

Effect of Nacelle Motions on Rotor Performance and Drivetrain Dynamics in Floating Offshore Wind Turbines Using Fully Coupled Simulations

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Abstract

This study investigates the effect of nacelle motions on the rotor performance and drivetrain dynamics of floating offshore wind turbines (FOWTs) through fully coupled aero–hydro–elastic–servo–mooring simulations. Using the National Renewable Energy Laboratory 5 MW monopile-supported offshore wind turbine and the OC4 DeepCwind semisubmersible wind turbine as case studies, the research addresses the complex dynamic responses resulting from the interaction among wind, waves, and turbine structures. Detailed multi-body dynamics models of wind turbines, including drivetrain components, are created within the SIMPACK framework. Meanwhile, the mooring system is modeled using a lumped-mass method. Various operational conditions are simulated through five wind–wave load cases. Results demonstrate that nacelle motions significantly influence rotor speed, thrust, torque, and power output, as well as the dynamic loads on drivetrain components. These findings highlight the need for advanced simulation techniques for the design and optimization of FOWTs to ensure reliable performance and longevity.

Keywords Drivetrain; Coupled simulation; Monopile wind turbine; Semisubmersible platform; Nacelle motion

1 Introduction

Offshore wind farms present various benefits compared with onshore installations, such as stronger and more stable wind resources, larger installation areas, and minimal disruption to local populations (Danovaro et al., 2024; Yang et al., 2019; Hong et al., 2024; Zhou et al., 2023a). As a result, the focus on the deployment of wind turbines is increasingly shifting from land to sea. However, many promising offshore wind energy resources are found in waters deeper than 60 m (Jonkman, 2007), where fixed platform installations are prohibitively costly (Sclavounos et al.,

2008). This situation has led to the development of floating offshore wind turbines (FOWTs), such as spar, barge, and tension-leg platform wind turbines (Grant et al., 2023; Zhou et al., 2023b; Edwards et al., 2024), which can capture wind energy in deep waters.

Floating platforms introduce new engineering challenges, particularly regarding the dynamic responses of wind turbine structures and the design of drivetrain components. The dynamic behavior of FOWTs is more complex than that of bottom-fixed wind turbines due to the coupling effects of wind and wave loads, substantial rotor angular displacements, and gyroscopic effects (Sweetman and Wang, 2012). Advanced aero–elastic tools, including FAST (El Beshbichi et al., 2023), GH Bladed (Xing et al., 2023), and HAWC2 (Alhrshy et al., 2023), can simulate the global dynamic responses of offshore wind turbines under various environmental conditions. FAST (El Beshbichi et al., 2023), which is an open-source software developed by the National Renewable Energy Laboratory (NREL), is widely used in academic and industry research due to its flexibility and capability to simulate aero–hydro–servo–elastic responses in wind turbines, such as floating platforms. FAST is highly customizable, which makes it ideal for integrating user-defined modules. However, its drivetrain modeling capabilities are less detailed than SIMPACK’s multi-body system approach. FAST is highly suitable for coupled simulations that involve wind, wave, and turbine

Article Highlights

- A fully-coupled aero-hydro-elastic-servo model of wind turbines with a detailed drivetrain is created.
- The effect of nacelle motions on rotor performance and drivetrain dynamics of wind turbines are studied.
- Finds indicates that the nacelle motion can greatly influence the standard deviations of tooth contact forces.

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interactions, but its representation of the drivetrain components remains relatively simplified. GH Bladed (Xing et al., 2023) is a widely utilized commercial software specifically designed for the wind industry. It offers a robust platform for simulating the aerodynamic, structural, and control system interactions of onshore and offshore wind turbines. While GH Bladed is often employed for the certification and fatigue analysis of wind turbines, it focuses primarily on the global response of the entire turbine system; thus, it offers less detailed modeling of drivetrain dynamics than SIMPACK (SIMPACK, 2020). HAWC2 (Alhrshy et al., 2023) is an advanced aero–elastic code that focuses on simulating the dynamic behavior of wind turbine structures, particularly in offshore and floating platform applications. It advances sophisticated models for analyzing the structural responses of wind turbines under combined wind and wave loads. Similar to GH Bladed and FAST, HAWC2 excels in the global simulation of wind turbine dynamics but falls short in performing detailed drivetrain component analysis. The software mainly focuses on structural behaviors, with less emphasis on drivetrain dynamics than SIMPACK’s capabilities.

SIMPACK (SIMPACK, 2020) is an advanced multi-body simulation (MBS) software that is extensively used in analyzing and optimizing dynamic mechanical systems, including wind turbines. Although SIMPACK was initially developed for sectors such as automotive and rail, it has been effectively adapted for the wind energy industry, where it plays a critical role in simulating the dynamic responses of wind turbine components under various operating conditions. SIMPACK can offer comprehensive tools for the dynamic modeling and simulation of wind turbine drivetrains. These tools allow engineers to analyze their performance under various operating conditions with a high degree of accuracy. A key feature of SIMPACK in drivetrain modeling is its capability to simulate the drivetrain as a complex multi-body system. Each component can be modeled as either a rigid or a flexible body. This flexibility in modeling is essential for capturing the true dynamic behavior of the drivetrain, especially considering the significant deformations and stresses that components experience under operational loads. The capability of SIMPACK software to model flexible bodies is particularly important for the drivetrain (Guo et al., 2013) because it allows for detailed analysis of components like shafts. These components can undergo bending and torsional vibrations due to varying wind loads and mechanical interactions within the system. SIMPACK also excels in modeling the interactions among different drivetrain components. For example, it can simulate the nonlinear contact interactions between gear teeth in the gearbox or the coupling effects between the rotor and generator. This level of detail is essential for precisely predicting the dynamic loads and stress distributions throughout the drivetrain, which in turn is vital for

fatigue analysis and lifecycle prediction of the components.

Current industry standards for gearbox design depend on global loads at the hub, with load spectra and equivalent loads used for component-level design as outlined by DIN 3 990 (DIN, 1987) and DIN ISO 281 (DIN, 2007). However, the lack of detailed dynamic load information at the component level limits comprehensive assessments of adverse load conditions. The growing size and flexibility of modern wind turbines further complicate drivetrain dynamics, which causes difficulty in designing high-quality components using traditional tools. Consequently, more advanced modeling methods need to be developed.

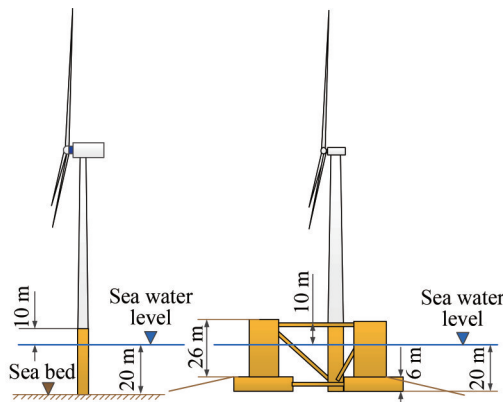
This study investigates the nacelle motions of the OC4 semisubmersible floating wind turbine, which is widely utilized for load verification and structural control research (Wang et al., 2024; Xue et al., 2024; Tian et al., 2024; Hu and He, 2017; Lian et al., 2023; Ding et al., 2019). While previous research primarily focused on global structural responses, this study emphasizes the dynamic response characteristics of drivetrain components in FOWTs. By using fully coupled aero–hydro–elastic–servo–mooring simulations, this research aims to provide a more detailed understanding of the effect of nacelle motions on rotor performance and drivetrain dynamics.

