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Experimental comparisons of dynamic properties of floating wind turbine systems based on two different rotor concepts

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Abstract

This article presents research findings on the response characteristic differences between the thrust-matched blade system (TMBS) and the geometry-matched blade system (GMBS), which utilize redesigned thrust-matched and original geometry-matched blades, respectively, both based on the OC3 spar-type floating offshore wind turbine (FOWT). Particulars of this research are to examine the unique dynamic response characteristics of the TMBS, which includes a better performance-matched rotor relative to the GMBS. The response behaviors of the TMBS and GMBS are compared and studied based on a sequence of wind and irregular wave scenarios to reveal the unique roles that the thrust-matched rotor plays in the dynamic response behaviors of the floating wind turbine system. Gyroscopic effects of rotor rotation are found weakened in the TMBS, and yaw oscillation in the TMBS is not solely excited by rotor rotation, unlike in the GMBS. Coupling effects between surge and pitch are found in both the TMBS and GMBS under combined wind-and-wave condition. Furthermore, restraining effects of wind loads on motions in the GMBS and TMBS are both evident at natural frequencies while show distinct behaviors at the wave frequency. It is observed from the experimental measurements that the tower-top bending moment of the TMBS shows similar oscillation characteristics as that of the GMBS but with larger oscillation amplitudes. Furthermore, it is found that tower-top shear force and axial rotor thrust of the TMBS show distinct exciting motivators and much larger oscillation amplitudes relative to those of the GMBS. For both the TMBS and GMBS, the tensions measured in mooring lines are found to be coupled by yaw motion for wind-only cases while being clearly influenced by surge and heave couplings under integrated wind-and-wave load condition.

Key words: floating wind turbine; dynamic characteristics; model test; thrust-matched; geometry-matched; coupling effect

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1. Introduction

Floating offshore wind turbines (FOWTs) can capture steadier and stronger wind energy while potentially minimizing energy costs and noise/visual pollution levels relative to current traditional fixed wind turbines. Due to the increasing demand for energy and environmental protection concerns of the public, FOWTs have been developed rapidly in recent decades and have emerged as one of the most commercially promising form of clean energy. Worldwide, multiple prominent companies and research institutions have conducted research involving the use of a sequence of numerical simulation tools in OC3 and OC4 projects (Jonkman et al., 2009; Jonkman, 2010; Jonkman et al., 2012; Robertson, Jonkman and Musial, 2013), and many simulation codes have been developed and improved for fully coupled analyses of FOWT systems (Karimirad, 2011; Kvitema, Bachynski and Moan, 2012; Quallen et al., 2014; Bae, Kim and Shin, 2010; Gueydon and Xu, 2011). Among these studies, several have been performed with a focus on spar-type FOWT concepts given their strong hydrodynamic performance.

For the development and validation of large-scale floating offshore systems such as FOWTs, scaled model tests conducted in wave basins have been commonly employed as a refined scientific approach. Scale basin model tests generate accurate data on floating system responses while presenting fewer risks and involving less time and resources than prototype data collection methods. However, research on FOWTs is multidisciplinary, involving issues of aerodynamics, hydrodynamics, multi-structure dynamics (elastic), and automatic controls (servo) (Namik and Stol, 2010; Wang and Sweetman, 2013; Jeon and Lee, 2014; Salehyar and Zhu, 2015; Nejad et al., 2015). Consequently, establishing a proper methodology for accurately designing and fabricating floating wind turbine models and emulating aerodynamic and hydrodynamic environments has proven challenging. Thus far, a series of model tests on FOWTs have been performed (Neilson, Hanson, and Skaar, 2006; Shin, 2011; Cermelli et al., 2010; Martin et al., 2012; Koo et al., 2012; Goupee et al., 2012). In particular, it is impossible to employ Froude and Reynolds number scaling schemes simultaneously, thus each of these basin tests involves the use of Froude scaling methods, the customary choice when employing wave basin experiments. However, Froude scaling is not well suited to simultaneous aerodynamic aspects of experiments because it generates a very low model Reynolds number setting, and this significantly shifts the turbine rotor performance which strongly depend on the Reynolds number. Thus, the emulation of proper aerodynamic performance under a Froude-scaled and low Reynolds number model setting is challenging in the context of model floating wind turbine basin testing.

A number of approaches have been employed to address this issue. In model basin experiments on the WindFloat concept conducted by Roddier et al. (Roddier et al., 2010) and on the STC (Spar Tours Combination) concept conducted by Wan et al. (Wan, Gao and Moan, 2014), properly sized drag disks were used to represent turbine rotors and to emulate wind turbine aerodynamic loads under coupled model wind/wave conditions. Despite this approach was proved suitable for applying the gross wind turbine loads, further process for incorporating the effect of turbine control on the global dynamic response of the FOWT is impossible. As shown in the works of Nielsen et al. (2006) and Jonkman (2008), the wind turbine control is closely related to the integral dynamic responses of a given FOWT system. Over the last several years, the University of Maine has collaborated with the Maritime Research Institute Netherland (MARIN) basin in conducting a sequence of Froude-scaled model tests for spar-type, semi-submersible-type, and TLP-type floating wind turbines (Martin et al., 2012; Koo et al., 2012; Goupee et al., 2012) that were 1:50 geometrically scaled from the National Renewable Energy Laboratory (NREL) 5 MW reference wind turbine (Jonkman, 2010). However, the low model Reynolds number setting due to Froude-scale implementation resulted in an unmatched model rotor performance (e.g., power coefficient and thrust coefficient) relative to scaled values, which limits the information that can be gleaned from a model test.

In view of the facts presented above, a modified model blade with particularly-redesigned airfoil sections that better matches the prototype rotor performance under low Reynolds number settings is desirable for use in Froude-scale coupled model wind/wave basin tests. Considering this situation, in reference to the blade design proposed in (Fowler et al., 2013), a modified model blade was fabricated in this model test performed in the Deepwater Offshore Basin at Shanghai Jiao Tong University with a model set-up corresponding to a 1:50 Froude scale based on a spar-type FOWT. This modified blade shows better-matched aerodynamic performance with the prototype relative to the original NREL geometrically scaled one, which, to a large extent, compensates for the less accurately matched rotor performance drawbacks of the geometrically similar blade. Although the model FOWT with re-designed performance-matched blades was also retested in MARIN's follow-up basin tests (Kimball et al., 2014; de Ridder et al., 2014), only the semi-submersible floater was utilized. As a supplement, this paper focuses on another commonly used supporting floater, namely spar-type floater. These modified and original geometrically similar wind turbine blades are referred to as thrust-matched and geometry-matched blade in this paper, respectively. However, as the modified blade is not geometrically scaled down from the prototype, unique response features of this thrust-matched floating system may emerge.

