Comparisons of Dynamical Characteristics of a 5MW Floating Wind Turbine supported by a Spar-buoy and a Semi-submersible Using Model Testing methods

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Development of the floating offshore wind turbine technology is in need of more scaled model tests to investigate its dynamical characteristics. This paper presents the model testing investigations of the spar-buoy and the semi-submersible floating wind turbines, and conducts a series of comparisons on the experimental results of the two floating wind turbines. It is found that the spar-buoy floating wind turbine is more sensitive to the wind loading and has larger amplitudes of the platform motion in wind only cases, especially for the yaw motion. By contrast, the semi-submersible floating wind turbine is more sensitive to the wave loading, especially for the second order difference-frequency wave loading. In addition, the dynamic responses of the two floating wind turbines are both influenced by the current flow. Compared to the semi-submersible floating wind turbine, the more regular “figure-eight” surge-sway trajectory is observed in the spar-buoy floating wind turbines, showing the influence from vortex-induced-motion. The paper provides more valuable experimental details and results to the scientific community with regard to the spar-buoy and semi-submersible floating wind turbines. Moreover, the comparison of the dynamic behaviours of the two floating wind turbines in various conditions helps to understand the characteristics and mechanism about the floating wind turbine technology.

I. Introduction

Renewable energy technologies have aroused people attention with the increasingly severe climate change and environmental pollution issues caused by the fossil energy.1 In the mid-90s, professor William E. Heronemus2 firstly proposed the floating offshore wind turbine concept to exploit abundant wind resources in the deep-water districts. This concept recaptures attention with the development of the offshore wind turbine technology and the cost reduction. Compared with the conventional bottom-mounted wind turbines, the floating offshore wind turbines have prominent advantages,3-5 e.g., available wind resources in the deeper water regions, fewer space limitations, reduced noise and visual impact. Nevertheless, there are lots of engineering challenges unsolved for the floating offshore wind turbines technology,6 e.g., optimized floating wind turbine design, more advanced controller, coupled dynamics mechanism, verification on numerical tools, etc. Development of the floating wind turbine technology is still in progress.

Researchers all over the world proposed various new floating wind turbines seeking innovative supporting platforms. Based on the physical principle to achieve static stability, the floating wind
turbines can be roughly divided into three categories: \(^6\,^7\) ballast type (e.g., spar-buoy), buoyancy type (e.g., semi-submersible), and mooring lines type (e.g., tension leg platform (TLP)). The ballast type floating wind turbines achieve stability through the centre of gravity located below the centre of buoyancy to create a righting moment and high inertial resistance to rotational motion. The buoyancy type floating wind turbines are stabilized by the distributed buoyancy and the righting moment generated by the variation of the weighted water plane area. Mooring lines type floating wind turbines achieve stability through the resultant of force produced by the mooring lines tendon tension and the excessive buoyancy of the hull. Currently, the ballast type floating wind turbines (e.g., spar-buoy) and buoyancy type floating wind turbines (e.g., semi-submersible) are more popular, and some are even implemented to prototypes due to their low cost and great dynamic performances.

The first full-scale floating wind turbine demonstration, Hywind (a spar-buoy floating wind turbines), was conducted off the coast of Norway in 2009. \(^8\) In 2011, a full-scale semi-submersible floating wind turbine, WindFloat, was deployed 5 km off Portugal’s coast. \(^9\) From 2013 to 2015, the Fukushima floating offshore wind farm demonstration project was carried out using a 2MW compact semi-submersible floating wind turbine, a 7MW advanced spar-buoy floating wind turbine, a 7MW V-shape semi-submersible floating wind turbine and a floating power sub-station. \(^10\) The first offshore grid-connected wind turbine in the Americas, VolturnUS, was tested from 2013 to 2014 off Castine in eastern Maine, USA. \(^11\) The world’s first commercial wind farm with five Hywind floating wind turbines were deployed 29 kilometres off Peterhead, Scotland in 2017. \(^12\) However, prototypes relied heavily on industrial investments, which makes the valuable measured data unavailable to normal researchers. By comparison, the scaled basin model tests have many advantages to investigate complicated dynamic properties of the floating wind turbines, e.g., less risk, less time, less resources, better controls and repeatable environmental conditions. Some famous basin model tests are: in 2006, the Hydro Oil & Energy Company conducted a 1/47\(^{th}\) scale 5-MW spar-buoy floating wind turbine model test at MARINTEK (Norwegian Marine Technology Research Institute). \(^13\) In 2012, three 1/50\(^{th}\) scale model tests for three different floating wind turbines (a tension-leg, a spar-buoy and a semi-submersible) were carried out at the MARIN (Maritime Research Institute Netherlands) supported by the DeepCwind consortium. \(^14\) In 2014, a research team of the Norwegian University of Science and Technology (NTNU) performed a 1/50\(^{th}\) scale STC model test (an innovative combination of a wave power generation equipment and a spar-buoy floating wind turbine) at the towing tank of the MARINTEK. \(^15\) Nevertheless, most of works only present the details of the single floating wind turbine model test, but comparison of various floating wind turbines is relatively few. \(^16\,\,17\)

