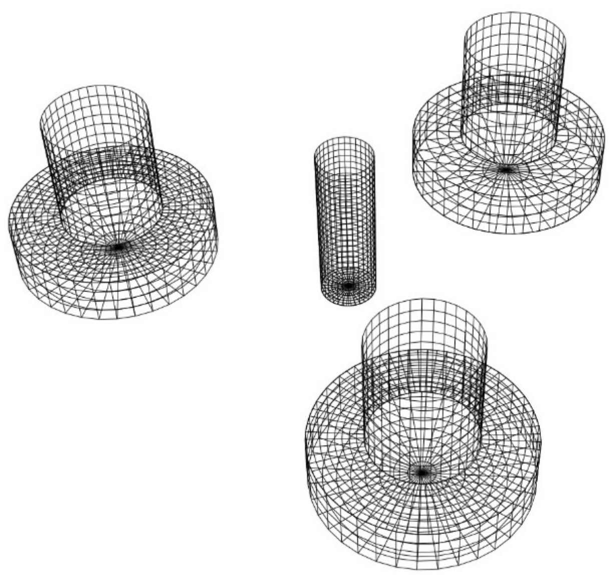


Figure 2. The semi-submersible platform model.

The frequency domain analysis is the first step in conducting a time domain analysis. The wave force and the radiation force are frequency dependent. We assume the fluid should be inviscid, incompressible, irrotational, and then we obtain the velocity potential as follows:

$$\varnothing(x,t) = \left(\varnothing_I(x,\beta,\omega_I) + \varnothing_D(x,\beta,\omega_I) + \sum_{j=1}^{6} \eta_j \varnothing_j(x,U,\omega_e) \right) e^{i\omega_e t} \quad (1)$$

where

$\varnothing_I$ is the incident wave potential;

$\varnothing_D$ is the diffracted wave potential;

$\varnothing_j$ is the radiation potential;

ω_e is the encounter frequency, which should be the same as wave frequency ω for FOWTs.

When we obtain the velocity potential, the hydrodynamic coefficients, added mass coefficients, and damping coefficients, can be given by the following:

$$A_{jk}^0 = -\frac{\rho}{\omega_e}\int Im(\varnothing_k)n_j\, ds \tag{2}$$

$$B_{jk}^0 = -\rho\int Re(\varnothing_k)n_j\, ds \tag{3}$$

Then, we obtain the nondimensional frequency domain properties of the semi-submersible shown in Figure 3 from MDLHydroDyn.