The purpose of this research study is to provide fresh model test data that compared the test results under various load conditions based on the thrust-matched blade system (TMBS) and geometry-matched blade system (GMBS) to underscore the unique dynamic characteristic of the TMBS and to recognize the role that thrust-matched blades can play in floating system response behaviors. This study may thus serve as a reference for the further improvement of high-performance model blade designs based on low Reynolds number conditions and future model basin testing procedures. Analyses and discussions are presented in relation to the following six main factors:

- 1) Gyroscopic effects of rotor rotation on yaw motion
- 2) Coupling effects between surge, pitch, and heave
- 3) Aerodynamic loading effects on motions
- 4) Dynamic characteristics of tower-top bending moment
- 5) Axial rotor thrust and tower-top shear force response behaviors
- 6) Mooring system response characteristics

2. Overview of floating wind turbine model tests

2.1 Scale methodology

The establishment of a proper scaling methodology that can be used to accurately design and fabricate a floating offshore wind turbine (FOWT) model and to emulate aerodynamic and hydrodynamic environments is of great importance. However, the impossibility of employing Froude and Reynolds number scaling schemes simultaneously complicates the process of floating wind turbine model testing. In hydrodynamic basin testing, a Froude number scaling scheme and geometric similarity mechanisms are typically utilized to properly scale gravitational and inertial properties of wave forces and of other domain-external forces of interest that may influence floating system dynamic responses. In contrast, in aerodynamic testing, a Reynolds number scaling scheme is commonly used to properly characterize the relationship between viscous and inertial forces in a fluid flow, whereas this scheme is not appropriate for a floating system subjected to wave loading. As the floating wind turbine system is mainly subjected to gravity, inertial and unsteady fluid forces, Froude number scaling is ultimately employed in model basin testing. However, the rotor performance that mainly characterized by the rotor thrust and torque will be strongly affected by the dissimilitude of the Reynolds number, as will be illustrated in detail below.

2.2 Effects of unmatched Reynolds numbers

The performance of rotor is mainly represented by the power coefficient C_p and thrust coefficient C_t , which are characterized by the following formula:

$$C_p = \frac{P}{\frac{1}{2} \rho v_0^3 A} \quad C_t = \frac{T}{\frac{1}{2} \rho v_0^2 A} \quad (1)$$

where P denotes rotor power, T denotes rotor thrust, ρ is the density of the air, v_0 is the velocity of incoming wind, and A is the swept area of the rotor. Normally, these two coefficients are functions of the tip-speed ratio (TSR), which is defined as:

$$TSR = \frac{\omega R}{v_0} \quad (2)$$

where ω is the rotor angular speed, R is the rotor radius, and v_0 is the velocity of incoming wind. In addition, the relationship between the Reynolds numbers of the full and model scales can be expressed as:

$$\frac{Re_m}{Re_p} = \frac{\rho V_m L_m \mu}{\rho V_p L_p \mu} = \frac{1}{\lambda^{3/2}} \quad (3)$$

where the scale parameter λ , which represents the ratio between the lengths of the prototype and the model, was set to 50 in this model test. Therefore, the Reynolds number for model scale was 1/354 of that for full scale. In addition, the model blade of the GMBS is geometrically scaled down from the NREL 5-MW reference wind turbine blade which is designed for a much higher full-scale Reynolds number (as described further in the following content). Consequently, utilizing this geometry-scaled model blade under low Reynolds number conditions will lead drastic changes in rotor performance, as depicted in Fig. 1 drawn from Martin et al. (2012).

Fig. 1 Comparison of model and prototype aerodynamic performances (Figure from Martin H R et al., 2012)

As shown in this figure, the model rotor aerodynamic performance is markedly lower than the theoretical prototype performance that calculated from NREL's coupled aero-hydro-servo-elastic simulator, FAST, particularly for the power coefficient (Martin et al., 2012), resulting in a lower model rotor thrust and torque than the prototype-scaled target values based on Eq. 1. Therefore, to obtain the target model rotor thrust, which is the key force property for most basin model test cases, the model wind speed has to be increased (Martin, 2011). However, the increase of model wind speed will produce undesirable excess drag on the non-rotor structures (e.g., tower or floater portion that above the water plane). Consequently, a modified model-scale blade with power and thrust coefficients that more closely match those of the prototype when subjected to a Froude-scale wind field is most desirable. This modified blade was reported by Fowler et al. (2013) mainly based on AG24 airfoil and is referred to as "thrust-matched blade" in this research paper. After modification, the aerodynamic performance of

this thrust-matched blade is shown in Fig. 2. Exhaustive descriptions of the geometry-matched blade and thrust-matched blade design can be found in (Martin, 2011) and (Fowler et al., 2013), respectively.

Fig. 2 Comparison of thrust and power coefficients for the prototype target, tested geometry-matched model and redesigned thrust-matched wind turbine as obtained from simulations and test data (Figure from Fowler et al., 2013)

It should be noted that it is difficult to create an airfoil that highly matches the prototype lift and drag coefficients and subsequent prototype power and thrust coefficients (Martin, 2011). Therefore, to simplify the design process, the emphasis of the thrust-matched blade design was placed only on creating a simple geometry that matched the C_T curve in the vicinity of design TSR (approximately 7) and maximized the peak value of the C_P curve (Martin, 2011). Fig. 2 clearly shows that the thrust-matched design adequately matches the target with regard to thrust coefficients near the rated wind speed operational TSR of approximately 7, and the power coefficient of the thrust-matched design more closely matches the full-scale prototype target performance than the geometry-matched design marked as “Model Data” in Fig. 2. Thus, this modified, thrust-matched blade and the original geometry-matched blade were both used in the model test program, and the test results based on the TMBS and GMBS settings are compared.

The model floating wind turbine based on the GMBS is 1/50th geometrically scaled down from the OC3 project specifications (Jonkman et al., 2009; Jonkman, 2010). The parameters of the mooring system and the water depth for the GMBS and TMBS were referred to MARIN’s basin test (Koo et al., 2012). The TMBS used the same model components as those of the GMBS, although its blades differed. A model water depth of 4 m was employed to simulate a 200 m prototype value. The assembled spar-type model GMBS and TMBS developed for this experimental research study are presented in Fig. 3.