The rest of the paper is structured as follows. Section 2 introduces the assessed wind turbine systems. Section 3 details the development of fully coupled aero–hydro–elastic–servo–mooring simulation models for two wind turbines. Section 4 presents five selected wind–wave load cases for simulation. Section 5 provides the results and analyses of the simulations. Section 6 elaborates the conclusions and presents the findings.

2 Description of the wind turbine system

2.1 Offshore wind turbine

In this study, the NREL 5 MW monopile-supported offshore wind turbine (Jonkman et al., 2009) and the OC4 DeepCwind semisubmersible wind turbine (Robertson et al., 2014a) are studied as representatives of fixed-pile wind turbines and FOWTs, respectively. Figure 1 illustrates the schematic of the two wind turbines. The NREL 5 MW baseline wind turbine is installed atop both foundations. For the fixed-pile wind turbine, the tower is mounted on the monopile with a rigid foundation. The tower base begins at an elevation of 10 m above mean sea level (MSL), with the monopile extending from the tower base down to the seafloor at 20 m below MSL. For the OC4 DeepCwind wind turbine, the platform has a draft of 20 m, and the tower is cantilevered at an elevation of 10 m above MSL to the top of the main column of the platform.



(a) Bottom-fixed wind turbine (b) Semisubmersible wind turbine

Figure 1 Schematic of two offshore wind turbine models

2.2 Mooring line system and dynamics

The semisubmersible platform is secured using three catenary lines, which are symmetrically distributed around the Z-axis of the platform. The layout and characteristics of the mooring line system are shown in Figure 2 and Table 1.

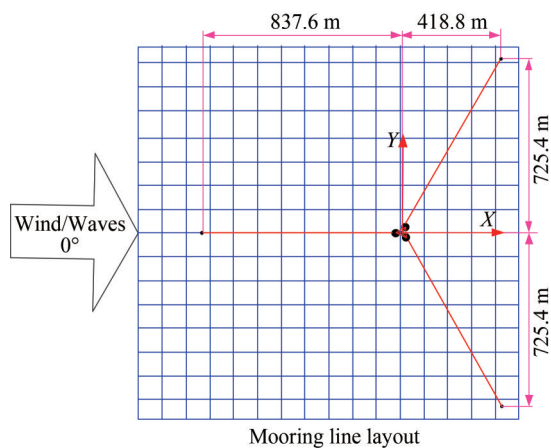


Figure 2 Layout of the mooring system

Table 1 Properties of the mooring lines

Number of mooring lines	3
Angle between adjacent lines (°)	120
Depth to anchors below MSL (m)	200
Depth to fairleads below MSL (m)	14
Radius to anchors from platform centerline (m)	837.6
Radius to fairleads from platform centerline (m)	40.868
Unstretched mooring line length (m)	835.35
Mooring line diameter (m)	0.076 6
Equivalent mooring line mass density (kg/m)	113.35
Equivalent mooring line extensional stiffness (N)	7.536×10^8

In this work, the mooring lines are modeled using a lumped-mass method (Hall, 2015), which discretizes a

continuous mooring line into a finite number of interconnected segments, each represented by a node, as shown in Figure 3. In this method, the mooring line is divided into N segments, which result in $N+1$ nodes. Each node i has a position vector $\mathbf{r}_i$, which includes its x , y , and z coordinates. The internal axial force $\mathbf{F}_{\text{axial}}$ between two adjacent nodes i and $i+1$ is determined by the axial stiffness k_{axial} and the axial damping coefficient c_{axial} (Hall, 2015):

$$\mathbf{F}_{\text{axial}} = k_{\text{axial}} \left(\frac{\mathbf{r}_{i+1} - \mathbf{r}_i}{|\mathbf{r}_{i+1} - \mathbf{r}_i|} \right) (|\mathbf{r}_{i+1} - \mathbf{r}_i| - L_0) + c_{\text{axial}} \left(\frac{d(\mathbf{r}_{i+1} - \mathbf{r}_i)}{dt} \right) \quad (1)$$

where L_0 is the unstretched length of the segment. External forces acting on the mooring line encompass hydrodynamic forces, weight, and buoyancy. The hydrodynamic force $\mathbf{F}_{\text{hydro}}$ on node i is calculated using Morison's equation (Morison et al., 1950):

$$\mathbf{F}_{\text{hydro}} = \frac{1}{2} \rho C_d A \left(\mathbf{u} - \frac{d\mathbf{r}_i}{dt} \right) \left| \mathbf{u} - \frac{d\mathbf{r}_i}{dt} \right| \quad (2)$$

where ρ is the fluid density, C_d is the drag coefficient, A is the cross-sectional area, and $\mathbf{u}$ is the fluid velocity. For nodes in contact with the seafloor, additional contact forces are modeled to prevent penetration and account for frictional effects.

2.3 Drivetrain model

In this study, an advanced drivetrain model is developed using the MBS tool SIMPACK (SIMPACK, 2020), as presented in Figure 4. This model is composed of a main shaft, a high-speed gearbox, a coupling, and a generator. The high-speed gearbox features two planetary stages and one parallel stage, with the first and second stages employing four and three planet gears, respectively. The gears are represented as rigid bodies with tooth compliance. The coupling, which is designed to accommodate parallelism and angular deviations between the gearbox and generator, is modeled with four rigid bodies and three torsional springs. The generator encompasses a rotor and a stator, which are modeled as rigid bodies. Notably, a feedback torque is applied between the stator and rotor.

2.4 Control system

A variable-speed, variable-pitch baseline wind turbine control system, which was proposed by Jonkman et al. (2009), is applied to control the wind turbine operation. This control system includes a torque controller alongside a collective pitch controller, each operating independently within distinct operational regions of the monopile offshore

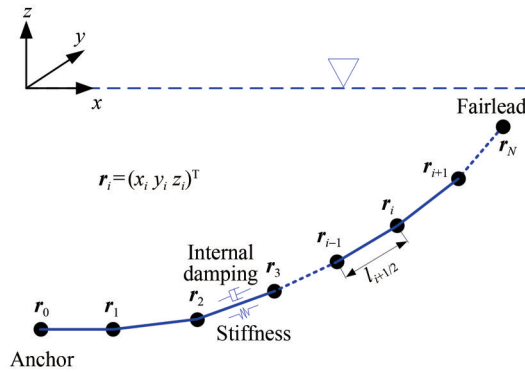


Figure 3 Mooring line discretization

wind turbine, as illustrated in Figure 5. The operational regions are divided into five parts based on generator speed (Jonkman et al., 2009; Robertson et al., 2014a; Xie et al., 2024). In Region 1, which falls below the cut-in wind speed, the wind accelerates the rotor to start the wind turbine startup, which results in zero torque and no power output. Region 1 1/2 is a linear transition between Region 1 and Region 2. Within Region 2, the generator torque is proportional to the square of the generator speed to maximize wind energy capture. Similarly, Region 2 1/2 is a linear transition from Region 2 to Region 3. In Region 3, which occurs above the rated wind speed, the generator torque is inversely proportional to generator speed to ensure a consistent power output. When the turbine operates above-rated conditions, the pitch controller adjusts the pitch angles of the blades. This controller uses a gain-scheduled propor-

tional-integral controller based on the speed error between the filtered and rated generator speed.