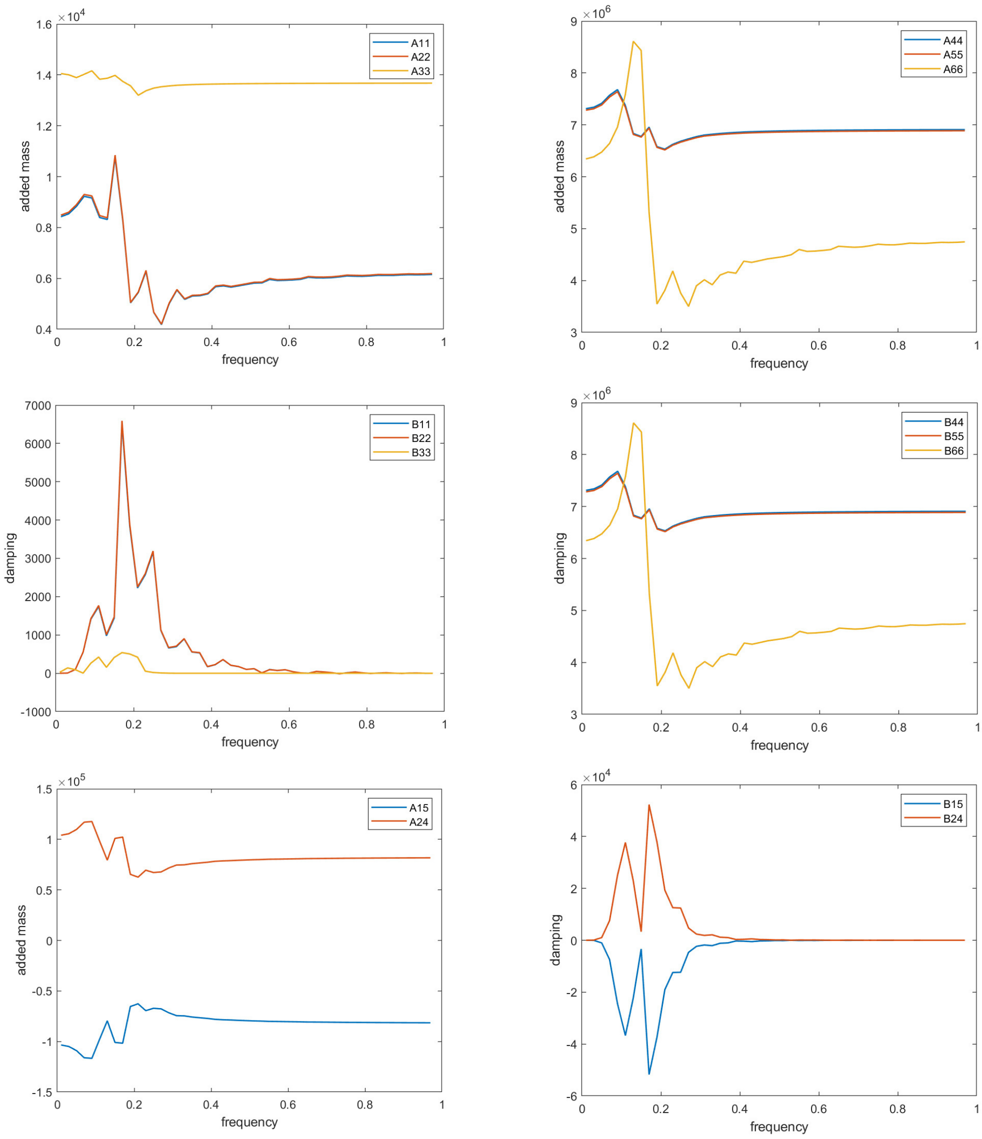


Figure 3. The nondimensional frequency domain of added mass and damping.

The governing equation for the whole system is the following:

$$(M + A)\ddot{x}(t) + \int_0^t K(t-\tau)\dot{x}(\tau)d\tau = F(t) \tag{4}$$

The motion vector x(t) represents the displacements of six degrees of freedom (DOF). M is the mass or inertia term, and A is the added mass or added inertia term. K is the damping term. $K(t-\tau)$ is the memory kernel, which is related to the radiation damping and restoring forces of the system. F(t) represents the external forces and moments, including hydrodynamic loads from waves and aerodynamic loads from wind, acting on the FOWT. The main loads applied to the system are hydrodynamic loads and wind loads. The hydrodynamic load consists of diffraction force and Froude–Krylov force induced by incoming waves. The total force in the hydrodynamic system can be expressed as follows:

$$F_{total} = F_{\mathrm{FK}} + F_{diffraction} + F_{radiation} + F_{viscous} + F_{restoring} + F_{scattering} \tag{5}$$

The radiation forces are created by the motion of the floating body, which makes waves. The viscous forces are generated by the fluid's viscosity (seawater). The restoring forces are caused by the difference in the weight and buoyancy and the effect of the mooring system. The linear radiation and scattering forces are obtained from MDLHydroDyn. Based on the instantaneous position and orientation, the nonlinear Froude–Krylov forces, the nonlinear hydrostatic forces, and the nonlinear inertial forces can be computed.

For this paper, we calculated the nonlinear hydrodynamic forces and Froude–Krylov forces by SIMDYN, incorporating Wheeler stretching up to the instantaneous position and orientation. The underwater pressure is given by the following:

$$p(t,x,y,z) = -\rho\frac{\partial\varnothing_I}{\partial t}(t,x,y,\hat{z}) - \frac{\rho}{2}|\nabla\varnothing_I(t,x,y,\hat{z})|^2 \tag{6}$$

where

$$\hat{z} = z - \eta(t,x,y) \leq 0$$

The first term is the linear term, and the second term is the nonlinear term. The forces and moments are obtained by integration of the pressure over the instantaneous wetted surface area S_B:

$$F_I(t) = \int P(t,x,y,z)\cdot\boldsymbol{n}dS \tag{7}$$

$$M_I(t) = \int P(t,x,y,z)\cdot(\boldsymbol{x}\times\boldsymbol{n})dS \tag{8}$$

The frequency domain program calculates the scattering wave force based on the wave force RAO. The Fourier transform of the incident wave is used to obtain the force in the time domain. In the case of a single-wave excitation frequency, the radiation force has two components, one due to the added mass and the other due to radiation damping.

$$F_{radiation} = -A(\omega)\ddot{x} - B(\omega)\dot{x} \tag{9}$$

Restoring forces are obtained using the instantaneous buoyancy and weight of the platform.

$$F_{restoring} = \int -\rho g z\cdot\boldsymbol{n}dS + \boldsymbol{W} \tag{10}$$

$$M_{restoring} = \int -\rho g z\cdot(\boldsymbol{x}\times\boldsymbol{n})dS + (\boldsymbol{x_G}\times\boldsymbol{W}) \tag{11}$$

In order to calculate the viscous force, the Morison equation is used, which is the most important part of damping forces.

4. Simulation Results and Discussion

4.1. The Program Verification

In this paper, we will start by applying the random wave without wind load; the significant wave height is 5 m, and the wave period is 7 s. The results are presented in Figures 4–7.

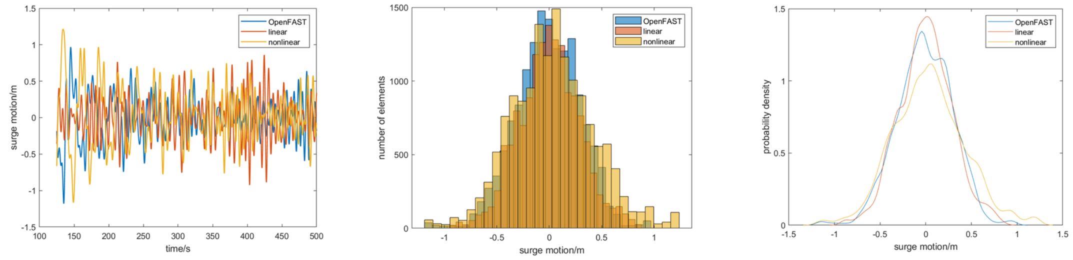


Figure 4. The response of the surge motion.