Fig. 3 GMBS and TMBS models in the basin

3. Model Description

In this section, two kinds of blade are described. One is referred to as a geometry-matched blade, and the other is termed a thrust-matched blade. The geometry-matched blade was 1/50th geometrically scaled down from the 5-MW NREL reference wind turbine blade, and the model blade properties reported by Martin (2011) were utilized to fabricate the blade model for our test procedure. The thrust-matched blade was based on the design presented in (Fowler et al., 2013), which was constructed mainly based on the Drela AG24 airfoil. Simultaneously achieving large-dimension and low-mass targets of model blade complicates both material selection and manufacturing processes. A woven carbon fibre epoxy composite material was finally selected to fabricate these two kinds of blade due to its low-mass property. A comparative image of the geometry-matched and thrust-matched model blades is presented in Fig. 4.

Fig. 4 A comparative image of the a) thrust-matched blade and b) geometry-matched blade

The mass of the geometry-matched model blade was measured at 137 g, which is 1.05% lighter than that required. However, as noted by Fowler et al. (2013), the aerodynamic performance of the rotor is the primary concern and no attempt has been made to maintain the distributed blade mass properties. Thus, it is virtually impossible to achieve such low scaled mass and such large dimension targets for the thrust-matched blade in the test program. It is, however, possible to fabricate a thrust-matched blade based on the design presented in (Fowler et al., 2013) to ensure the aerodynamic rotor performance and take various steps in the manufacturing process to minimize the model blade mass. The mass of the thrust-matched model blade was finally measured at 832 g.

Other portions of the model wind turbine were scaled down from the 5-MW horizontal axial reference wind turbine of the National Renewable Energy Laboratory (NREL) and OC3 Hywind tower (Jonkman et al., 2009; Jonkman, 2010) under a scale parameter λ of 1:50. Parameters of various components of the model wind turbine (such as tower, spar-type floater and mooring systems) are presented in (Duan et al., 2015a). The masses and center of mass (CM) locations of the main components used in the wind turbine for the designation, GMBS and TMBS are listed in Table 1 at full scale (Jonkman et al., 2009; Jonkman, 2010). It should be noted that, unless specified otherwise, all CM locations are provided with respect to the still water level (SWL) in this paper.

Table 1 Comparison of Mass and CM locations of the wind turbine components

Item	Designation		Full-Scale Measurement of the GMBS		Full-Scale Measurement of the TMBS	
	Mass (kg)	Center of mass (m)	Mass (kg)	Center of mass (m)	Mass (kg)	Center of mass (m)

Blade (three in total)	53,220	90	52,659	90.65	319,800	90.65
Hub	56,780	90.17	57,272	90.65	57,272	90.65
Nacelle	240,000	89.35	232,291	90.65	470,347	90.65
Tower	249,718	43.4	287,128	51	287,128	51
Total Wind turbine	599,718	70.35	749,532	69.45	1,254,728	77.99

Due to the influence of the data cables, the mass of the model wind turbine seems inevitable to be overweight. In MARIN's test, the total full-scale mass of the model wind turbine is 699,400 kg (Martin, 2011), which is 16.62% overweight with respect to the mass of designation. In this test, the total full-scale mass of the model wind turbine was found to be 749,532 kg based on the GMBS. Nevertheless, as a large-dimension and heavy-mass thrust-matched rotor with superior aerodynamic performance (more-closely-matched C_p and C_t curves with prototype ones) was utilized in this model test procedure, the total full-scale mass of the model wind turbine based on the TMBS must be increased further. It should be noted that the mass of the nacelle based on the TMBS is heavier than that based on the GMBS, as a roller bearing was utilized in the TMBS tests to prevent the load sensor from exceeding the measuring range, and due to this component, the TMBS nacelle mass was increased.

As listed in Table 1, the GMBS and TMBS wind turbines are overweight, and the CM location values more or less differ from the target values. To compensate for these effects on the integrated floating system, some measurements were conducted. In principle, the model should attempt to closely replicate the full-scale total floating system mass levels and to approach its CM value as closely as possible both for the GMBS and TMBS. The results of this approach are reported in Table 3, and the parameters of the spar-type floater for the designation, GMBS and TMBS are listed in Table 2 at full scale. In Table 2, SWL denotes the still water level, and a minus sign denotes that a CM location falls below the SWL. Platform yaw inertia levels were not measured in this model test.

Table 2 Main properties of the spar-type floating platform

Item	Unit	Designation	Full-Scale Measurement of the GMBS	Full-Scale Measurement of the TMBS
Platform Mass, including Ballast	kg	7,466,330	7,316,578	6,811,317
CM Location below the SWL along the Platform Centerline	m	-89.9155	-94.1495	-98.6729
Platform Roll Inertia around the CM	kg•m ²	4,229,230,000	4,656,382,813	5,532,437,500
Platform Pitch Inertia around the CM	kg•m ²	4,229,230,000	4,656,382,813	5,532,437,500
Platform Yaw Inertia around the Platform Centerline	kg•m ²	164,230,000	not measured	not measured

Table 3 Comparison of mass and CM locations of the entire floating system

Designation		Full-Scale Measurement of the GMBS		Full-Scale Measurement of the TMBS	
Mass (kg)	Centre of mass (m)	Mass (kg)	Centre of mass (m)	Mass (kg)	Centre of mass (m)
8,066,048	-78	8,066,110	-78.947	8,066,045	-71.192

As shown in Table 3, the full-scale mass and CM location of the GMBS closely match the target values. The full-scale mass of TMBS is nearly identical with the desired one. Nevertheless, the CM location of the TMBS differs somewhat from the designation. This higher CM location of TMBS will shorten the metacentric height so that causes a relatively smaller restoring moment which may result in a relatively larger mean pitch tilt, and this point will be described in more detail in the following content. Additionally, it can be concluded from Table 3 that the aforementioned principle used to adjust the mass and CM of the model floater for approaching the target mass

and CM of the entire floating system works successfully.

Several instruments were used to accurately capture the 6-DOF dynamic loads and motions of the FOWT system. Load cell #1 was located between the nacelle and tower to measure the 6-DOF forces and moments between them, and primarily to measure the tower top shear forces and bending moments. Load cell #2 was positioned in the nacelle to capture 6-DOF forces and moments in the nacelle and primarily to capture the rotor thrust force. An accelerometer was installed in the rear of the nacelle for the measurement of 3-DOF nacelle accelerations. In this experiment, a non-contact active optical motion capture system was used to measure the 6-DOF motions of the floating system, and four active optical markers were fixed at the end of the tower. Several of these important aspects are shown in the photographs presented in Fig. 5. Note that the TMBS included the same sensors used in the GMBS.

Fig. 5 Assembly configuration of sensors

Additionally, three tension sensors were positioned at the joints of the two short mooring lines (lines B and C) for the measurement of mooring line tension levels, as shown in Fig. 6. A detailed description of the mooring system can be found in (Duan et al., 2015a).