Considering aforementioned situation, this paper presents comparison of the dynamical characteristics of a spar-buoy and a semi-submersible floating wind turbine using the experimental results conducted at the Deepwater Offshore Basin of Shanghai Jiao Tong University. In the following, the scaling methodology with correction approaches is described (in Section II.A), followed by a description of the wind field test (in Section II.A) and a description of the model configuration (e.g., the wind turbine configuration, the model tower configuration, the floating platform configuration, the mooring lines configuration, etc. in Section II.B). Subsequently, a series of comparison on dynamic properties of the spar-buoy and the semi-submersible floating wind turbines are analyzed and discussed through the decay motion test, responses in wind-only cases, in wave-only cases, in combined wind-wave cases and in combined wind-wave-current cases, respectively (in Section III). The paper provides the following contributions:

(1) The article provides more valuable experimental details and data to the scientific community for
their purpose of verification on their numerical tools, experimental design and investigation on the characteristics of the floating wind turbines.

(2) Through comparing dynamic behaviours of the spar-buoy and the semi-submersible floating wind turbines in varies conditions, it can be a reference for designing new floating wind turbines concepts or optimizing the existing concepts, especially for the hybrid-type floating wind turbines in the future.

(3) The article reveals dynamic characteristics of the two floating wind turbines and compares their discrepancies with the current flow, which is few published and valuable.

II. Model test set-up

A. Scaling methodology and Reynolds number dissimilitude solution

In general, Froude number (the ratio of inertia forces to gravity forces) is employed for wave loading scaled in water basin tests, but Reynolds number (the ratio of inertia forces to viscous forces for fluid flow) is more common for wind loading scaled in wind tunnel tests. A floating wind turbine is made up of a wind turbine and a floating platform structure, meaning that Froude number similitude and Reynolds number similitude should be satisfied simultaneously in a floating wind turbine model test. Nevertheless, Reynolds number similitude is impractical in the wind/wave basin environment. Therefore, Froude number similitude instead of Reynolds number similitude is employed for a floating wind turbine model test in practice. Based on Froude number law with geometric scaling ratio of 50:1, the Reynolds number at model scale is much smaller than the prototype’s, which results in great difference in rotor performances between the scales, especially for the aerodynamic thrust force. On account of this problem, the solution “adjustable wind speed method” was used to improve the aerodynamic thrust force in the model tests. This method was performed as follows: firstly, the wind turbine was fixed 3 m downstream from the wind generator system. And then, the power (frequency) of the wind generator system was tuned until the aerodynamic thrust force acting on the rotor was equivalent to the target value. For instance, the aerodynamic thrust force acting on the prototype floating wind turbine is 770.4 kN at full scale in the condition with the wind speed of 11.4 m/s. In practice, the power of the wind generator system was tuned until the aerodynamic thrust force on the model rotor was also equivalent to 770.4 kN. At this time, the actual measured wind speed in the model test was 12.8 m/s at full scale, which was slightly greater than the prototype value of 11.4 m/s.

In most floating wind turbines model tests using the “adjustable wind speed method”, the electric motor is scheduled to drive the rotor, for instance, MARIN’s tests. The model wind speed hence has to be increased a lot, which gives rise to undesirable aerodynamic loading on the tower and the platform hull above water surface. In contrast, the model rotor presented in the paper is purely driven by the wind loading not the electric motor, which is closer to reality. As for the electric motor, it is merely used to represent the wind turbine generator with adjustable resistance properties and the controller is inactive in the test. Therefore, the adjustment of the wind speed in the model test presented in the paper is less than that in the MARIN’s tests. It is beneficial to reducing the undesirable wind impact on the tower and the platform hull above water surface. The rotor thrust force, wind generator frequency, wind speed and the rotational speed at full-scale are listed in Table I.

TABLE I. Measured in wind field tests.
The wind generator system (see Fig. 1a) is made up of 9 controllable fans (3 by 3 stacked square configuration) with an effective wind output area of the square of 3.76 m, which covers the extreme range of the rotor in most cases. A honeycomb screen (see Fig. 1b) was fabricated to cover the outlet of the wind generator system to reduce wind flow turbulence. More details about the wind field tests process and data can be found in the Ref.19.

![Fig. 1](image)

**FIG. 1.** (a) Wind generator system and (b) honeycomb screen.

### B. Model description

#### 1. Rotor-Nacelle Assembly structure

The model blades (see Fig. 2a) are geometric copies of the 5MW NREL horizontal axis reference wind turbine. The model blades were fabricated as a hollow structure (see Fig. 2b) using a woven-carbon-fiber-epoxy composite material with the mass of 137g. In order to reduce the complexity of the model blades, the blades are stiff. Subsequently, shown in Fig. 2c, the blades are mounted to the hub at 0 degree pitch angle, and the hub is connected to the motor through the shaft. As can be seen in Fig. 2c, a load cell installed at the interface between the rotor-nacelle assembly (RNA) structure and the tower is used to measure the forces and moments here. Another load cell is installed at the tail of the RNA structure. An accelerometer is also fixed in the rear of the nacelle to measure the 3-DOF accelerations of the RNA structure. The properties of components of the RNA structure at full-scale is listed in Table II.