However, a conventional pitch-to-feather control approach in wind turbines leads to a decrease in steady-state rotor thrust as wind speed rises beyond the rated level. As highlighted by Nielsen et al. (2006), this effect may induce negative damping within the system, which potentially results in significant resonant motions in a floating offshore wind turbine. The analyses highlight the importance of maintaining positive and maximized damping for the platform-pitch mode.

Adjustments are introduced to the monopile wind turbine control system for its application to the semisubmersible offshore wind turbine to address the negative damping concern. The first adjustment involves reducing the gains in the blade-pitch-to-feather control system to guarantee that the blade-pitch control frequency is below the dominant frequencies of the system, particularly the platform-pitch natural frequency. The second adjustment entails changing the control law in Region 3 from constant generator power to constant generator torque, which helps mitigate the rotor-speed excursions amplified by the decrease in gains within the blade-pitch controller.

3 Aero-hydro-elastic-servo-mooring coupled model

The overall topology of the FOWT is presented in

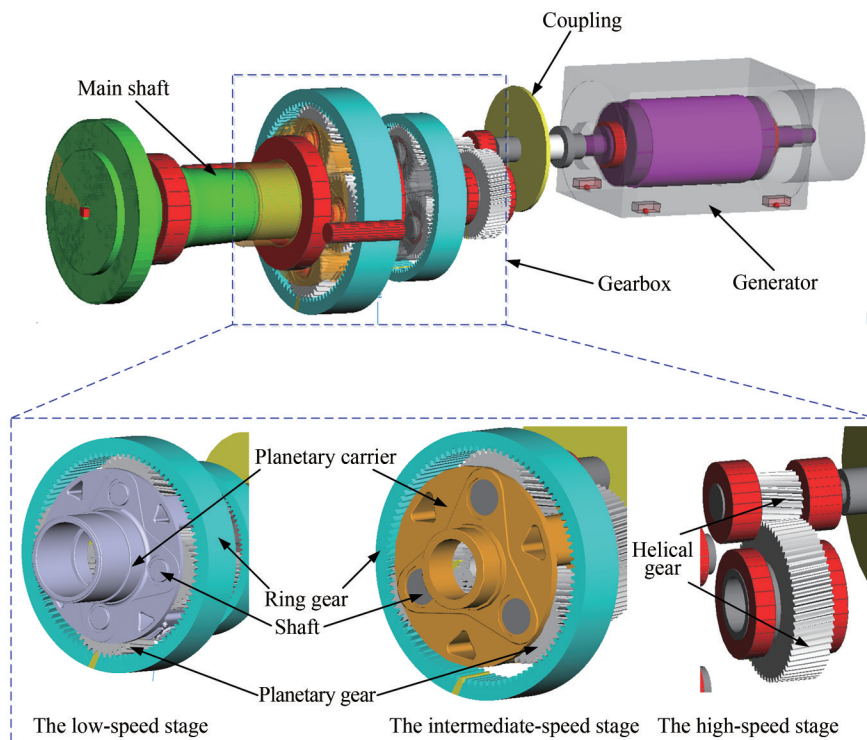


Figure 4 Overall drivetrain configuration

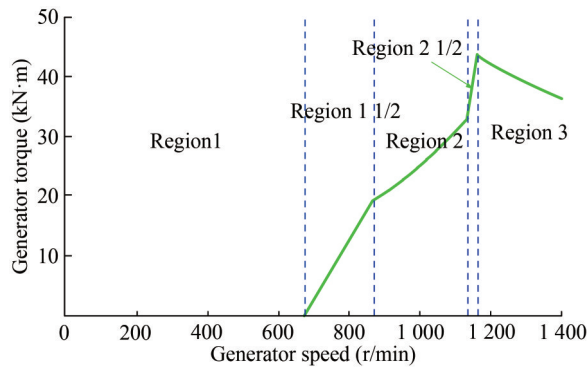


Figure 5 Control curve of generator torque for the monopile offshore wind turbine (Xie et al., 2024)

Figure 6. The blade is modeled as a flexible body using the Timoshenko beam theory, while the tower employs the Euler–Bernoulli beam theory. The hub, floating foundation, nacelle, and yaw devices are regarded as rigid bodies. For coupled simulations, the wind turbine model created in SIMPACK is exported to Simulink as an S-function. This integration involves aerodynamics, hydrodynamics, structural dynamics, the servo system, and mooring line dynamics, which result in a detailed aero–hydro–elastic–servo–mooring model of the FOWT wind turbine. For the monopile wind turbine, the mooring line module is omitted, the tower is rigidly connected to the seafloor directly, and all

other settings remain unchanged.

In this study, the aerodynamic loads on wind turbine blades are calculated using the AeroDyn module (Jonkman et al., 2015) in conjunction with SIMPACK. The AeroDyn module estimates the influence of the wake through induction factors, which are determined based on the quasi-steady blade-element momentum (BEM) theory. This theory needs an iterative nonlinear solution process. In the quasi-steady BEM framework, induction responds instantly to changes in loading conditions. The induction and resulting inflow velocities and angles are calculated based on the local flow at each analysis node on the blades, considering the relative motion between the fluid and the structure. The BEM approach incorporates Prandtl tip-loss, Prandtl hub-loss, and Pitt and Peters skewed-wake corrections, with the skewed-wake correction being applied after the BEM iteration. The calculation of tangential induction is also part of the BEM iteration. The Beddoes–Leishman unsteady aerodynamic model is used to account for flow hysteresis, including unsteady attached flow, trailing-edge flow separation, dynamic stall, and flow reattachment.

Hydrodynamic loads are determined using potential-flow theory and Morison’s equation while accounting for forces such as excitation from incident waves, radiation due to platform motion, and viscous forces (Robertson et al., 2014b). The wind turbine is managed using a pitch-torque