Fig. 6 Mooring system layout

A definition of the 6-DOF motion based on the reference frame for the GMBS and TMBS is shown in Fig. 7. The origin, R , of this reference coordinate system is located at the intersection of the tower centerline and the still water plane surface, where RX is oriented in the direction opposing that of the wind, waves, and current. Moreover, 6-DOF forces and moments for the two load cells and 3-DOF accelerations are also shown in Fig. 7. Wind, wave, and current loads were always directed at 180° orientations during all of the basin tests.

Fig. 7 Definition of coordinates for the 6-DOF motions, forces, moments and accelerations

Seven load cases were defined as outlined in Table 4 to examine the differences between the dynamic characteristics of the two floating systems: the GMBS and TMBS. The test program focused upon three categories including wind only, irregular waves only and a combination of wind and irregular wave settings. Three prototype wind speeds ranging from 5 m/s to 18 m/s are presented. Note that all the wind load conditions applied in this test program were simulated as the steady wind field. In this table, H_s , T_p , and γ represent the significant wave height, spectrum peak period, and spectrum peak factor, respectively. The random wave environment of LC4 was selected to match a one-year return period of the Gulf of Maine (Koo et al., 2012). The test matrix was designed in a manner to experimentally isolate the effects of wind, waves and the combination of wind and waves.

Table 4 Case definitions of the basin test

Remark	Load Case	Wind Speed of the prototype (m/s)	H_s (m)	T_p (sec)	γ
Wind only	LC1	5	-	-	-
	LC2	11.4	-	-	-
	LC3	18	-	-	-
Irregular waves only	LC4	-	7.1	12.1	2.2
Wind with irregular waves	LC5	5	2	8	3.3
	LC6	11.4	7.1	12.1	2.2
	LC7	18	7.1	12.1	2.2

4. Preliminary calibration experiments

Prior to the basin tests, a series of calibration tests were conducted, including the investigation of the wind field quality for determining the spatial homogeneity and turbulence intensity, a fixed wind turbine test for the confirmation of a relationship between wind speeds, rotor thrusts, rotor speeds and frequencies of the wind-generating machine drive, free decay tests to identify the natural periods of the integrated floating wind turbine system based on the GMBS and TMBS and a hammer test of the tower was also utilized to evaluate the natural frequencies of the tower. Once these identification tests had been conducted, the basin tests were initiated. The results of the identification tests are presented and analyzed in this chapter.

4.1 Investigation of the Wind field

To accurately capture the coupled behaviour under simultaneous aerodynamic and hydrodynamic loading, it

was important to design and build a wind generation system capable of providing a controllable wind field. The system developed for this research study is pictured in Fig. 8. It consisted of 9 independently controllable axial fans in a 3 x 3 stacked square configuration. The dimensions of the effective wind output area are 3.76 m times 3.76 m. The system can be used to generate model wind speeds up to 9.53 m/s. To enhance the wind environment quality for steady wind speeds, a honeycomb screen was attached to the front of the wind generation system.

Fig. 8 SJTU Wind Generation System

The quality of the wind to be generated during the model test program was investigated using an array of DANTEC Dynamics MiniCTA anemometers. The array was designed to measure the time-series of the wind at forty-five measurement points and is illustrated in Fig. 9. As shown the array consisted of nine measurement points along the horizontal direction arranged at five different vertical elevations. This array was positioned 3 m downstream from the wind generation system based upon the typical distance between the floating wind turbine system and the wind generating system during the model basin testing. The objective was to characterize the spatial wind speed uniformity and the turbulence intensity in the near field of the spar-type floating wind turbine model.

Fig. 9 Location of the wind field measurement points in the array

The example of the approach used in the characterization of the wind field is presented in Fig. 10. The uniformity of the wind speed and the turbulence intensity are presented in Fig. 10 at model scale based on a targeted wind-making machine frequency of 6.2 Hz which represents the 5 m/s wind velocity load case for both GMBS and TMBS, as listed in Table 5. The wind speed surface as shown represents the smoothed mean wind velocity values of the time histories, and the turbulence intensity surface is the corresponding temporal standard deviation of the time histories divided by the mean wind speed of the time history at each point in the grid (Fowler

et al., 2013). The solid black circle is used to define the rotor plane in the wind field, and the black cross at its center indicates the positioning of the hub center at the $x=1.88$ m, $y=1.506$ m. As observed from these two figures, the spatial uniformity of the wind field is fair, and the turbulence intensity is generally lower than 20% within the rotor plane.

Fig. 10 Wind Speed Profile and Turbulence Intensity at the spar wind turbine model location

4.2 Fixed wind turbine test

The purpose of the fixed wind turbine test was to obtain the target rotor thrust level (the key parameter influencing dynamic behaviors of the floating system) by adjusting the frequency of the wind-generating machine drive and consequently adjusting the wind speed. In this test procedure, to better simulate the prototype rotor operational state, the rotor motion was completely induced by the applied wind loads. Pitch control of the wind turbine blades was not considered in this test program. Therefore, to completely achieve the proper thrust force under each wind speed condition, the wind speed needed to be increased, and the rotor rotational speed varied accordingly. Additional details of the test approach can be found in (Duan et al., 2015a). The relationships between wind speeds, rotor thrust levels, rotor speeds and frequencies of wind-generating machine drive were determined and listed in Table 5. Note that the 1P and 3P (derived from the rotor speed) of these two systems are also presented because some dynamic response behaviours are closely related to them. And this point will be interpreted in detail in the below content.

Table 5 Fixed wind turbine test results

Prototype	Wind Speed (m/s)	5	11.4	18
	Rotor Speed (rpm)	7.5	12.1	12.1
	Rotor Thrust (kN)	276	770.4	451.1
GMBS Measurements	Wind Speed (m/s)	9.4	12.8	11.1
	Rotor Speed (rpm)	7.9	14.4	10.9
	Wind-Generating Machine Drive Frequency (Hz)	6.2	8.3	7.3
	1P (rad/s)	0.827	1.508	1.141
	3P (rad/s)	2.482	4.524	3.42
TMBS Measurements	Wind Speed (m/s)	9.4	13.8	11.8
	Rotor Speed (rpm)	10	9.7	12.3
	Wind-Generating Machine Drive Frequency (Hz)	6.2	8.8	7.7
	1P (rad/s)	1.047	1.016	1.288

	3P (rad/s)	3.142	3.047	3.864
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It should be noted from Table 5 that the measured wind speed decreases when the prototype wind speed is higher than the rated wind speed, as the blade is fixed on the hub during the test, whereas the prototype blade pitches gradually to feather when the prototype wind speed is higher than the rated wind speed. Therefore, the model windward area is larger than that of the prototype, so the model rotor does not require as high of a wind speed as the prototype does to achieve the desired thrust level. In addition, owing to the wind-excited driving mechanism of rotor rotation, the extent of the wind speed increase for the GMBS substantially reduced comparing to MARIN's test, resulting in the reducing of the undesirable excess drag on the non-rotor structures above the water plane. And the variations of the measured rotor speeds for the GMBS shown in Table 5 are acceptable (Duan et al., 2015b).