#### TABLE II. Properties of the RNA structure.

<table>
<thead>
<tr>
<th>Item</th>
<th>Blades (3)</th>
<th>Hub</th>
<th>Nacelle</th>
<th>Cables &amp; Sensors</th>
<th>Total wind turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (kg)</td>
<td>52,659</td>
<td>57,272</td>
<td>232,291</td>
<td>120,182</td>
<td>462,404</td>
</tr>
<tr>
<td>CM (m)</td>
<td>90.65</td>
<td>90.65</td>
<td>90.65</td>
<td>53.16</td>
<td>80.91</td>
</tr>
</tbody>
</table>
The model tower was fabricated with reference to the OC3 Hywind tower\textsuperscript{21}. Schematic of the model tower are shown in Fig. 3a (mass is 287,128kg and the barycenter is 51m at full-scale). An aluminum 6061 alloy material was employed to fabricate the tower in view of its relatively low cost, low stiffness, and higher resistance to the deterioration in the wind/wave basin.

In order to identify the natural frequencies of the model tests, a hammer test was conducted. As shown in Fig. 3b, the model tower was connected to a load cell and then mounted to the land inversely. Subsequently, to hit the middle of the model tower quickly with a hammer and the bending moment caused by the tower vibration was measured by the load cell. The first and second natural frequencies of the model tower alone were recorded in Table III. Since the model tower would be mounted to the supporting floating platform in the formal basin tests, the natural frequencies of the tower would be changed more or less in different floating platforms. According to the frequency spectrum of the tower responses of the spar-buoy and semi-submersible floating wind turbine in the formal tests, the tower natural frequencies in the two floating wind turbines are recorded in Table III. It is unexpected that the natural frequencies of the tower increases when mounted to the spar-buoy and semi-submersible supporting platforms. By comparison, the tower natural frequencies of the spar-buoy floating wind turbine is greater than the semi-submersible floating wind turbine’s a bit, which likely results in different tower vibration responses of the two floating wind turbines subjected to the same condition. A similar research finding is given by Martin\textsuperscript{15}.

### TABLE III. Measured tower bending natural frequencies.

<table>
<thead>
<tr>
<th>Form</th>
<th>1\textsuperscript{st} FA (rad/s)</th>
<th>2\textsuperscript{nd} FA (rad/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower alone</td>
<td>2.63</td>
<td>4.21</td>
</tr>
<tr>
<td>Tower placed on spar-buoy</td>
<td>2.88</td>
<td>4.48</td>
</tr>
<tr>
<td>Tower placed on semi-submersible</td>
<td>2.66</td>
<td>4.27</td>
</tr>
</tbody>
</table>
3. Supporting floating platform

Schematic of the spar-buoy floating platform and image of the hammer test.

3. Supporting floating platform

Schematic of the spar-buoy and a semi-submersible floating platform are shown in Fig. 4. The spar-buoy floating platform is a copy of that of the OC3-Hywind floating wind turbine. It is made up of two different size cylinder structures and a tapered structure. The cylinder above the taper is slender than the cylinder below the taper to reduce hydrodynamic loading near the free water surface. The spar-buoy floating wind turbine achieves stability by separation between the center of buoyancy and the center of gravity. The center of gravity hung below the center of buoyancy to create a righting moment and high inertial resistance to rotational motion, e.g., pitch motion and roll motion. As for the semi-submersible floating wind turbine, the OC4-DeepCwinds semi-submersible floating platform is adopted, which consists of four main columns, lots of smaller diameter pontoons and cross components. One main column at the center is smaller and supports the tower structure. Other three offset columns are connected to the center column and the other small components are connected to these columns. The semi-submersible floating platform is stabilized using the distributed columns and the righting moment produced by the variation of the weighted water plane area. The tower is cantilevered at the top of the floating platform of 10 m above the still water level. The 6-DOF motions of the floating platform were measured by the active optical markers installed near the base of the tower (see Fig. 5). Properties of the spar-buoy and semi-submersible platform at full-scale are listed in Table IV. Most obviously, the total mass and rotational inertia of the semi-submersible floating wind turbine is greater than the spar-buoy floating wind turbine. And the centre of gravity of the spar-buoy floating wind turbine is much lower than the semi-submersible floating wind turbine.

TABLE IV. Properties of the spar-buoy and semi-submersible platform at full-scale.