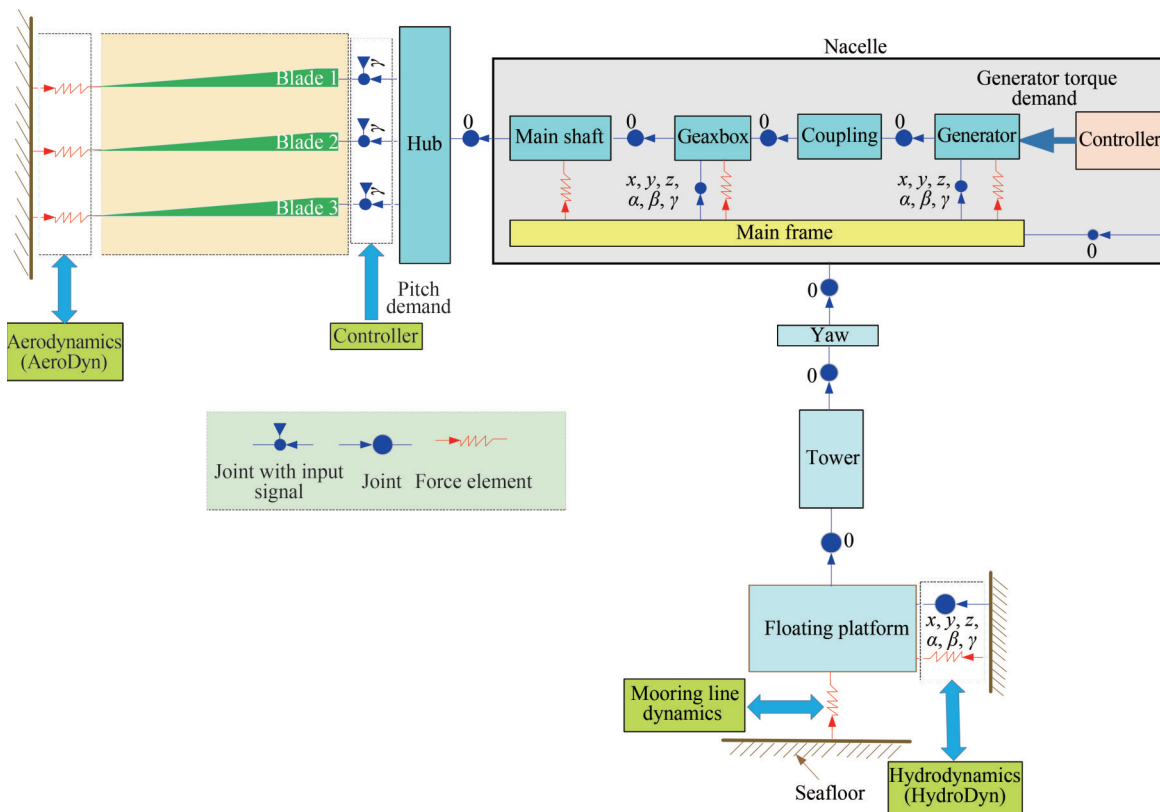


Figure 6 Topology of the floating offshore wind turbine

controller implemented in MATLAB/Simulink. Within Simulink, the mooring line dynamics module (MLDM) requires inputs such as process time, coupling time step, and the position and velocity of the platform at each time step. MLDM outputs a force vector in six degrees of freedom for the floating structure. The SIMPACK S-function in the coupling routine produces outputs such as simulation time, platform position, and velocity. These outputs are used as inputs for MLDM at every time step, which enables it to calculate the dynamic response of the mooring system and return the force vector to the S-function. This force vector is applied to the floating platform at MSL to incorporate the dynamic effect of the mooring system on the wind turbine model. In addition, MLDM computes fairlead and anchor tensions, which are returned to the S-function. Figure 7 shows the coupled simulation interfaces among different dynamics modules.

4 Load conditions

Based on normal sea state data from (Jonkman, 2007; Hu and He, 2017), this study selects five typical wind–wave

load cases, as shown in Table 2. These load cases correspond to different operational conditions of the wind turbine: cut-in wind speed, below the rated wind speed, near the rated wind speed, higher than the rated wind speed, and cut-out wind speed. The Kaimal turbulent model is used to generate the wind field (Kaimal et al., 1972), while the wave conditions are derived from the JONSWAP spectrum. Each turbulent wind simulation runs for 800 s, with the initial 200 s omitted to ensure the normal operation of the turbines.

5 Results and analyses

5.1 Comparison of nacelle motions

Figure 8 shows the absolute values of the average and standard deviations (STDs) of nacelle surge (NclSurge), sway (NclSway), and heave (NclHeave) motions for the semisubmersible floating wind turbine and the bottom-fixed wind turbine under five different load cases. The analysis of these nacelle motions is important for understanding the dynamic behavior of the wind turbines and

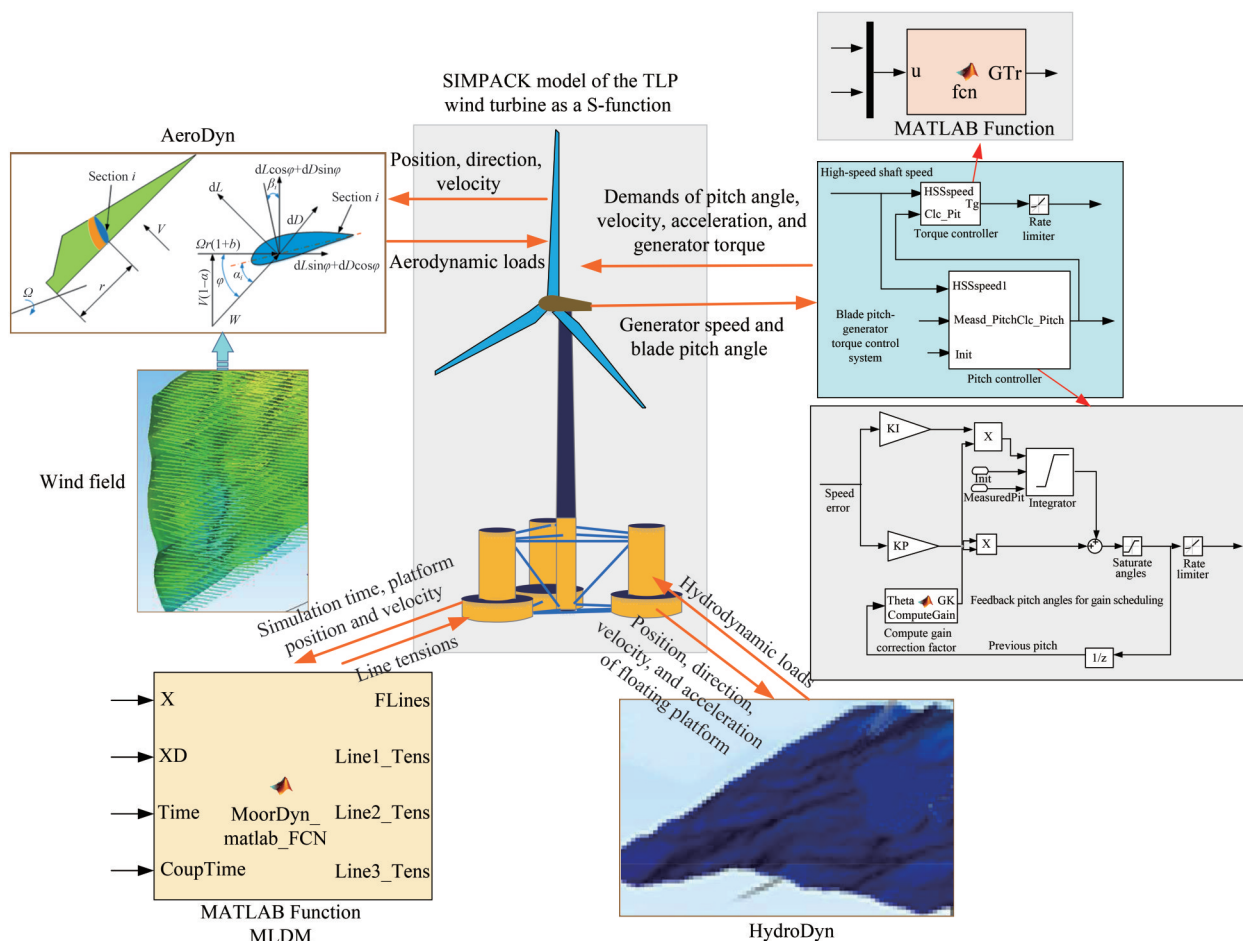


Figure 7 Coupled simulation interfaces among different dynamics modules of the wind turbine