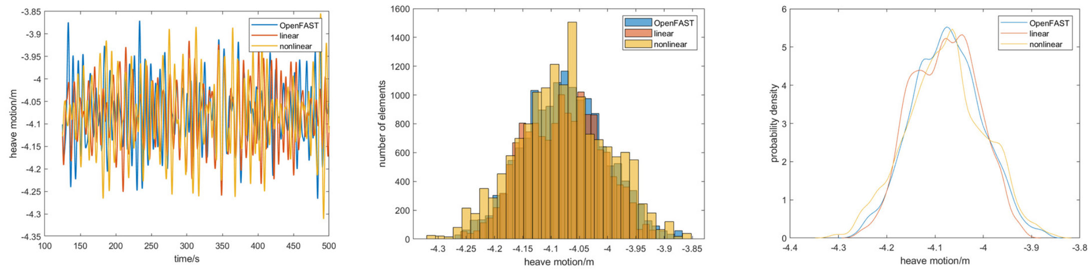


Figure 5. The response of the heave motion.

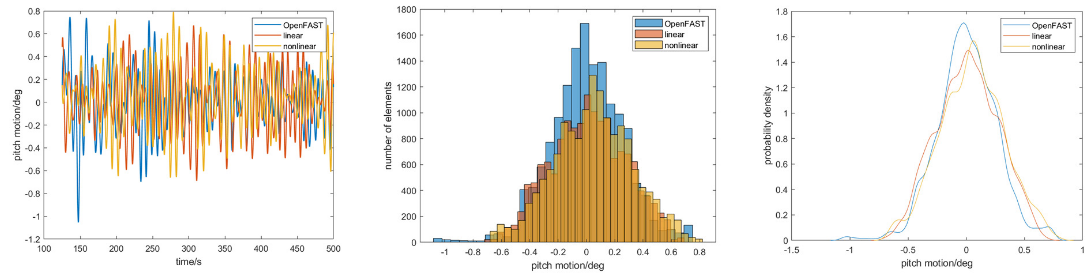


Figure 6. The response of the pitch motion.

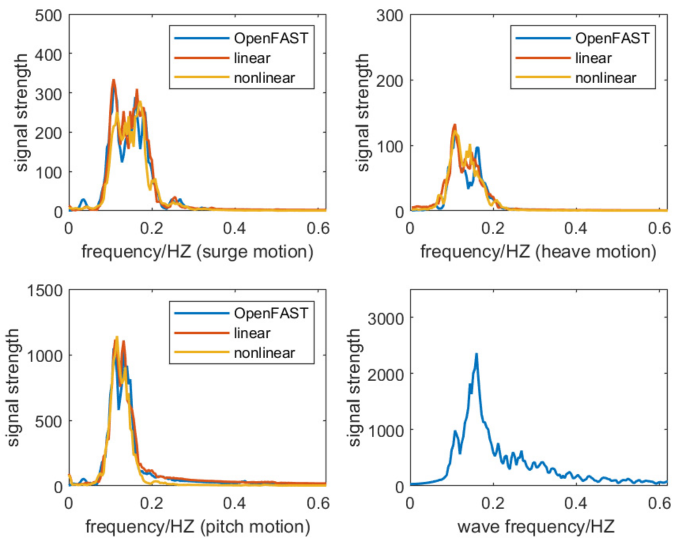


Figure 7. The response in the frequency domain.

Then, we apply regular waves to the platform, as these waves can accurately estimate much of the platform's response and serve as a clear benchmark for assessing the accuracy of the simulation. In our test model, we examine a typical scenario where the wave height is 10 m, and the wave period is 7 s. The results are presented in Figure 8.

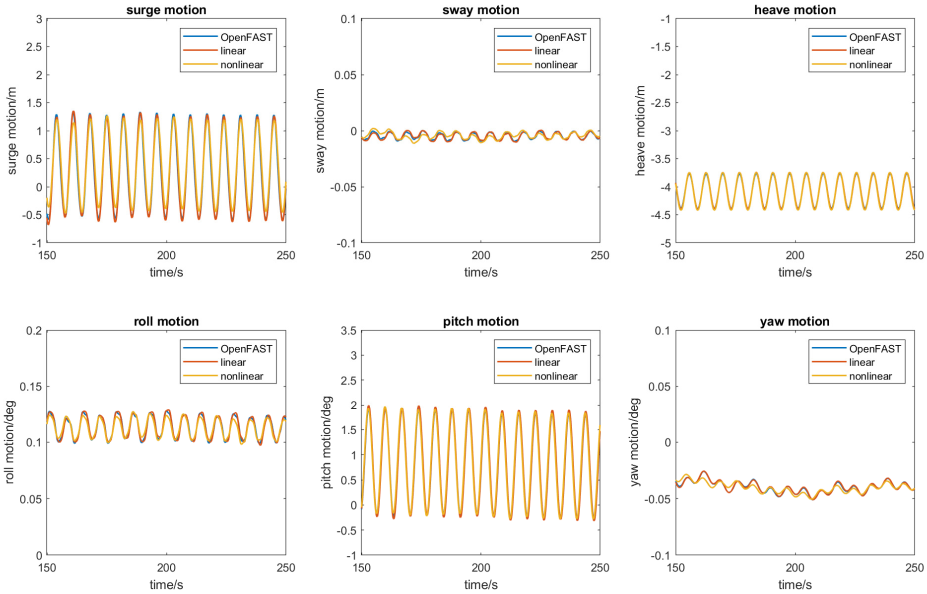


Figure 8. A comparison of the results of OpenFAST and OpenFAST coupled with SIMDYN.