4.3 Free decay test response

Free decay tests were conducted in calm water to identify natural periods of the integrated floating wind turbine system based on the GMBS and TMBS. The results of the free decay tests for surge, pitch and heave based on the GMBS and TMBS are listed in Table 6, as they are the most significant motions for a spar-type floating wind turbine.

Table 6 Free decay test results

Decay type	GMBS		TMBS	
	Natural period (s)	Natural angular frequency (rad/s)	Natural period (s)	Natural angular frequency (rad/s)
Surge	40.471	0.16	41.327	0.15
Pitch	33.941	0.19	58.511	0.11
Heave	27.538	0.23	28.284	0.22
Yaw	5.946	1.06	11.162	0.56

4.4 Frequency response of the wind tower

The natural structural frequency of the wind turbine tower was evaluated using a hammer test procedure. The rotor-nacelle assembly was not included in this test configuration. The detail information on the test approach can be found in in (Duan et al., 2015b), and the results are presented in Table 7.

Table 7 Tower natural frequency

First mode natural angular frequency (rad/s)	Second mode natural angular frequency (rad/s)
2.6	4.21

5. Test Results and Discussion

In using two kinds of blade systems, these two floating systems (GMBS and TMBS) show various dynamic response characteristics. This chapter compares the response results based on these two floating systems (GMBS and TMBS) under a sequence of wind/wave load cases on purpose of reflecting the distinct response characteristics of the thrust-matched and wide-blade floating wind turbine system relative to those of the traditional geometrically scaled system. We in turn reveal the unique role that the thrust-matched rotor plays in the dynamic response behaviors of the wind turbine floating system, which can serve as a reference for the future further improvements of the model blade designs and model basin testing methods employed under low-Reynolds-number conditions.

5.1 Gyroscopic effects of rotor rotation on yaw motion

In addition to generating electricity, the wind turbine rotor rotation will excite an extra load, resulting in an additional contribution to the yaw motion experienced by the floating platform. This behavior is known as the so-called gyroscopic effect of rotor rotation. The characteristics of the gyroscopic effects on yaw motion based on the GMBS have been discussed in detail in (Duan et al., 2015a). LC2 and LC6 are selected to identify differences in gyroscopic effects between these two floating systems (GMBS and TMBS) and to highlight unique characteristics of the TMBS and the role that the thrust-matched rotor plays in the response behaviors of the wind turbine floating system under wind-only and combined wind-and-wave load conditions. As listed in the test matrix in Table 4, the external wind load of LC2 reflects a prototype rated wind speed condition of 11.4 m/s. The combined loading case, namely LC6, reflects the additional excitation of random waves besides the rated wind excitation effects. The power spectral density (PSD) of yaw motions for these two loads based on the GMBS and TMBS are presented in Fig. 11.

Fig. 11 Comparisons of yaw PSD based on TMBS and GMBS under LC2 and LC6

First, focusing on the wind-only case denoted by LC2, the calculated rotation-excited angular frequencies and peak angular frequencies of yaw for LC2 based on the GMBS and TMBS are listed in Table 8.

Table 8 Comparisons between rotation-excited and peak angular frequencies under LC2

Item	Unit	GMBS	TMBS
Rotation-excited angular frequencies	rad/s	1.508	1.016
Peak angular frequencies	rad/s	1.43	0.996

The rotation-excited angular frequencies (1P) were calculated based on the rotor speed listed in Table 5 (Duan et al., 2015a). It is interesting to note from Table 8 that the peak angular frequencies are nearly identical with those of rotation-excited, which indicates that the yaw oscillations of the GMBS and TMBS are both excited by the gyroscopic effect of rotor rotation. Nevertheless, relative to the GMBS, the TMBS shows much smaller oscillation amplitudes of the rotation-induced yaw responses either experiencing wind-only loading or exposed to an integrated wind-wave field, as depicted in Fig. 11, implying that the gyroscopic effects on TMBS have been weakened. Furthermore, by comparing the response curves of the GMBS (or TMBS) based on these two load cases, it can be observed that the incoming wave amplified the rotation-excited oscillation component of yaw, both for the GMBS and TMBS. Particularly, the incident wave additionally excited a response component of the TMBS at the wave angular frequency and this part of oscillation component was found to be even larger than the rotation-induced one. However, this wave-frequency vibration component is not reflected in the response behaviors of the GMBS.

5.2 Coupling effects between surge, pitch, and heave

Surge, pitch and heave are always the most significant platform motions for a spar-type FOWT, and the coupling effects among them have been discussed in (Duan et al., 2015a). This section focuses on the unique effects of the thrust-matched rotor on surge, pitch, and heave response behaviors. This discussion is based on a combined wind-and-wave case (LC5). The spectra of these three motions for LC5 based on the TMBS and GMBS are superimposed and presented in Fig. 12 and Fig. 13, respectively.

Fig. 12 PSD results of surge, pitch and heave motions for TMBS under LC5

Fig. 13 PSD results of surge, pitch and heave motions for GMBS under LC5

Fig. 12 shows that under combined wind-and-wave condition, surge and pitch responses reflect oscillation components at the natural angular frequencies of each other, denoting that surge and pitch motions are strongly coupled with one another. In addition, from the zoomed-in image shown in Fig. 12, one can conclude that the heave motion only oscillates at the natural frequency of itself while does not reflect any response component neither at the natural frequency of surge nor pitch, representing the heave motion is relatively independent and not subject to any coupling effect of surge or pitch. This conclusion is consistent with surge, pitch and heave response characteristics in the GMBS, as depicted in Fig. 13 and described in (Duan et al., 2015a). Furthermore, it can be observed from Fig. 12 and Fig. 13 that the surge oscillation responses are the most significant, pitch responses the second most significant, and heave responses the least significant, both for the GMBS and TMBS. In particular, in the TMBS, the surge, pitch, and heave responses all reflect the yaw-coupling effect but are negligible relative to

the responses found at the natural angular frequencies. Nevertheless, such yaw-induced coupling is not reflected in the response behaviors of the GMBS, as shown in Fig. 13. Additionally, it should be noted that in the TMBS, the natural frequency of surge (0.15 rad/s) is close to that of pitch (0.11 rad/s), causing the two oscillating components in the surge response curve in Fig. 12 (one is at the surge natural frequency and the other at the pitch-coupled frequency), very close to each other. And the situation of pitch is the same as that of surge, as depicted in Fig. 12. However, in the GMBS, as the natural frequencies of surge and pitch move further closer to each other (0.16 rad/s for surge and 0.19 rad/s for pitch), neither the response of surge nor pitch in Fig. 13 reflects the two oscillation components as shown in Fig. 12 (one is recorded at its natural frequency, and the other is recorded at the natural frequency of the coupled counterpart motion), implying that these two components may have merged as a result of being positioned too close to one another.