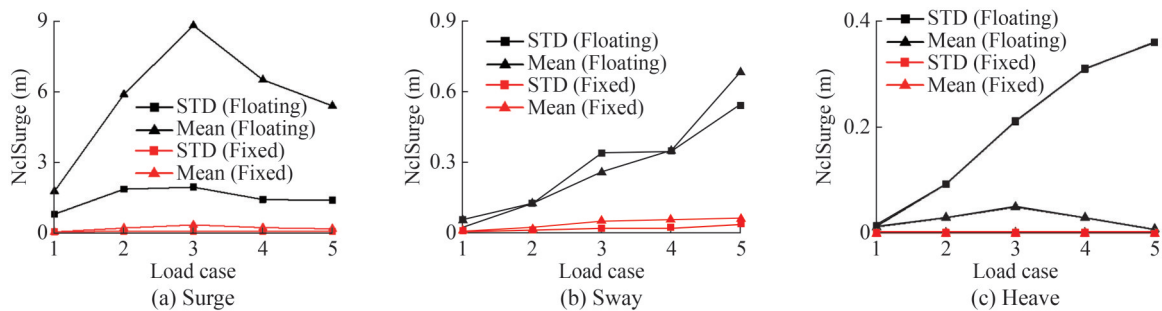
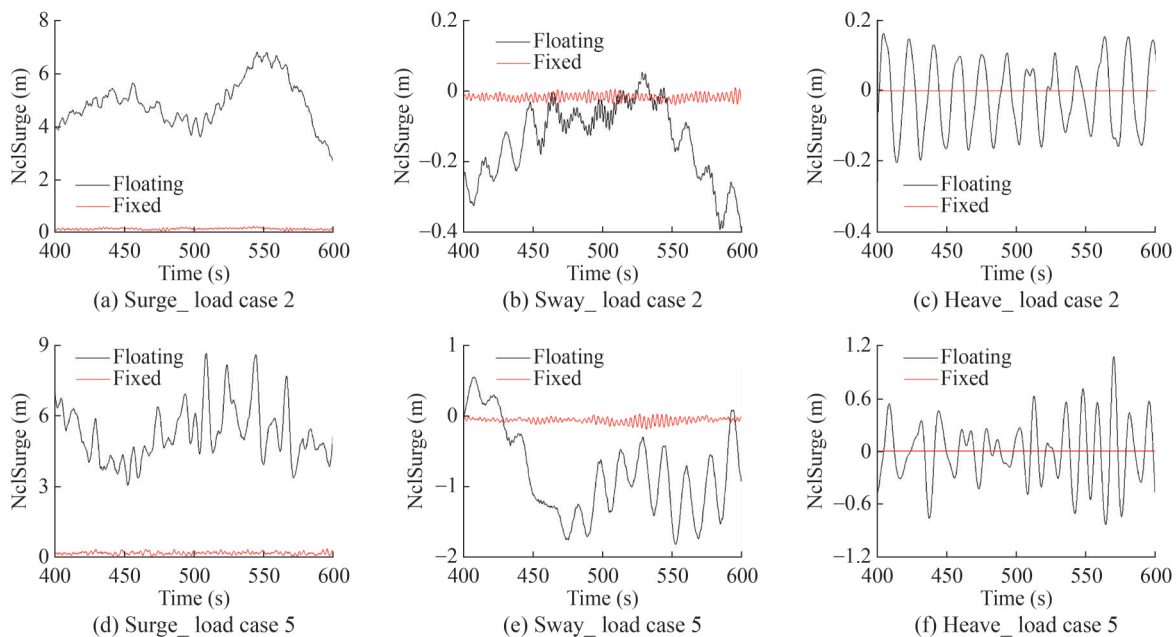
Table 2 Wind-wave load cases

Load case	Wind condition		Wave condition	
	Mean wind speed (m/s)	Turbulence intensity (%)	Significant wave height (m)	Wave peak period (s)
1	4	Level B	1.7	12.5
2	8		2.0	12.8
3	12		2.6	14.9
4	18		4.0	15.5
5	24		5.6	15.9

the resulting effects on rotor performance and drivetrain dynamics. For brevity and clarity, only the time histories of responses for 200 s under load cases 2 and 5 are presented in Figure 9.

Nacelle surge motion is the fore-aft movement of the nacelle, and it is primarily influenced by the external forces acting along the rotor axis of the turbine. The figures shown above indicate that the semisubmersible wind turbine exhibits significantly higher average surge motion than the bottom-fixed wind turbine across all load cases. The maximum average surge motion for the semisubmersible

wind turbine is 8.8 m, which is observed under load case 3 (rated wind speed). By contrast, the bottom-fixed turbine exhibits a much smaller maximum average surge motion of 0.3 m under the same load case. This result can be attributed to the blade-pitch angles adjusted by the pitch controller to maintain the rated rotor speed above the rated wind speed. This condition reduces rotor thrust forces and weakens nacelle surge movements. The STD of nacelle surge motion for the semisubmersible wind turbine is also notably higher, which reaches a maximum value of 1.9 m under load case 3. The bottom-fixed turbine, with its rigid

**Figure 8** Absolute values of averages and STDs of nacelle motions of the two wind turbines under load cases 1–5**Figure 9** Time histories of nacelle motions of the bottom-fixed and floating wind turbines under load cases 2 and 5

foundation, exhibits a maximum STD of 0.06 m, reflecting much more stable nacelle surge motion.

Nacelle sway motion represents the side-to-side movement of the nacelle, which is perpendicular to the rotor axis. As depicted in the figures shown above, the semisubmersible wind turbine again shows larger average sway motion than the bottom-fixed wind turbine. The maximum average sway motion for the semisubmersible wind turbine is 0.68 m, which is observed under load case 5 (high wind speed). This value is significantly higher than the maximum average sway motion of 0.06 m observed in the bottom-fixed wind turbine. The STD of nacelle sway motion for the semisubmersible wind turbine also increases with the severity of the load cases, and it reaches a peak value of 0.54 m under load case 5. This trend suggests that the floating platform is more susceptible to lateral movements under extreme conditions, which could affect the overall stability of the wind turbine. However, the bottom-fixed wind turbine exhibits minimal sway with a maximum STD of 0.03 m, which indicates consistent lateral stability across all load cases.

Nacelle heave motion refers to the vertical displacement of the nacelle, which is influenced primarily by wave action. Figures 7–8 show that the semisubmersible wind turbine undergoes significant vertical motion, with a maximum average heave motion of 0.05 m under load case 3. The STD of nacelle heave motion for the semisubmersible wind turbine reaches a maximum of 0.36 m under load case 5, which implies a high degree of variability in vertical displacement as the platform responds to wave and wind forces. On the contrary, the vertical motions of the bottom-fixed wind turbine are negligible due to the fixed foundation.

The analysis of nacelle motions reveals that the semisubmersible floating offshore wind turbine generally experiences larger and more variable nacelle movements than the bottom-fixed wind turbine. These significant nacelle motions profoundly affect the rotor performance and drive-

train dynamics. For instance, the large surge motion observed in load case 3 could lead to substantial fluctuations in rotor thrust and torque. These fluctuations affect the overall power output and increase the fatigue loads on drivetrain components. Similarly, the pronounced sway and heave motions could induce additional lateral and vertical forces on the drivetrain. Thus, advanced control strategies are necessary to mitigate these effects and ensure reliable turbine operation. By contrast, the bottom-fixed wind turbine undergoes much smaller nacelle motions. The reduced variability in these motions, as indicated by the lower STDs, suggests that the bottom-fixed wind turbine is more stable and less susceptible to dynamic loading variations. As a result, it is a more predictable system under varying environmental conditions.