From Figure 6, it is obvious that, for random cases, the motions' range generated by OpenFAST and the linear and nonlinear modules of SIMYDYN-OpenFAST are the same, and the distributions are very similar. Random cases cannot be entirely consistent, not only because of the randomness of the external loads but also because of the nonlinearity of the system, including the interactions from other modules. The program is capable of accurately predicting response ranges in all directions. Additionally, frequency domain analysis reveals that the majority of responses from the three methods fall within the same frequency range, which can be obtained from Figure 7. However, due to the limitations of the Fast Fourier Transform (FFT), converting non-stationary motions from the time domain to the frequency domain in a nonlinear system lacks precision, which means that the results from the three methods cannot be identical. To enhance clarity in our study, we utilized a filtering technique to minimize noise, leading to a smoother dataset. The close clustering of most response peaks is quite evident. Furthermore, we have included the wave amplitude in the frequency domain as a reference to support the responses of those motions. To fully explore the nonlinear characteristics of the response—such as the bifurcation diagram, chaos, or the nonlinear magnification curve—our current analysis cannot delve deeply into these aspects due to the numerous nonlinear relationships present in the system, which also introduce various noises. While we can employ filters to smooth the data, it is important to note that this process may obscure certain "special cases" arising from these nonlinear relationships. Therefore, at this stage, we can only ascertain the range of frequencies involved. For a more thorough investigation into the nonlinear characteristics, it would be advantageous to analyze specific motions or pairs of coupled motions independently [25]; however, this falls outside the current scope of our work, which should be categorized under nonlinear dynamic control theory; more details can be found in Ref [26].

To illustrate our findings clearly, we also perform a regular case study; the results are shown in Figure 8. The responses in six directions are very closed, especially the results from OpenFAST and the linear module of SIMDYN-OpenFAST, and there are some 'coupled errors', which are very small and can be ignored. The nonlinear module differs slightly from other results due to the different calculation theories, which we explained in Section 2.

From the above analyzed cases, we observe that, when platform motion is minimal, there is no significant difference between the results generated by OpenFAST and the linear and nonlinear modules of SIMYDYN-OpenFAST. This observation aligns with our previous research on response analysis in ships [21], barges [22], and wave energy converters [23]. These figures highlight the accuracy of our program and validate the consistency between OpenFAST and the linear module of SIMYDYN-OpenFAST. Furthermore, it indicates that, when wave loads remain within normal ranges, nonlinear forces do not significantly impact the calculations due to the relatively small variations in instantaneous positions. Since the sway, roll, and yaw responses are so small, they will not be discussed in this paper.

4.2. The Impacts of Nonlinear Forces

In order to examine the impacts of the nonlinear forces, extreme conditions are applied. Table 2 outlines several extreme wave conditions that will serve as the reference points for this study.

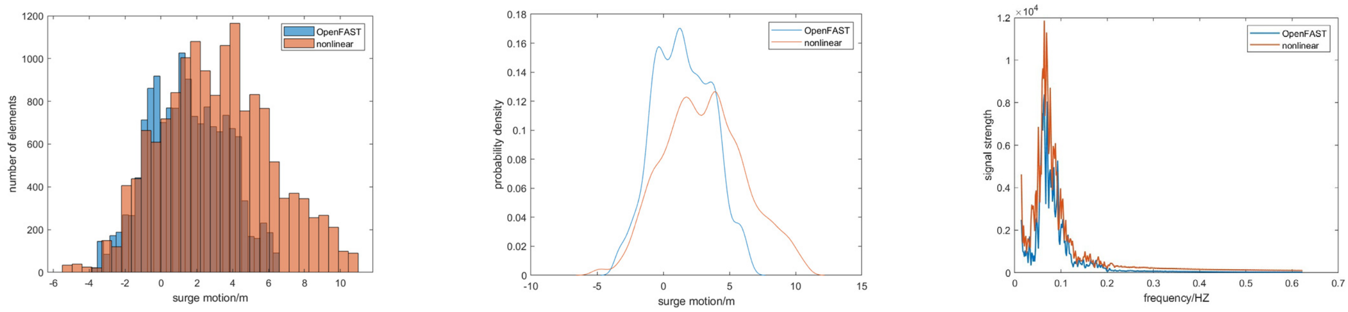
Table 2. The wave heights and periods corresponding to different hurricanes.