<table>
<thead>
<tr>
<th>Types</th>
<th>Platform mass with ballast (kg)</th>
<th>Center of gravity (m)</th>
<th>Pitch inertia (kg.m²)</th>
<th>Roll inertia (kg.m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spar-buoy</td>
<td>7,316,578</td>
<td>-94.15</td>
<td>4,656,382,813</td>
<td>4,656,382,813</td>
</tr>
<tr>
<td>Semi-submersible</td>
<td>12,878,750</td>
<td>-13.50</td>
<td>6,310,000,000</td>
<td>6,310,000,000</td>
</tr>
</tbody>
</table>
4. Mooring system and offset tests

The spar-buoy floating wind turbine is moored by a taut mooring system (see Fig. 6a), three delta connections\(^2\) are used to improve the yaw stiffness of the spar-buoy. Each delta connection consists of three mooring segments of vary properties. Tension sensors at the junction between the mooring segments A, B and C are used to measure the tension force of the mooring lines in the basin tests. For the semi-submersible floating wind turbine (see Fig. 6b), three catenary mooring lines connected to the fairleads located at the top of the based columns are used to hold the floating platform against wind, waves and current flow. As can be seen that the catenary lines is spread symmetrically about the centre of the platform at each 120°, and the three tension sensors at the junction between the mooring lines and fairleads are used to measure tension force of the mooring line. Comparison of the mooring lines properties of the two floating wind turbines at full-scale are listed in Table V.
FIG. 6. Layout of mooring system of (a) spar-buoy and (b) semi-submersible.

TABLE V. Properties of the mooring system of the two floating wind turbines

<table>
<thead>
<tr>
<th>Items</th>
<th>Spar-buoy</th>
<th>Semi-submersible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mooring lines amount</td>
<td>A: 3; B &amp; C: 6</td>
<td>3</td>
</tr>
<tr>
<td>Angle between adjacent lines (°)</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Depth of anchors (m)</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Depth of fairleads (m)</td>
<td>70</td>
<td>14</td>
</tr>
<tr>
<td>Radius of anchor (m)</td>
<td>445</td>
<td>853.7</td>
</tr>
<tr>
<td>Radius of fairleads (m)</td>
<td>5.2</td>
<td>40.868</td>
</tr>
<tr>
<td>Unstretched mooring line length (m)</td>
<td>A: 424.35; B &amp; C: 30</td>
<td>835.5</td>
</tr>
<tr>
<td>Mooring line diameter (m)</td>
<td>A: 0.167; B &amp; C: 0.125</td>
<td>0.0766</td>
</tr>
<tr>
<td>Equivalent line mass density (in air) (kg/m)</td>
<td>A: 22.5; B &amp; C: 12.6</td>
<td>113.35</td>
</tr>
<tr>
<td>Extensional stiffness (MN)</td>
<td>A: 121; B &amp; C: 68</td>
<td>735.6</td>
</tr>
</tbody>
</table>

The mooring line stiffness along longitudinal and transversal direction for the two floating wind turbines is measured by the offset tests and shown in Fig. 7. The tension-offset curves of the two mooring lines systems are similar in general, but the stiffness of the mooring lines of the spar-buoy floating wind turbine are greater than those of the semi-submersible floating wind turbine.
C. Coordinate system and Environment

The model tests for the two floating wind turbine were launched at the Deepwater Offshore Basin of Shanghai Jiao Tong University. The water basin equipped with wave, wind and current generating system and other advanced testing facilities, is 50 m in length, 40 m in width and 10 m in depth. Coordinates for the 6-DOF motion and sensors of the floating wind turbine models are shown in Fig. 8. The coordinate origin ‘o’ is located at the intersection of the tower centreline and the initial water surface, and the positive X₀ coordinate axis is in the opposite direction of the wind, wave and current during the tests.

D. Fee-decay tests

Fee-decay tests were conducted to identify some primary dynamic characteristics of the two floating wind turbines, e.g., natural frequencies and damping ratio of the 6-DOF motion. The measured results are listed in Table VI, and compared in Fig. 9. Fig. 9 clearly shows that the surge and sway stiffness of the spar-buoy floating wind turbine are greater than those of the semi-submersible floating wind turbine. It is caused by the larger stiffness of the taut mooring system used in the spar-buoy (see Fig. 7). The heave, roll and pitch natural frequencies of the spar-buoy are smaller than those of the semi-submersible a bit. This is due to the fact that the semi-submersible floating wind turbine has larger waterline plane, higher vertical center of buoyancy and greater displacement of volume. Fig. 9 clearly shows that the yaw stiffness of the spar-buoy floating wind turbine is much greater than the semi-submersible floating wind turbine, which is largely due to that the delta connection mooring system of the spar-buoy floating wind turbine increases the yaw stiffness. As to damping coefficient, the damping of the semi-submersible floating wind turbine are greater than the spar-buoy floating wind turbine’s except for the yaw motion. This is caused by that lots of submerged trusses and pontoons of the semi-submersible platform increase the hydrodynamic damping. However, it is unexpected that the damping of the yaw motion of the spar-buoy is greater. It is possibly because of the larger structural damping of the delta mooring lines configuration used in the spar-buoy floating wind turbine.

In conclusion, the semi-submersible platform has relatively larger waterline plane, larger rotational inertia, higher vertical center of buoyancy, greater displacement of volume and amount of submerged components, hence it has greater heave stiffness, roll stiffness, pitch stiffness and
hydrodynamic damping. In contrast, it is noted that the delta mooring lines system used in the spar-buoy floating wind turbine increases its yaw stiffness and damping a lot.

TABLE VI. Natural frequencies and damping of the two floating wind turbines.