5.2 Comparison of rotor performances

Table 3 and Figure 10 present a detailed comparison of rotor performance, including rotor power (RotPwr), rotor speed (RotSpeed), rotor thrust (Thrust), and rotor torque (RotTrq) for the semisubmersible wind turbine and the bottom-fixed wind turbine under various load cases. The performances are assessed in terms of mean values and STDs across different load cases. Negative values in Figure 10 indicate that the results for the floating wind turbine are smaller than those for the bottom-fixed turbine. Time histories of rotor performances under load cases 2 and 5 are presented in Figure 11.

Rotor power output is a critical performance metric for analyzing the efficiency of a wind turbine. Table 3 shows that the mean rotor power for the semisubmersible wind turbine varies across the load cases, with a maximum value of 5 339 kW observed in load case 4 (above-rated wind speed). On the contrary, the bottom-fixed wind turbine achieves a slightly lower maximum mean power of 5 319 kW under the same load case. This difference is due to the more significant nacelle motions in the semisubmersible wind tur-

Table 3 Mean values and STDs of variables of the floating and bottom-fixed wind turbines

Statistics	Load case	RotPwr (kW)		RotSpeed (r/min)		Thrust (kN)		RotTrq (kN·m)	
		Semisubmersible	Monopile	Semisubmersible	Monopile	Semisubmersible	Monopile	Semisubmersible	Monopile
Mean values	1	202.34	202.23	7.12	7.12	108.6	108.49	268.14	268.01
	2	1 908.42	1 912.91	9.20	9.21	350.23	350.72	1 928.22	1 930.23
	3	5 016.48	4 974.28	11.96	11.9	553.62	548.64	3 994.17	3 985.97
	4	5 338.94	5 318.57	12.03	12.02	364.88	366.03	4 237.50	4 229.56
	5	5 333.41	5 323.41	12.01	12.01	271.1	272.62	4 239.91	4 237.78
STDs	1	111.76	111.78	0.16	0.17	29.2	29.39	145.26	145.4
	2	758.76	769.23	0.90	0.91	85.4	86.51	600.82	607.76
	3	829.36	767.46	0.55	0.31	79.06	83.09	570.94	569.48
	4	1 147.39	973.83	0.89	0.31	75.52	79.93	852.33	779.50
	5	1 527.41	1 335.03	0.83	0.38	62.34	61.50	1 169.41	1 067.91

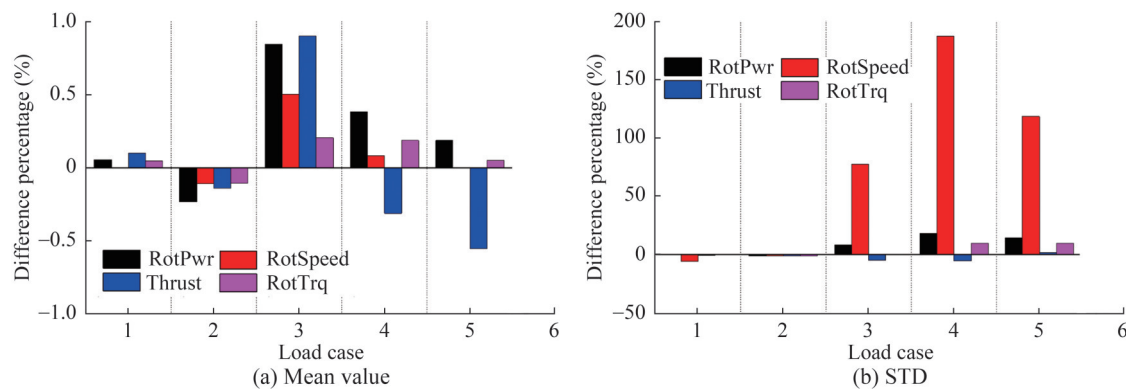


Figure 10 Difference percentages of mean values and STDs of variables versus the bottom-fixed case

bine, which can enhance or reduce power capture depending on the dynamic response of the platform. The STD of rotor power for the semisubmersible wind turbine is considerably higher than that of the bottom-fixed wind turbine, particularly in load case 5 (high wind speed), where it reaches 1 527 kW. This increased variability in power output implies that the semisubmersible wind turbine experiences more pronounced power fluctuations due to the dynamic nature of its floating platform. The bottom-fixed wind turbine, with a maximum STD of 1 335 kW, exhibits a more stable power output, which suggests more consistent performance under varying environmental conditions. Figure 10 further illustrates the percentage differences in mean values and STDs of rotor power between the semisubmersible and bottom-fixed wind turbines. The semisubmersible wind turbine exhibits a negative percentage difference in mean rotor power, particularly in load case 2, where the difference is -0.23% . This result indicates that the motions of the floating platform may lead to reduced power output compared with that of the bottom-fixed wind turbine under certain conditions.

Rotor speed is a direct indicator of the capability of the turbine to convert wind energy into mechanical energy. As shown in Table 3, the mean rotor speed for both wind turbines remains close to the rated value of 12.1 r/min under load cases 3 and 4, which reflects the effective operation of pitch-torque controllers that maintain stable rotor speed despite varying wind conditions. However, the STD of rotor speed is significantly higher for the semisubmersible wind turbine, with a maximum value of 0.90 r/min in load case 2. The bottom-fixed wind turbine presents a similar maximum standard deviation. Figure 10 also shows a notable percentage difference in the standard deviations of rotor speed between the two wind turbines, with the semisubmersible wind turbine having a 187% higher STD in load case 4. This finding further highlights the challenges in maintaining consistent rotor speed in floating wind turbines, which are more susceptible to dynamic loading variations.

Rotor thrust represents the axial force exerted by the wind on the rotor, and it directly influences the structural

loads of the turbine. Table 3 reveals that the mean rotor thrust for both wind turbines is similar, with the semisubmersible wind turbine reaching a maximum of 553 kN in load case 3. The STD of rotor thrust is generally smaller for the semisubmersible wind turbine, and it peaks at 85 kN in load case 2. Figure 10 shows that the maximum percentage difference in STDs of rotor thrust between the two wind turbines reaches -5.52% , particularly in near-rated and above-rated load cases. This result indicates that, although the motion of the nacelle and the floating platform is remarkable, the reasonable pitch control of blades can still effectively restrain the rotor thrust.

Rotor torque is an important parameter for drivetrain performance because it directly affects the mechanical power transmission from the rotor to the generator. Table 3 shows that the mean rotor torque for the semisubmersible wind turbine reaches a maximum of 4 240 kN·m in load case 5, which is slightly higher than the bottom-fixed turbine's maximum of 4 238 kN·m. Therefore, the floating wind turbine may experience higher torque loads due to its platform dynamics. However, the STD of rotor torque is significantly greater for the semisubmersible wind turbine, with a peak value of 1 169 kN·m in load case 5. This result indicates more substantial fluctuations in torque, which could lead to pronounced wear and potential failure of drivetrain components. The bottom-fixed wind turbine, with a maximum STD of 1 068 kN·m, exhibits more stable torque performance, which reflects its more predictable load conditions. Figure 10 illustrates that the percentage difference in rotor torque variability between the two wind turbines can be as high as 9.5% in certain load cases, which highlights the increased operational risks associated with floating wind turbines.