Hurricanes Name	Fran	Lili	Georges	Floyd
Wave height(m)	11.64	11.20	10.88	14.20
Periods (s)	14.29	13.25	13.2	15.4

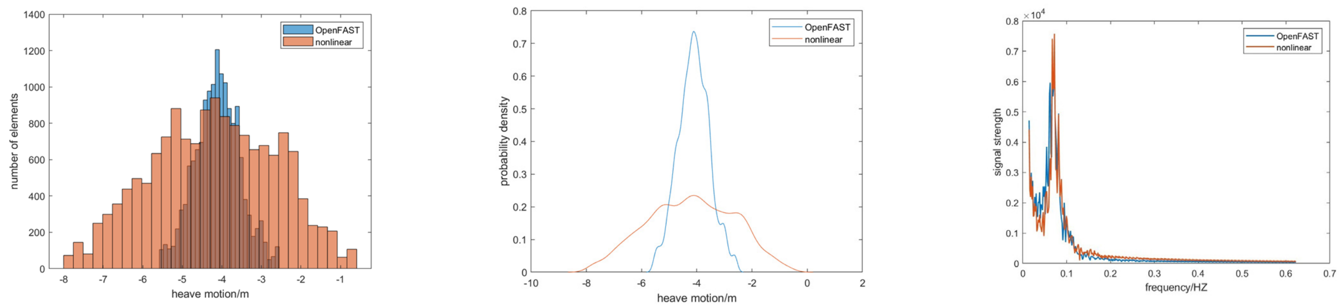
In the random case analyzed, the significant wave height is measured at 15 m, with a wave period of 14 s. The random wind generated by TurbSIM v2 [27] has an average speed of 18 m/s. The results are presented in Figure 9. We chose to conduct the random case first, as it holds greater significance in real-world scenarios. It is evident that the range of responses is larger in nonlinear situations. The surge direction response remains relatively unchanged compared to the other directions due to the mooring system. As external random loads increase, the heave response becomes larger, and the pitch angle tilts more in the load direction, which is expected. However, such phenomena are not identifiable in linear modes. We also performed a frequency domain analysis, as completed previously, to determine if there were any notable frequencies that might impact our platforms. In our case, we did not observe any. However, other notable frequencies could arise in other scenarios, contingent on the relevant design factors of the system.

We then examine a regular wave with a height of 13 m, a period of 14 s, and a consistent wind speed of 18 m/s. The results are depicted in Figure 10. The trends observed are quite similar to those in the random case. In the time domain, it is evident that, in the surge motion, the response did not change much, and the responses in the heave and pitch motions became larger.

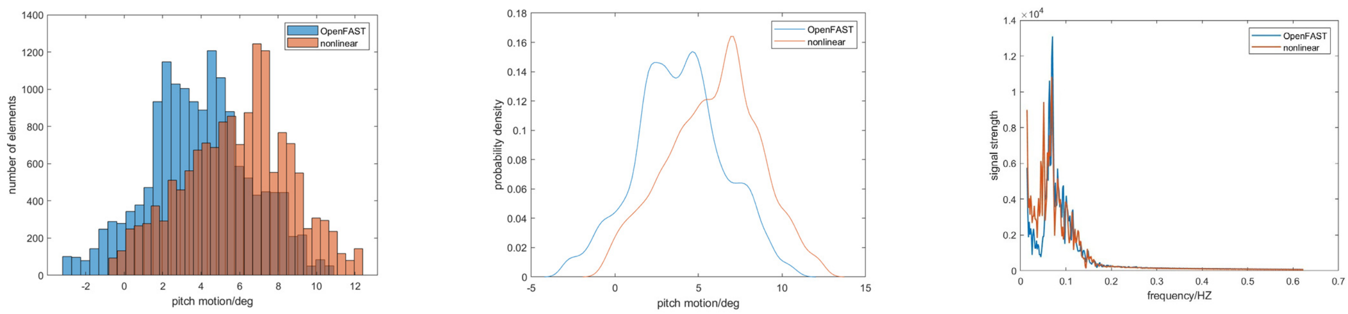
Therefore, the results from the random and regular load cases indicate that the primary responses of concern are heave and pitch. These two motions are closely coupled during instantaneous calculations, which highlights the importance of nonlinear forces, especially when the motion amplitude is large under extreme conditions.



(**a**)



(**b**)



(**c**)

Figure 9. A comparison of the results of OpenFAST and OpenFAST coupled with SIMDYN. (**a**) Responses in surge direction. (**b**) Responses in heave direction. (**c**) Responses in pitch direction.

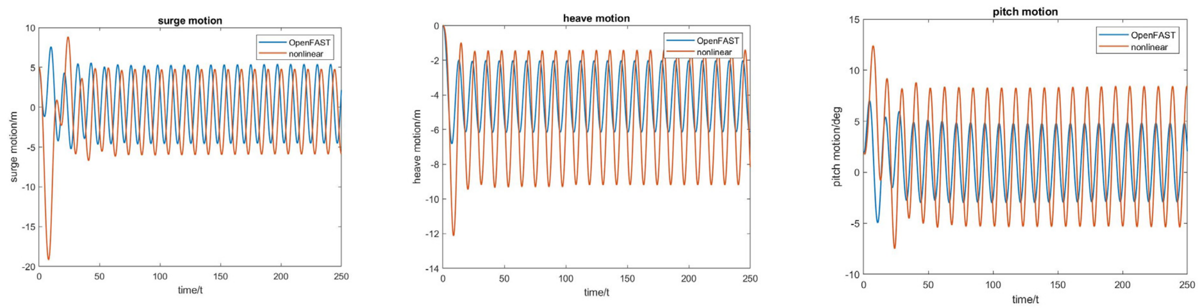


Figure 10. A comparison of the results of OpenFAST and OpenFAST coupled with SIMDYN.