<table>
<thead>
<tr>
<th>Motion</th>
<th>Natural frequency (rad/s)</th>
<th>Damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge</td>
<td>0.154</td>
<td>0.038</td>
</tr>
<tr>
<td>Sway</td>
<td>0.153</td>
<td>0.040</td>
</tr>
<tr>
<td>Heave</td>
<td>0.238</td>
<td>0.028</td>
</tr>
<tr>
<td>Roll</td>
<td>0.177</td>
<td>0.013</td>
</tr>
<tr>
<td>Pitch</td>
<td>0.194</td>
<td>0.023</td>
</tr>
<tr>
<td>Yaw</td>
<td>1.06</td>
<td>0.054</td>
</tr>
</tbody>
</table>

FIG. 9. Comparison of (a) natural frequencies and (b) damping of the two floating wind turbines.

A set of test cases are carried out to investigate dynamic behaviours of the spar-buoy and semi-submersible floating wind turbine, which are shown in Table VII. The wind and wave listed in Table VII are in the heading direction during the tests with a duration of 8.5 min (1 h at full-scale). Where $H_s$ represents the significant wave height, $T_p$ represents the spectral peak wave period, and $\gamma$ represents the spectral peak parameter.

TABLE VII. Test matrix.

<table>
<thead>
<tr>
<th>Cases Type</th>
<th>Case No.</th>
<th>Wind speed (m/s)</th>
<th>Current (m/s)</th>
<th>$H_s$ (m)</th>
<th>$T_p$ (s)</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind only</td>
<td>LC1</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>LC2</td>
<td>11.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>LC3</td>
<td>23</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Wave only</td>
<td>LC4</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>8</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>LC5</td>
<td>0</td>
<td>0</td>
<td>7.1</td>
<td>12</td>
<td>2.2</td>
</tr>
<tr>
<td>Wind-wave</td>
<td>LC6</td>
<td>5</td>
<td>0</td>
<td>2</td>
<td>8</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>LC7</td>
<td>11.4</td>
<td>0</td>
<td>7.1</td>
<td>12</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>LC8</td>
<td>23</td>
<td>0</td>
<td>7.1</td>
<td>12</td>
<td>2.2</td>
</tr>
<tr>
<td>Wind-wave-current</td>
<td>LC9</td>
<td>23</td>
<td>1.2</td>
<td>7.1</td>
<td>12</td>
<td>2.2</td>
</tr>
</tbody>
</table>
III. Results and discussion

In this section, a series of comparison of dynamic responses between the spar-buoy and the semi-submersible floating wind turbine are carried out in wind-only cases, wave-only cases, combined wind-wave cases, and combined wind-wave-current cases, respectively. Through this work, it helps to understand the dynamic characteristics and differences of the spar-buoy and the semi-submersible floating wind turbines, and contributes to designing new floating wind turbines concept, especially for hybrid-type floating wind turbines in the future.

A. Wind-only case

In the wind-only cases, the wind loading and wind-induced motions are usually the key issues. Wind speed measured by the sensor (close to the hub of the wind turbine) for the cases LC1 and LC2 are shown in Fig. 10. As can be seen in Fig. 10b, the low-frequency component of the model wind field is major but the high-frequency component is negligible. The wind loading likely gives rise to the low-frequency motion of the platform more or less, which is discussed later in this section.

![Time series of wind speed](image)

(a)

![Frequency spectrum of Wind speed](image)

(b)

FIG. 10. Wind speed: (a) in time series and (b) in frequency spectrum.

The shear force on the interface between the tower and the rotor-nacelle-assembly structure (measured by the Load Cell#1, see Fig. 8) of the two floating wind turbines is plotted in Fig. 11. It shows that the shear force here is influenced by the rotating rotor at the 1P, 2P and 3P frequency (1P, 2P and 3P denote the frequencies which are once, twice and three times the rotational frequency of the rotor, respectively) and tower natural frequencies. Comparing the two floating wind turbines, the semi-submersible floating wind turbine has much greater response around its first-order tower natural frequencies for LC1 (5m/s), but the spar-buoy has greater response for LC2 (11.4m/s). As mentioned in Table III, the natural frequencies of the tower of the spar-buoy floating wind turbine is greater than that of the semi-submersible floating wind turbine. Hence, the 3P frequency for LC1 is closer to the first-order natural frequency of the tower of the semi-submersible floating wind turbine, giving rise to the resonant response of the tower structure at this time. There is a similar situation for LC2 to the spar-buoy floating wind turbine due to its larger tower natural frequency.
The surge, pitch and yaw motions of the two floating wind turbines for LC1 and LC2 are compared in Figs.12-14, respectively. The dynamic response of the two floating wind turbines increases as the wind state grows more severe not only in time-domain but also in frequency-domain. It shows that the surge and pitch motion of the two floating wind turbine have low-frequency responses and resonant responses. It is due to the low-frequency wind loading (see Fig. 10b). Compared to the semi-submersible floating wind turbine, the average surge and pitch motion of the spar-buoy floating wind turbine is greater (see the boxplots in Fig. 12) and show greater low-frequency motion responses (see the power spectral density curves in Fig. 12). In addition, it is interesting that the surge motion of the spar-buoy floating wind turbine shows 1P frequency responses, which indicates that the spar-buoy floating wind turbine is more sensitive to the wind excitation loading. This is due to that the spar-buoy floating wind turbine has lower centre of gravity and smaller waterline plane, and thus results in the larger aerodynamic moment but smaller hydrostatic restoring moment relative to the centre of gravity. More interestingly, the yaw motion of the spar-buoy floating wind turbine shows much greater responses amplitude than that of the semi-submersible floating wind turbine. In the frequency-domain, the peak of the power spectral density occurs at the 1P frequency, which is mainly caused by the gyroscopic moment and the vertical component of the aerodynamic torque with a rotating rotor. Comparing with the semi-submersible floating wind turbine, the spar-buoy floating wind turbine has smaller yaw radius and the smaller yaw inertia in spite of greater yaw stiffness induced by the delta mooring line.