To more clearly show distinctions between the GMBS and TMBS for the more significant and concerned motions (surge and pitch), we compare the surge and pitch motions of the GMBS and TMBS for LC5 in Fig. 14. Heave response behaviors are not compared for analysing because of their low oscillation levels. Fig. 14 shows the TMBS has a larger response component at natural frequency while a smaller oscillation component at wave frequency compared to the GMBS, both for surge and pitch.

Fig. 14 Comparison of surge and pitch responses in the GMBS and TMBS under LC5

To more deeply understand the pitch response distinctions between these two systems and the role of thrust-matched rotor plays on the pitch responses, the statistics of pitch motion in GMBS and TMBS based on LC5 is compared and presented in Table 9. As can be indicated in Table 9, TMBS shows a larger mean pitch tilt as expected due to the relatively smaller restoring moment resulted from its higher CM location (listed in Table 3).

Table 9 Statistics of pitch responses in the GMBS and TMBS under LC5

	Unit	Max	Min	Mean
GMBS	deg	-1.89	-3.01	-2.45
TMBS	deg	-3.28	-4.28	-3.74

5.3 Aerodynamic loading effects on motions

Wind loads have a pronounced restraining effect on the surge, pitch and heave oscillation responses found in the GMBS as described in (Duan et al., 2015a). Effects of wind loads on GMBS and TMBS response behaviors are compared in this section to explore the role that the thrust-matched rotor plays in the restraining behaviors of aerodynamic forces. The PSD results of the surge, pitch, and heave motions for LC4 and LC6 in the GMBS and

TMBS are superimposed in figures from Fig. 15 to Fig. 17.

It can be observed from Fig. 15 to Fig. 17 that in the GMBS, wind loads clearly restrain oscillation components at natural frequencies while nearly not affecting wave response components for these three motions as described in (Duan et al., 2015a). Comparatively, in the TMBS, wind loads also have evident suppression effects on oscillation components at natural frequencies for these motions, especially for surge motion, wherein restraining effects can prove quite significant, as shown in Fig. 15. However, restraining effects of wind loads on wave response components in the TMBS present distinct characteristics relative to those in the GMBS. More specifically, in the TMBS, wind loads clearly restrain the wave-frequency oscillation component of surge while slightly amplifying that of pitch and leaving that of heave virtually unchanged, as shown in Fig. 15 to Fig. 17.

Fig. 15 PSD results of surge for TMBS and GMBS under LC4 and LC6

Fig. 16 PSD results of pitch for TMBS and GMBS under LC4 and LC6

Fig. 17 PSD results of heave for TMBS and GMBS under LC4 and LC6

5.4 Dynamic characteristics of tower-top bending moment

For the floating wind turbine system, the axial rotor thrust, tower-top shear force and tower-top bending moment are always the most significant parameters, as they are strongly related to electricity generation efficiency and to the structural safety of the entire floating system. Therefore, this section focuses on the tower-top bending moment, and the shear force will be discussed in the next section with the axial rotor thrust. Note that only the $Fx1$ tower-top shear force, $Fx2$ axial rotor thrust, and $My1$ tower-top bending moment shown in Fig. 7 are analyzed in this paper. For the sake of brevity, $Fx2$ axial rotor thrust is denoted by axial rotor thrust, and $Fx1$ and $My1$ are denoted by tower-top shear force and bending moment, respectively. Distinctions between the dynamic characteristics of tower-top bending moments based on the GMBS and TMBS are examined by comparing the results of response behaviors of these two types of floating systems. The tower-top bending moment of the TMBS shows similar response characteristics as those of the GMBS as well as some differences. These points will be discussed in detail in the following content. PSD comparisons of the tower-top bending moments based on the TMBS and GMBS for LC2 are depicted in Fig. 18.

Fig. 18 PSD comparisons of tower-top bending moment responses for TMBS and GMBS under LC2

Fig. 18 shows that the tower-top bending moment features of the TMBS are similar to those of the GMBS. Tower-top bending moment oscillation in the TMBS is dominated by the coupled excitation of yaw oscillation, which is the same as response features of the GMBS. However, under certain wind load conditions (e.g., LC2), the

oscillation amplitude of the tower-top bending moment in the TMBS is more than 50% lower than that in the GMBS, as shown in Fig. 18.

This discussion thus far has presented response comparisons based on the wind-only condition. Response comparisons of tower-top bending moments both for wind-only and combined wind-and-wave load cases based on these two floating systems are shown in the following section. LC2 and LC6 are used in the comparisons to examine effects of incoming waves on tower-top bending moments in the GMBS and TMBS. Spectra of tower-top bending moments for these two cases based on the GMBS and TMBS are overlaid in Fig. 19.

Fig. 19 PSD comparisons of tower-top bending moments for TMBS and GMBS under LC2 and LC6

It can be observed from Fig. 19 that the incoming wave effects on the GMBS and TMBS are very similar. Incoming waves amplify the oscillation amplitudes of yaw-excited coupling to some extent and additionally excite wave-frequency response components of tower-top bending moments in the GMBS and TMBS. Nevertheless, the wave-frequency response is dominated by the yaw-coupled oscillation, implying either experiencing wind-only loading or exposed to an integrated wind-and-wave field, the yaw-excited coupling is always the dominant contributor for the tower-top bending moment oscillation response in the GMBS and TMBS. Although the tower-top bending moment features in the GMBS and TMBS are similar, the oscillation amplitudes of the TMBS are much larger than those of the GMBS both for wind-only and combined wind-and-wave cases. This difference may be caused by the heavier TMBS rotor mass.

5.5 Axial rotor thrust and tower-top shear force response behaviors

The axial rotor thrust serves as one of the most important parameters of a floating wind turbine system, as it closely relates to platform motions and to the structural safety of the mooring and integrated floating system. However, due to the manufacturing and installation requirements, the data collected through this model test are not the thrust forces applied directly on the hub, but rather contain the inertial forces induced by the motor installed in front of the load cell. Even so, the test data can still reflect the major dynamic characteristics of thrust forces generated due to wind or integrated wind-wave effects. The axial rotor thrust and tower-top shear force are combined together in this section, as their dynamic characteristics are similar to some extent. The spectra of tower-top shear force and axial rotor thrust for LC3 based on the GMBS and TMBS are overlaid in Fig. 20.