4.3. The Reason Discussion

The nonlinearity arises from both the Froude–Krylov force and the restoring force. To assess which of these forces plays a more significant role in the overall nonlinear behavior, we conducted a probability density estimate; using a normal kernel function helps to estimate the probability distribution of a set of data points. This method is part of the Kernel Density Estimation (KDE), which is a way to estimate the probability density function (PDF) of a random variable without making specific assumptions about the data. In this method, a normal distribution, also known as a Gaussian kernel, is placed at each data point. These normal distributions are then added together to create a smooth estimate of the overall distribution. The results of this analysis are presented in Figures 11 and 12.

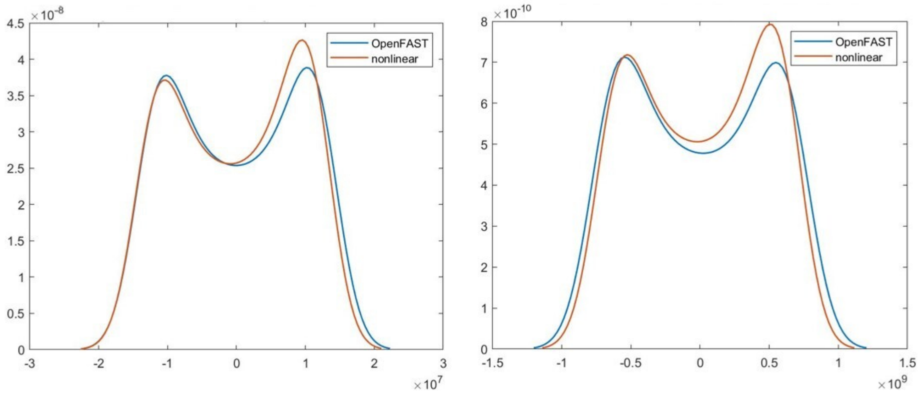


Figure 11. A comparison of the density estimate for the Froude–Krylov force in heave and pitch directions. Note: *x* axis presents Froude–Krylov force; *y* axis presents probability density.

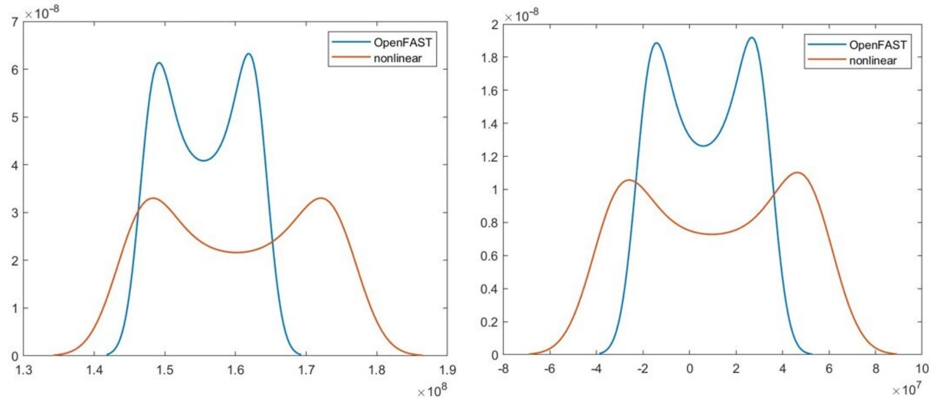


Figure 12. A comparison of the density estimate for the hydrostatic force in heave and pitch directions. Note: x axis presents hydrostatic force; y axis presents probability density.

Figures 11 and 12 show the distributions of the Froude–Krylov force and hydrostatic force from different methods. It is evident that the force distributions for the Froude–Krylov force from both methods are quite comparable, especially in contrast to the findings related to the hydrostatic force. Notably, the range of the nonlinear hydrostatic force is considerably broader than that of the linear method's results. Moreover, as shown in Figure 10, the range of the heave motion is substantial, suggesting that the amplitude of the platform's instantaneous buoyancy and weight varies considerably during nonlinear analysis. This likely explains why the primary contributor to nonlinearity in these cases is the force associated with nonlinear hydrostatics. In contrast, while the nonlinear Froude–Krylov force increases, the symmetry of the platform results in minimal changes to the instantaneous wetted surface. However, for asymmetric platforms, greater attention should be given to the nonlinear Froude–Krylov force.

To stabilize the platform's motion during large amplitude movements, it is essential to enhance the restoring force. One effective approach is to increase the wetted surface area while maintaining the positions of the centers of gravity and buoyancy to stabilize the heave motion. When subjected to large amplitude motion, the instantaneous buoyancy does not change significantly, which can help reduce the impacts of the nonlinear restoring force. Our team has previously developed an optimization framework utilizing genetic algorithms for the automated parametric optimization of the Octabuoy semi-submersible design [28]. In light of this recommendation, we present one of the optimization methods from an engineering perspective, deliberately omitting any economic analysis.

4.4. Optimization Method for Large Amplitude Platform Motion

The model is shown in Figure 13, and the general parameters are listed in Table 3.