5.3 Comparison of tooth contact forces

The tooth contact forces are calculated using the slicing method, as detailed in (Flodin and Andersson, 2001). The mean values, STDs, and 90th percentiles of these forces are also calculated. The results are presented as percentage differences compared with the responses of the bottom-

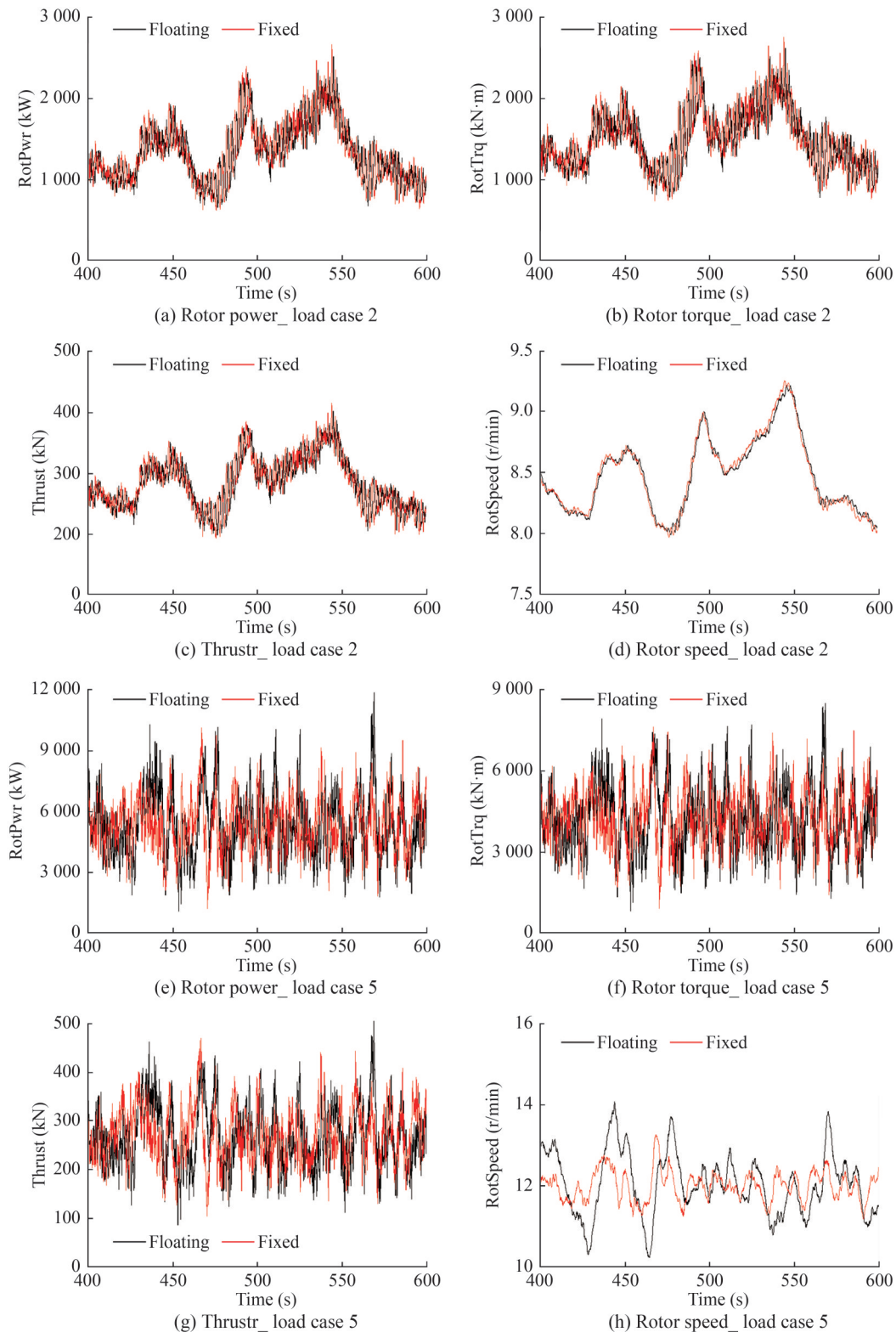


Figure 11 Time histories of rotor responses of the bottom-fixed and floating wind turbines under load cases 2 and 5

fixed turbine, as illustrated in Figure 12. In this figure, LSS, IMS, and HSS denote the low-speed stage, intermediate-speed stage, and high-speed stage, respectively. The terms Sun-Planet and Planet-Ring refer to the meshing gear

pairs, while Circumferential, Radial, and Axial mean the directions of the tooth contact forces. The results for the low-speed and intermediate-speed stages are obtained from one planet gear pair, although multiple planet gears are

available in these stages. In addition, the negative values represent that the result of the floating wind turbine is smaller than that of the bottom-fixed wind turbine. For

example, Figure 13 shows the time histories of tooth contact forces in the high-speed stage gear pair across circumferential, radial, and axial directions under load case 5.

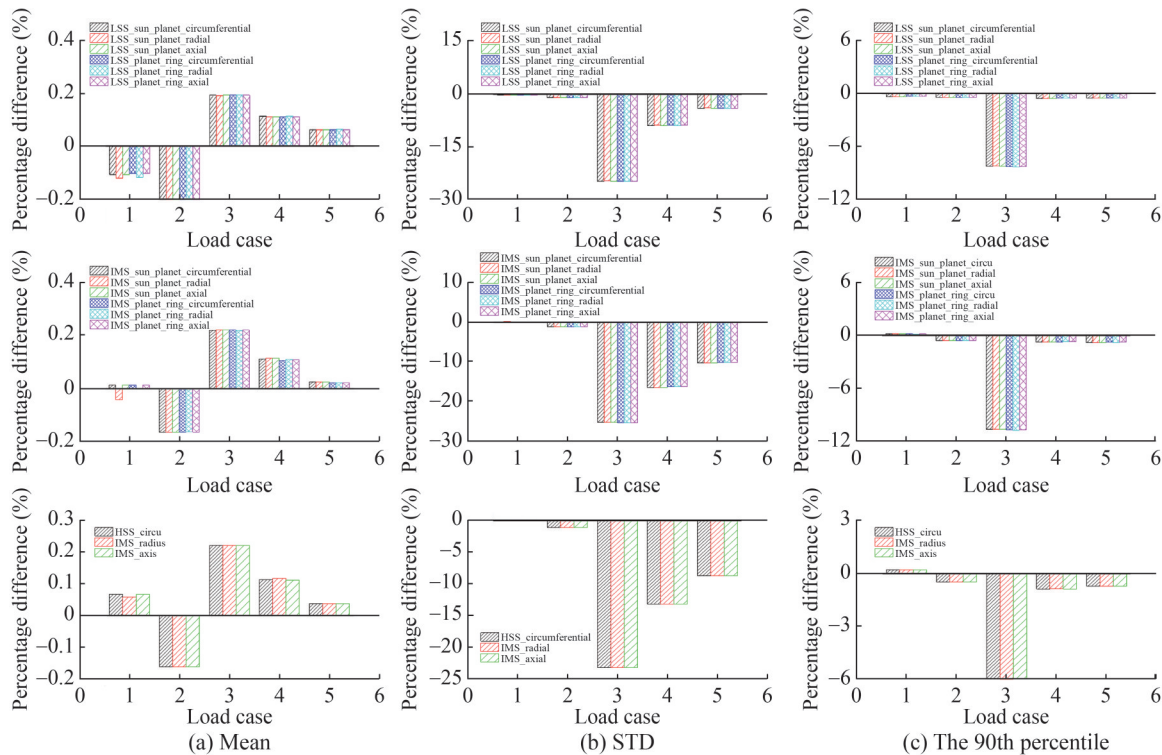


Figure 12 Difference percentages of tooth contact forces of the floating wind turbine versus the bottom-fixed wind turbine