Fig. 20 Comparison of the PSD results for TMBS and GMBS under LC3

It can be observed from the zoomed-in image shown in Fig. 20, which presents the response behaviors of the tower-top shear force and axial rotor thrust in the GMBS, that the tower-top shear force and axial rotor thrust in the GMBS show very similar dynamic characteristics and both totally incorporate three oscillation components, excited by yaw coupling, first-order tower vibration and 3P effect, respectively. Additionally, the 3P-excited oscillation dominates the other spectral peak contributions for both the tower-top shear force and axial rotor thrust in the GMBS, as shown in this zoomed-in image. However, the TMBS responses show distinct characteristics. The response behaviors of tower-top shear force are no longer similar to those of the axial rotor thrust. The oscillation of tower-top shear force basically includes two components. One is excited by yaw coupling, and the other is excited by the first-order tower vibration which is also the dominant excitation for tower-top shear force. The axial rotor thrust force in the TMBS, however, only oscillates at the angular frequency of yaw coupling effect, is no longer influenced by the tower elasticity or 3P effects, distinguished from the response characteristics of axial rotor thrust in the GMBS. Generally speaking, oscillation amplitudes of tower-top shear force and axial rotor thrust of the TMBS are much higher than those of the GMBS, and thus, oscillations of the GMBS are disregarded when comparing to those of the TMBS.

Discussion above focuses on the response behaviors of axial rotor thrust and tower-top shear force under wind-only condition. In the following section, we present a more detailed account of the role of combined-wind-and-wave fields in these two load types by comparing axial rotor thrust and tower-top shear force response behaviors in the TMBS and GMBS under wind-only and combined wind-and-wave conditions (LC3 and LC7, respectively). Spectra of axial rotor thrust and tower-top shear force of the TMBS and GMBS under LC3 and LC7 are superimposed and presented in Fig. 21 and Fig. 22, respectively.

Fig. 21 Comparison of the PSD results of tower-top shear force for TMBS and GMBS under LC3 and LC7

Fig. 22 Comparison of the PSD results of axial rotor thrust for TMBS and GMBS under LC3 and LC7

It can be indicated from the zoomed-in images shown in Fig. 21 and Fig. 22, which stands for the tower-top shear force and axial rotor thrust responses in the GMBS, respectively, that the tower-top shear force and axial rotor thrust dynamic characteristics based on the GMBS are still similar under combined wind-and-wave loading condition. The three aforementioned oscillation components found under wind-only condition are influenced by the incoming wave to some extent. Nevertheless, the most significant role the incoming wave plays on the GMBS is to induce oscillation components of these two load types at the wave angular frequency, which dominate the other spectral peak contributions. However, tower-top shear force and axial rotor thrust response behaviors in the TMBS and GMBS show evident distinct characteristics whereas also reflect some commonalities under integrated wind-and-wave loading condition. For the tower-top shear force in the TMBS, the incident random wave has virtually no effect on the oscillation component excited by the first-order tower vibration while somewhat amplifies the yaw-coupling oscillation amplitude due to the aforementioned amplification effect of incoming waves on yaw motion, as previously noted in Fig. 11. Most important of all, there is of course additional response spectral peak associated with the random seaway that dominates the other two spectral peak contributions, implying that the influence of incoming wave is also the most significant excitation factor relative to the effects of tower elasticity or yaw coupling. Incoming wave effects on tower-top shear forces in the TMBS and GMBS are actually similar if not considering the 3P-excited oscillation component.

The response behaviors of axial rotor thrust in the TMBS under combined wind-and-wave condition differ considerably from those of TMBS tower-top shear forces, as shown in Fig. 21, and from those of GMBS axial rotor thrust, as shown in the zoomed-in image in Fig. 22. The incoming wave also excites the wave-frequency response and amplifies the yaw-coupled oscillation amplitude, similar to the effects on TMBS tower-top shear forces and on GMBS axial rotor thrust. However, the yaw-coupled oscillation component of TMBS axial rotor thrust dominates the wave-frequency response, implying that the yaw-coupling effect, rather than the wave-frequency excitation, serves as the most significant motivator of TMBS axial rotor thrust, which is distinct from the response characteristics of GMBS axial rotor thrust and GMBS and TMBS tower-top shear forces under combined wind-and-wave condition. Generally speaking, from the overlapping comparison curves shown in Fig. 21 and Fig. 22, it can be concluded that the oscillation amplitudes of the TMBS are much larger than those of the GMBS for both tower-top shear force and axial rotor thrust either under wind-only or combined wind-and-wave condition.

5.6 Mooring system response characteristics

The dynamic characteristics of mooring tensions in the GMBS and TMBS are compared and discussed in this section. The mooring system was instrumented with three tension sensors located at the joints of two short mooring lines (B and C lines) to measure the tensions on the mooring lines as illustrated previously in Fig. 6. PSD comparisons of the tension of mooring line 2 (TOML2) and tension of mooring line 3 (TOML3) based on the GMBS and TMBS are implemented and presented in Fig. 23. It is recognized that because of the symmetry of the mooring system configuration, the mooring line 2 has been alternatively selected.

Fig. 23 Comparison of the PSD results of TOMLs in the TMBS and GMBS under LC2

Fig. 23 shows that TOML2 and TOML3 for the TMBS/GMBS both show oscillation responses at the same peak angular frequency as that of yaw oscillation of the TMBS/GMBS under LC2, denoting that the rotation-induced yaw has a coupling effect on the mooring system dynamic responses of the TMBS and GMBS when exposed to wind loads. Additionally, the oscillation amplitude of TOML3 is slightly higher than that of TOML2 both in the TMBS and GMBS. However, the oscillation amplitudes of TOML2 and TOML3 in the GMBS are much higher than those in the TMBS.

The above discussion merely compares the response characteristics of the mooring system for these two floating systems under the wind-only condition. However, the response behaviors of the mooring system that is subjected to a combined wind-wave excitation show very distinct characteristics relative to those found under wind-only condition. The excitation contributor transfers from yaw coupling to the other motivator. Consequently,

mooring system responses under integrated wind-wave load conditions in the GMBS and TMBS are presented and compared in the following section. As shown in Fig. 7, based on the wind and wave direction, mooring lines 1 and 2 are in more danger of breaking, as they present higher levels of tension than mooring line 3. When encountering loads, mooring lines 1 and 2 stretch, whereas mooring line 3 compresses. Therefore, greater attention should be placed on mooring lines 1 and 2 for safety purposes. Thus, this section mainly focuses on TOML2. PSD comparisons of TOML2 in the TMBS and GMBS under LC4 and LC6 are presented in Fig. 24.