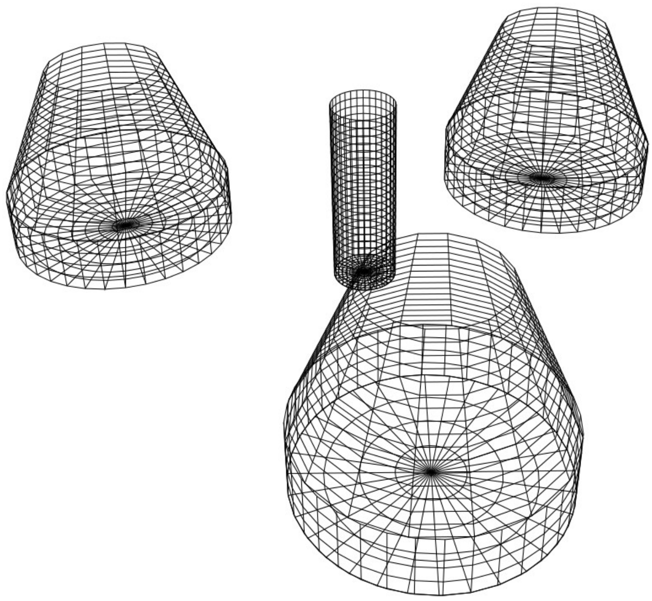


Figure 13. The optimized model.

Table 3. General parameters of the optimized platform.

Water Plane area(m^2)	368
Displacement(m^3)	19,986
Center of Buoyancy (z) (m)	−12
Center of Gravity (z) (m)	−5
Metacentric Height GM (m)	0.82
Water Depth (m)	320
Wave direction (deg)	180
Wave type	Regular wave
Depth of platform base below SWL (total draft) (m)	20
Elevation of main column (tower base) above SWL (m)	10
Diameter of main column (m)	6.5
Diameter of offset (upper) columns (m)	12
Diameter of base columns (m)	24

Then, we obtain the nondimensional frequency domain properties of the new model shown in Figure 14 from MDLHydroDyn.

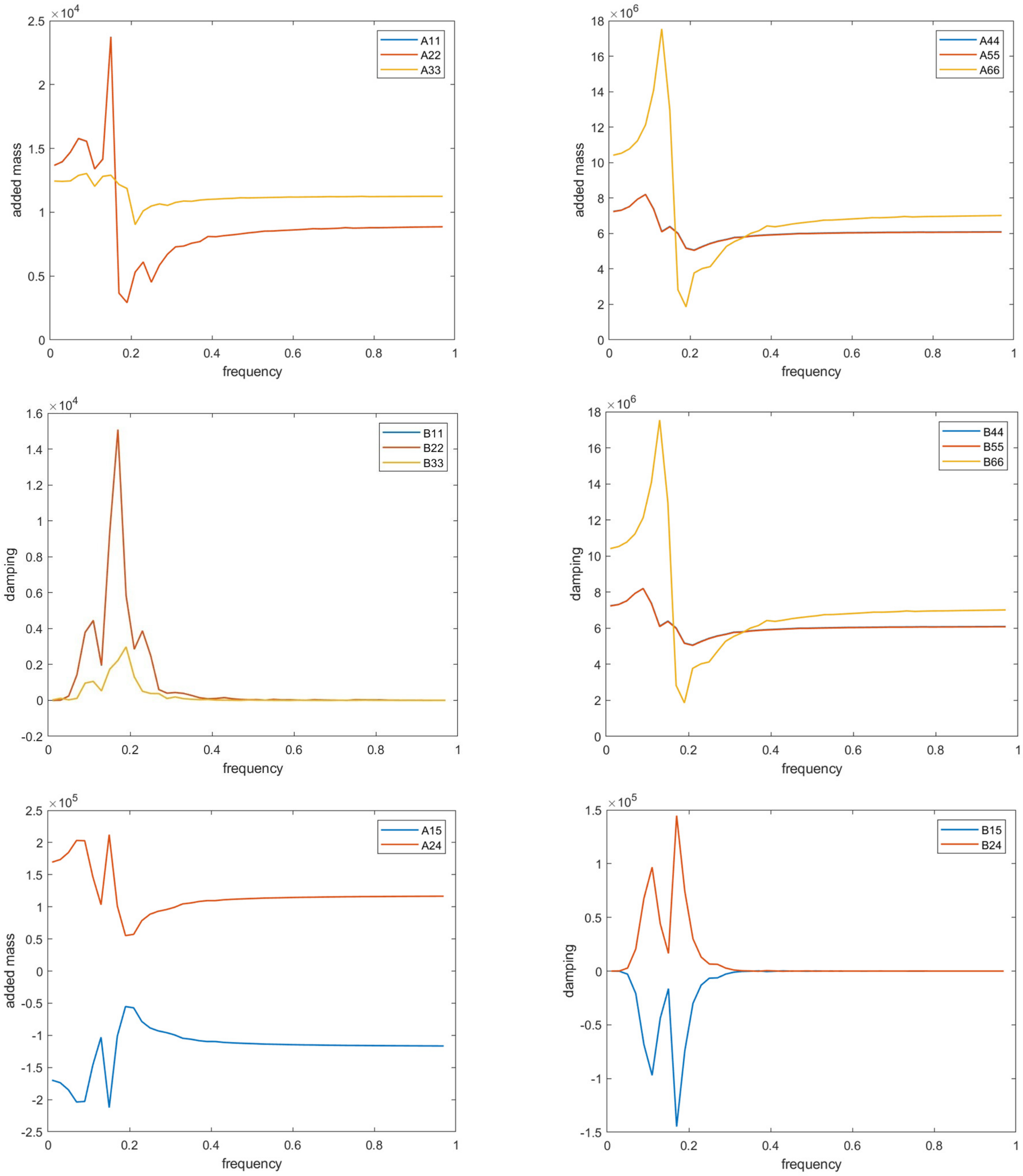


Figure 14. Nondimensional frequency domain of added mass and damping of the new model.