(a) 
(b) 

FIG. 11. Comparison of shear force for (a) LC1 and (b) LC2.

(a) 
(b) 

FIG. 12. Comparison of surge motion for (a) LC1 and (b) LC2.
B. Wave-only case

Power spectral density of the wave elevation measured in the two floating wind turbine tests for the cases LC4 and LC5 is shown in Fig. 15. It shows a good agreement of the two floating wind turbines tests that the wave spectral peak is around 0.80 rad/s for LC4 and around 0.54 rad/s for LC5, which are coincide with the theoretical values well.
Cell#1 for the wave-only cases (LC4, LC5) are presented in Fig.16. The two floating wind turbines all show response peaks at the pitch motion natural frequency, in the wave-energy domain, and at the tower natural frequency. Nevertheless, the impact on the different floating wind turbines is different a bit. Comparing the two floating wind turbines, the semi-submersible floating wind turbine shows greater pitch-induced responses but smaller wave-induced response than the spar-buoy floating wind turbine in frequency-domain.

For the wave-only cases (LC4 and LC5), Fig.17-19 show that the 6-DOF motions of the two floating wind turbines have narrow-banded peak responses at their natural frequencies and wave excitation responses in the wave-energy domain. Moreover, the motion increases as the more severe wave state (from LC4 to LC5). By comparison, the resonant response amplitude of the surge and pitch motion of the semi-submersible floating wind turbine is greater than the spar-buoy floating wind turbine, especially for the pitch motion. The difference in the pitch resonant motion is due to that the semi-submersible platform has the larger waterline plane and is hence subjected to the greater wave-induced overturning moment. The difference in the surge resonant motion is resulted from the fact that the surge motion of the semi-submersible floating wind turbine is more sensitive to the second-order difference-frequency wave loading. As to the yaw motion, the two floating wind turbines all show resonant yaw responses at their yaw natural frequencies. As listed in Table VI, the yaw natural responses of the semi-submersible floating wind turbine is smaller and closer to the lower frequency domain, hence the yaw resonant motion of the semi-submersible floating wind turbine increases as the spectral peak wave frequency moves to the low-frequency domain from LC4 to LC5. An opposite situation for the spar-buoy floating wind turbines because of its larger yaw natural frequency. Moreover, the yaw motion of the spar-buoy floating wind turbines seems to be more sensitive to the wave excitation loading. Nevertheless, compared with the yaw motion induced by the wind loading mentioned earlier, the yaw motion of the floating wind turbines induced by the wave loading is much smaller.
C. Combined wind-wave case

For combined wind-wave cases, the shear force measured by the Load Cell#1 is more complicated than that mentioned earlier, affected by the wind loading, wave loading, the tower vibration, the platform motion, and the rotating rotor. By comparison, the shear force of the semi-submersible floating wind turbine shows a much greater responses peak at its first-order tower natural frequency for LC6, which is in agreement with that occurs in wind-only case (see Fig. 11a). For LC7, the spar-buoy floating wind turbine shows greater wave-induced responses and the first-order tower natural frequency
response, which is in agreement with that in the wind-only cases (see Fig. 11b) and the wave-only case (see Fig. 16b).

The surge, pitch and yaw motions of the two floating wind turbines in combined wind-wave cases are shown in Figs. 21-23. In general, the surge and pitch motions responses in combined wind-wave cases are similar to the responses occur in the wind-only and the wave-only cases to a certain extent. The average value and the low-frequency responses of the surge and pitch motion of the spar-buoy floating wind turbine are greater, which are in line with those in the wind-only cases. By comparison, the semi-submersible floating wind turbine has greater surge and pitch resonant responses and wave-induced responses generally, especially for the pitch motion, which is more agreement with that in the wave-only cases. Nevertheless, the yaw motion of the spar-buoy floating wind turbine is much greater and shows a peak at the 1P rotating frequency, which is in agreement with that in the wind-only cases.

FIG. 20. Comparison of shear force for (a) LC6 and (b) LC7.