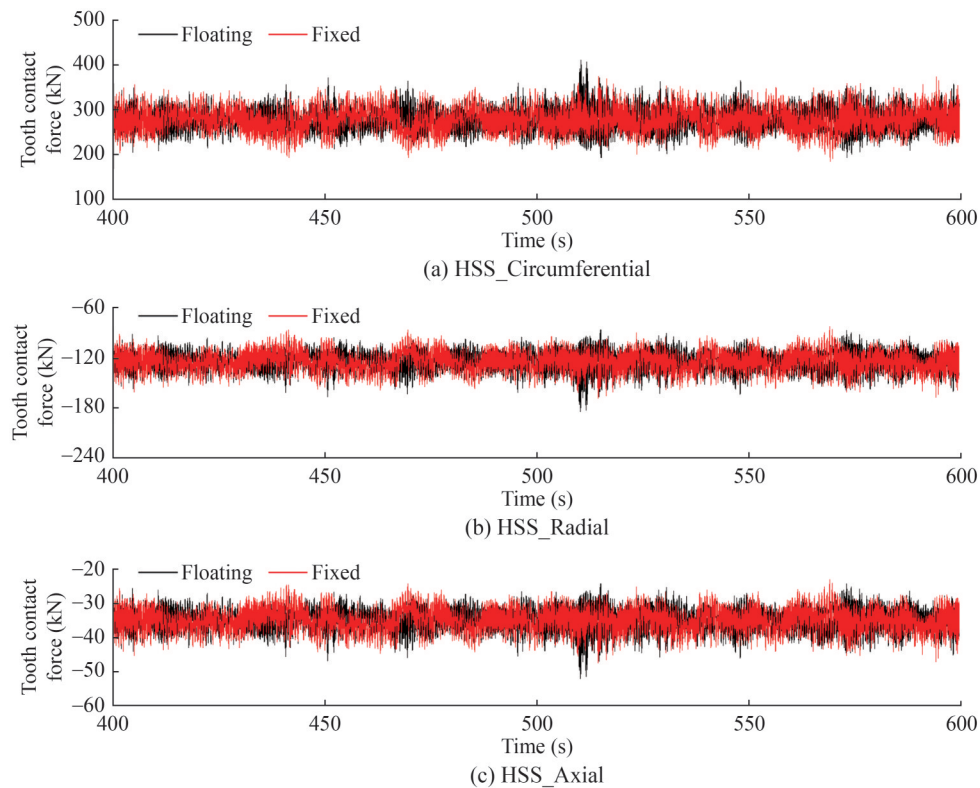


Figure 13 Time histories of tooth contact forces of the high-speed stage under load case 5

The mean values of gear contact forces in the LSS of the floating wind turbine are slightly smaller than those of the bottom-fixed wind turbine, and the maximum percentage difference is only approximately 0.20%. This small difference indicates that, under lower wind speeds, the motion of the floating platform does not significantly alter the average load experienced by the gears. This result can be attributed to the relatively stable operating conditions where the wind forces are mild, and the dynamic behavior of the platform is subtle enough to cause major deviations in gear loads. When the wind speed exceeds the rated value, the mean gear contact forces in the LSS of the floating wind turbine slightly increase. The maximum rise is nearly 2%, particularly in load case 2. This increase occurs because, at higher wind speeds, the dynamic responses of the floating platform become more pronounced. The motion of the platform can introduce additional forces on the gears as it adjusts to maintain stability in rougher conditions. However, the improvement is still relatively small, which suggests that the control systems of the turbine and the inherent design of the floating platform help manage these dynamic forces effectively. Ultimately, significant overloading is prevented.

The STDs and 90th percentiles of the gear forces in the LSS, IMS, and HSS are consistently smaller in the floating wind turbine than in the bottom-fixed wind turbine across nearly all load cases. The maximum decrease occurs at load case 3, with reductions of up to 24.7% in the STD and 8.3% in the 90th percentile for the LSS. Similar trends are detected in the IMS and HSS stages, with the most significant reductions also occurring at load case 3. These reductions show that the nacelle motion associated with the floating wind turbine has a damping effect on the variability and extreme values of gear contact forces. The capability of the floating platform to move with the waves and wind likely absorbs some of the fluctuating forces that would otherwise be transmitted directly to the drivetrain in a bottom-fixed turbine. This dynamic response minimizes the occurrence of extreme forces and smooths out the overall load profile on the gears. The control system in the floating wind turbine is designed to optimize the pitch of the turbine to stabilize its operation under varying wind and wave conditions.

The findings indicate that nacelle motion has a generally positive influence on the STD and the 90th percentile of gear contact forces. This effect is most noticeable when the turbine operates near or above-rated wind speeds. In this case, the dynamic adjustments of the floating platform help mitigate sharp increases in force variability and extreme loading. By contrast, the mean values of the gear contact forces are only slightly influenced by nacelle motion. This slight influence indicates that, while the floating platform introduces some additional dynamic forces, these forces are effectively managed by the design and control systems

of the turbine to maintain a consistent average load on the gears. The motion of the platform primarily serves to redistribute and smooth out these forces rather than significantly increasing or decreasing the overall load.

6 Conclusions

This study comprehensively examined the effects of nacelle motions on the rotor performance and drivetrain dynamics of floating offshore wind turbines. The NREL 5 MW monopile-supported and OC4 DeepCwind semisubmersible wind turbines were examples for the analysis. Fully coupled simulations were conducted to determine the intricate interactions among aerodynamic, hydrodynamic, structural, and mooring forces. The main conclusions are enumerated as follows:

- 1) The semisubmersible floating wind turbine undergoes larger nacelle motions than the bottom-fixed wind turbine due to significant platform movements that intensify with the increase in load severity. These larger motions could potentially influence the long-term structural integrity and operational efficiency of the semisubmersible floating wind turbine. Thus, they require further analysis. The increased nacelle motions may lead to higher fatigue loads and affect the stability of the semisubmersible floating wind turbine. Therefore, advanced control strategies are needed to mitigate these effects.

- 2) Nacelle motions significantly affect rotor performance, including rotational speed, thrust, torque, and power output. The rotor responses of the semisubmersible floating wind turbine exhibit greater variability, particularly in terms of STDs under various load cases. Despite these significant motions, the mean rotor speed remains close to the rated value due to the precise operation of pitch-torque controllers. However, the increased fluctuations imply a potential effect on energy capture efficiency and mechanical stress on components.

- 3) The inherent dynamic behavior of the semisubmersible floating wind turbine enables it to absorb and mitigate variable forces more effectively than a bottom-fixed wind turbine. The movement of the floating platform in response to wind and wave forces reduces the variability and extremity of the loads transmitted to the gears, particularly under challenging wind conditions. This condition leads to lower STDs and 90th percentiles of gear contact forces, while the mean values remain largely unaffected. These conditions suggest that the control systems and design of the wind turbine effectively manage the dynamic loads.

This study highlights the urgent need for advanced simulation techniques that incorporate detailed drivetrain dynamics, given that traditional methods focusing only on global loads fail to capture the complexities of floating offshore wind turbines. Our findings offer valuable insights for the

refinement of these simulation models, which leads to more accurate performance predictions and more robust turbine designs.

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