We utilized SIMDYN-OpenFAST and applied identical environmental conditions to the platform, with a wave height of 15 m and a wave period of 14 s. The wind speed is constant at 18 m/w. The resulting data are presented in Figure 15. It shows that the range of the responses in the heave and pitch directions becomes smaller. Our findings indicate that increasing the wetted surface area or enhancing the displacement volume, while maintaining other parameters constant and stabilizing the instantaneous buoyancy location, helps to mitigate the nonlinear effects of hydrostatic forces, particularly in the heave and pitch directions. However, there are limitations, particularly with the increased wet surface area, which introduces new requirements for materials, budget, the fabrication and installation teams. Additionally, optimizing the platform is not easy because we should consider other modules of the FOWTs, like the impacts on the mooring system. So, it is important to note that this revised model offers a design concept for platform optimization; we have not taken into account any additional factors. Additionally, there is a simpler approach to utilizing the control system to stabilize the instantaneous center of buoyancy, but this aspect belongs to control theory, which we will not address in our paper.

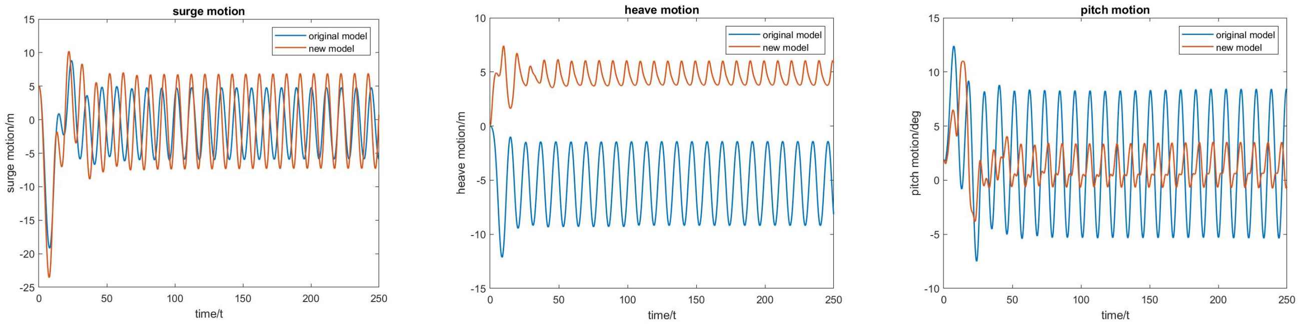


Figure 15. A comparison of the results of the original model and optimized model.

5. Conclusions

This paper examines the responses of a semi-submersible under extreme conditions through the coupled program SIMDYN-OpenFAST, which is designed to estimate the motion of floating offshore wind platforms in both linear and nonlinear contexts, particularly when subjected to varying wind and wave loads. The important results are as follows:

Under normal conditions, when the motion of a semi-submersible is characterized by small amplitudes, the impact of nonlinear forces—specifically the Froude–Krylov force and restoring force—remains minimal in the calculations.

When the amplitudes increase, these nonlinear forces significantly influence the platform's motion, especially in the heave and pitch directions.

Nonlinear hydrostatic forces are primarily responsible for the disparities observed when comparing linear and nonlinear scenarios.

To mitigate the nonlinear effects of hydrostatic forces, one approach is to stabilize the instantaneous buoyancy center to increase the wetted surface area or the displacement volume.

An optimized platform model has been provided that outperforms the original semi-submersible design, leading to a significant reduction in oscillation amplitude. But, it is important to note that this model does not take into account installation or economic considerations, serving primarily as a preliminary design that can be refined for future applications, particularly as environmental conditions or wind blade lengths change.

In this study, no resonance phenomena resulting from nonlinear forces were observed. However, it is possible for such phenomena to occur in extreme circumstances when the frequency of the platform aligns with that of the nonlinear forces. Furthermore, the presence of several modes may contribute to a larger platform's motion.

Therefore, understanding the nonlinear forces acting on floating offshore wind platforms is crucial for ensuring their safety and reliability. Extreme external loads, such as significant waves, wind gusts, and unpredictable environmental factors, can impose substantial forces on these structures. Investigating the nonlinear responses is essential for developing designs capable of withstanding and adapting to these severe conditions, thereby minimizing the risk of structural failure. This study can serve as a valuable reference for platform design, particularly in extreme conditions or when dealing with significant platform motions. During the design phase, especially when large-scale and costly experiments are impractical, it is advisable to analyze extreme conditions to identify performance limitations. It is important to consider the effects of nonlinear forces in such analyses. Furthermore, this study can inform the development of control systems, such as negative feedback control, to stabilize platform motion under challenging conditions. Ultimately, this research offers insights into mitigating the impact of nonlinear forces on the platform, proving beneficial not only for semi-submersible designs but also for spar platforms and other floating platforms.

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