Fig. 24 PSD comparison of TOML2 levels in TMBS and GMBS under LC4 and LC6

It is interesting to note from Fig. 24 that the response behaviors of TOML2 in the TMBS and GMBS show similar characteristics under combined wind-and-wave condition. They both show three oscillation components, with the first two recorded at the surge and heave natural angular frequencies and with the third one excited at the wave angular frequency, denoting that surge and heave motions have coupling effects on TOML2. Moreover, the surge-coupled response dominates the other two spectral peak contributors, manifesting that surge coupling serves as the key motivator among these three excitation components. Furthermore, the oscillation amplitudes of these three components in the TMBS and GMBS are little different, as a matter of fact. Additionally, the yaw-coupled oscillation observed previously under wind-only condition is found to be disregarded and covered by other response components when exposed to wind-wave loads.

6. Summary and Conclusions

The geometrically scaled model blade with a low model Reynolds number as a result of Froude scaling methodologies performs poorly when implemented in model basin testing programs. This unmatched performance can be greatly improved by utilizing the redesigned thrust-matched wide blade (Fowler et al., 2013). A model test of a spar-type floating wind turbine using the GMBS and TMBS was performed with the purpose of investigating and comparing the dynamic characteristics of these two floating concepts (GMBS and TMBS) under various load conditions in order to gain insight into the nature of the influence of this thrust-matched rotor on the complex floating system response behaviours. Our innovative test results and conclusions based on this model basin experiment can serve as a reference for the further development of high-performance model blade designs and model basin testing procedures in the future. Besides, based on the results presented in this paper, further research works can be conducted like some subsequent specific tests and simulations aimed to more deeply investigate the inherent cause of the differences in responses. The influence of a specific varying parameter (like varying blade inertia or blade chord) on the FOWT responses may also be able to be revealed in more detail in the future works.

Based on the comparisons and analyses of experimental measurements based on the TMBS and GMBS,

several interesting response behaviours were observed and are briefly summarized in Table 10 and as below.

- 1) Yaw oscillations in the GMBS and TMBS are both excited by the gyroscopic effects of rotor rotation, whereas the TMBS shows much smaller oscillation amplitudes under wind-only condition. The incident random wave amplifies the rotation-excited oscillation component of yaw for both the GMBS and TMBS while additionally excites a predominant wave-frequency response only in the TMBS.
- 2) Surge and pitch motions are strongly coupled with each another while heave motion occurs independently of this coupling effect, for both the TMBS and GMBS. The TMBS reflects yaw-coupling effects on surge, pitch and heave while very tiny. Additionally, surge/pitch motion in the TMBS includes a larger oscillation component at natural frequency but a smaller oscillation component at wave frequency relative to the surge/pitch motion in the GMBS.
- 3) Wind loads obviously restrain motion oscillation components at natural frequencies for both the GMBS and TMBS. However, restraining effects of wind loads on wave response components in the TMBS present distinct characteristics relative to those in the GMBS. Wind loads nearly do not influence the wave frequency response in the GMBS. Whereas, in the TMBS, wind loads clearly restrain the wave-frequency oscillation component of surge while slightly amplifying that of pitch and leaving that of heave virtually unchanged.
- 4) Under wind-only condition, tower-top bending moment oscillation is dominated by the coupled excitation of yaw motion in both the TMBS and GMBS. When subjected to integrated wind-wave loads, yaw-excited coupling still serves as the main contributor, whereas incident random waves amplify these yaw-coupled oscillations and additionally excite wave-frequency responses. Furthermore, oscillation amplitudes of the TMBS are much larger than those of the GMBS may result from the heavier TMBS rotor mass.
- 5) GMBS tower-top shear force and axial rotor thrust both incorporate three oscillation components and are both dominated by the 3P-excited oscillation. However, the tower-top shear force does not reflect the 3P-excited response and the axial rotor thrust is only associated with yaw coupling in the TMBS, when wind excitation is solely present. Main influences of the incoming wave on the GMBS and TMBS are to excite the dominant wave-frequency responses and somewhat amplify the yaw-coupled oscillation components while hardly affect the other components. Oscillation amplitudes of tower-top shear force and axial rotor thrust in the TMBS are much higher than those in the GMBS, either under wind-only or combined wind-and-wave condition.
- 6) TMBS and GMBS mooring tensions are both dominated by yaw coupling when exposed to wind loads while governed by surge and heave coupling as well as wave-frequency excitation when experiencing integrated wind-wave loads. Oscillation amplitudes of the TMBS are smaller under wind-only condition but differ little from those of the GMBS under combined wind-wave condition.

Table 10 Comparisons of dynamic response characteristics based on GMBS and TMBS

Dynamic response behaviors	Similarities	Differences
yaw response	excited by the gyroscopic effects of rotor rotation under wind-only condition & rotation-excited oscillation amplified by the incoming wave	wave-frequency response only reflected in the TMBS & TMBS shows much smaller oscillation amplitudes
motions of surge, pitch and heave	Surge and pitch motions are strongly coupled with each another while heave motion is out of this coupling effect	only TMBS reflects yaw-coupling effects on surge, pitch and heave responses & surge/pitch motion in the TMBS includes a larger natural-frequency oscillation but a smaller wave-frequency response

effect of wind loads	obviously restrain natural-frequency responses	nearly do not influence the wave frequency response in the GMBS but clearly restrain wave-frequency response of surge, slightly amplifying that of pitch and leaving that of heave virtually unchanged
tower-top bending moment	dominated by yaw-coupling under wind-only condition & incident waves amplify this predominant yaw-coupled response and additionally excite limit wave-frequency responses.	TMBS shows much larger oscillation amplitudes
tower-top shear force and axial rotor thrust	the incoming wave excites the dominant wave-frequency responses and somewhat amplifies the yaw-coupled oscillations while hardly affect the other components.	tower-top shear force does not reflect the 3P-excited response and the axial rotor thrust is only associated with yaw coupling in the TMBS & TMBS has much larger oscillation amplitudes
mooring tension responses	dominated by yaw coupling when exposed to wind loads while governed by surge and heave coupling as well as wave-frequency excitation when experiencing integrated wind-wave loads.	Oscillation amplitudes of the TMBS are smaller under wind-only condition but differ little from those of the GMBS under combined wind-wave condition.

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