(a)                             (b)
FIG. 21. Comparison of surge motion for (a) LC6 and (b) LC7.
It is found that the aerodynamic damping is likely to perform significant effects on the dynamic responses of the floating wind turbines.\textsuperscript{24,25} The surge and pitch motions of the two floating wind turbines for the wave-only case (LC5) and combined wind and wave case (LC7) are compared in Fig. 24. It shows that the surge and pitch resonant responses peaks of the two floating wind turbines in the combined wind-wave cases are all reduced obviously but there is little impact on the motion responses in wave-energy domain. This is more obvious for LC7 due to the higher wind speed employed. In contrast of the two floating wind turbines, it is unexpected to find that the aerodynamic damping effect of the semi-submersible floating wind turbine is more distinct than the spar-buoy floating wind turbine. As known that the incoming wind not only produces aerodynamic damping loading but also wind excitation loading. The aerodynamic damping loading suppresses the platform motion, but the wind excitation loading intensifies the platform motion. As mentioned earlier, the spar-buoy floating wind turbine is more sensitive to the wind excitation loading. Hence, the aerodynamic damping effect is offset by the wind excitation loading to some extent for the spar-buoy floating wind turbine.
In summary, the dynamic responses of the floating wind turbines in the combined wind-wave cases are influenced by various loads, e.g., the wind loading, the wave loading and the tower vibration. Nevertheless, it is not a simple superposition. The primary factors are different for different floating wind turbines, for example, the platform motion of the spar-buoy floating wind turbine is more sensitive to the wind loading, but that of the semi-submersible floating wind turbine is more sensitive to the wave loading. In addition, it is found that the aerodynamic damping effect of the semi-submersible floating wind turbines is more obvious than the spar-buoy floating wind turbine because that the spar-buoy floating wind turbine is more sensitive to the wind excitation loading.

D. Combined wind-wave-current case

Researchers found that the shape of wave is influenced by the current flow\textsuperscript{26-28}, and the wavelength becomes longer and the amplitude of the wave becomes smaller with the current flow in the wave direction, but opposite situation with the reverse current flow. This is also proved by the wave elevation measured in the basin tests (see Fig. 25). As shown in Fig. 25, the amplitude of the wave and the spectral density peak become smaller for the cases with the current flow in the wave direction.

The change of the wave with the current flow probably affects the dynamic responses of the floating wind turbines. Moreover, when the current is flowing past the submerged body, vortex...
shedding is likely produced around the submerged body and then causes additional drag force (surge direction) and lift force (sway direction) acting on the submerged body, which likely gives rise to the surge and sway motions of the floating wind turbines. The surge and sway motions of the spar-buoy and the semi-submersible floating wind turbine are shown in Figs. 26 and 27, respectively. The boxplots in Fig. 26 show that the mean surge motion of the floating wind turbine becomes greater. It is due to the drag force induced by the current flow. Fig. 26 also shows that the surge motion becomes smaller at the resonant frequency and in the wave-energy domain when subjected to the current flow. As mentioned earlier, the amplitude of the wave becomes smaller with the current flow in the wave direction, wave-induced surge responses hence become smaller. Interestingly enough, Fig. 27 shows that the sway motion becomes greater and gives rise to the sway resonance when subjected to the current flow. This is due to that the pulsating lift force induced by the vortex shedding intensifies the sway motion of the floating wind turbines.

Researches show that the frequency of the drag force induced by the vortex shedding is twice the frequency of the lift force, and the floater hence moves following the trajectory like a “figure-eight”. As shown in Fig. 28, the surge-sway trajectory of the two floating wind turbines for the combined wind-wave-current case (LC9) is more like “figure-eight” than that for the case without the current flow (LC8). Compared to the semi-submersible floating wind turbine, the surge-sway trajectory of the spar-buoy floating wind turbine is more regular like “figure-eight”. It is because that the submerged body of the spar-buoy floating wind turbine is a single cylinder, which is more like a typical
“flow around a circular cylinder” issue. By contrast, the semi-submersible floating wind turbine has lots of submerged pontoons. The combined action of the vortex-induced motion of these submerged pontoons of the semi-submersible floating wind turbine is more complex and irregular.

It is interesting to find that the yaw motion becomes greater in the combined wind-wave-current case (LC9), as shown in Fig. 29. This is due to the fact that the vortex shedding around the submerged body intensifies imbalance in the yaw motion direction. Compared to the spar-buoy floating wind turbine, the change of the yaw motion of the semi-submersible floating wind turbine between cases is more apparent (see Fig. 29). This is because that lots of submerged pontoons of the semi-submersible floating wind turbine make the yaw imbalance more obvious.

![Surge-sway trajectory with/without current (LC8 & LC9).](image1)

(a) Spar-buoy (b) Semi-submersible

FIG. 28. Surge-sway trajectory with/without current (LC8 & LC9).

![Comparison of yaw motion for cases with/without current (LC8 & LC9).](image2)

(a) Spar-buoy (b) Semi-submersible

FIG. 29. Comparison of yaw motion for cases with/without current (LC8 & LC9).

IV. Conclusions

This paper addresses the details of the scaled spar-buoy and the semi-submersible floating wind turbine model tests, and conducts a description of their configuration and the identification tests. Subsequently, the experimental results of the two floating wind turbines are compared and discussed in wind-only cases, wave-only cases, combined wind-wave cases and combined wind-wave-current cases, respectively. It is found that the dynamic behaviours of the two floating wind turbines have some similarities and some remarkable differences (listed in Table VIII). As a matter of fact, they have their own strengths and weaknesses. The comparison of the dynamic behaviours of the two floating wind turbines in various cases helps to understand the characteristics and mechanism about the floating wind turbine technology, and can be a reference for designing new floating wind turbines or optimizing the...
existing floating wind turbines.

### TABLE VIII. Summary of dynamical characteristics between the two floating wind turbines.

<table>
<thead>
<tr>
<th>Case</th>
<th>Similarity</th>
<th>Differences</th>
<th>Differences reasons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind-only</td>
<td>1. RNA is influenced by the rotating rotor, platform motion and tower vibration; 2. Motion shows peak responses at its resonant frequency and rotor rotational frequencies.</td>
<td>1. Resonant responses of the RNA of the spar-buoy occur in the higher rotating frequency case; 2. Spar-buoy has greater average surge and pitch motion and much greater yaw motion.</td>
<td>The tower natural frequencies of the spar-buoy is greater than the semi-submersible; Spar-buoy has lower centre of gravity, smaller water plane and smaller turning radius of yaw.</td>
</tr>
<tr>
<td>Wave-only</td>
<td>1. RNA shows peak responses at the pitch natural frequency and in wave-energy domain; 2. Platform motion shows narrow-banded peak responses at the natural frequencies and in wave-energy domain; 3. Platform motion increases as the more severe wave state.</td>
<td>1. RNA responses induced by the pitch motion are greater for the semi-submersible; But that induced by wave loading is greater for the spar-buoy; 2. Resonant response of the surge and pitch motion of the semi-submersible is greater, especially for the pitch motion; 3. Yaw motion of the spar-buoy is more sensitive to the wave loading.</td>
<td>The difference in the pitch resonance is due to the larger waterline plane of the semi-submersible subjected to the larger wave-induced overturning moment; The difference in the surge resonance is resulted from that the lower natural frequency of the surge of the semi-submersible is more sensitive to the second-order difference-frequency wave loading; The difference in the yaw motion is due to the smaller yaw radius and yaw inertia.</td>
</tr>
<tr>
<td>Wind-wave</td>
<td>1. RNA structure response is like a combination of that in wind-only case and wave-only case, respectively; 2. Platform motion shows narrow-banded peak responses at the natural frequencies and in wave-energy domain; 3. There is aerodynamic damping effect on the surge and pitch resonant responses, but there is an impact in wave-energy domain.</td>
<td>1. Spar-buoy has larger average surge and pitch motion responses. But the semi-submersible has the greater surge and pitch resonant responses and the wave-induced responses; 2. Yaw motion of the spar-buoy is much greater and is mainly dominated by the 1P rotating frequency; 3. Aerodynamic damping effect of the semi-submersible is more distinct.</td>
<td>Platform motion of the spar-buoy is more sensitive to the wind loading, but that of the semi-submersible is more sensitive to the wave loading, due to the difference in the centre of gravity, centre of buoyancy, area of waterline plane, platform configuration, mooring lines, etc.</td>
</tr>
<tr>
<td>Wind-wave -current</td>
<td>1. Average surge motion becomes greater due to the drag force induced by the current flow 2. Resonant responses and the wave excitation responses become</td>
<td>1. Compared to the semi-submersible, the surge-sway trajectory of the spar-buoy is more regular like “figure-eight”</td>
<td>The submerged body of the spar-buoy is a single cylinder. This is more like a typical “flow around a circular cylinder” issue. By contrast, the submerged body</td>
</tr>
</tbody>
</table>
smaller due to that the wave amplitude becomes smaller with the presence of the current flow.

3. Sway motion becomes greater and gives rise to the greater resonant sway motion;

4. Yaw motion is intensified with the current flow because of the vortex shedding around the submerged body.

5. Surge-sway trajectory for combined wind-wave-current case is more like “figure-eight” than that for the case without current flow.

of the semi-submersible is more complicated due to its lots of submersed pontoons.

ACKNOWLEDGMENT

The authors would like to acknowledge the support of SKLOE (State Key Lab of Ocean Engineering) in Shanghai Jiao Tong University.


Resonate
PSD of pitch motion (deg².s/rad)

Circular Frequency (rad/s)

Pitch-LC2-Spar
Pitch-LC2-Semi
Resonate

Surge-LC4-spar
Surge-LC4-semi

PSD of surge motion (m^2.s/rad)

Circular Frequency (rad/s)

Wave

Spar
Semi
PSD of surge motion (m^2/s/rad)

- **Surge-LC5-Spar**
- **Surge-LC5-Semi**

Circular Frequency (rad/s)

Inset box plots:
- Spar
- Semi
The graph shows the Power Spectral Density (PSD) of yaw motion (deg^2.s/rad) against circular frequency (rad/s). Two lines are plotted: a solid black line labeled "Yaw-LC4-Spar" and a dashed red line labeled "Yaw-LC4-Semi". Notably, there is a peak at a certain frequency indicating a resonant peak, with labels "Resonate" and "Wave" pointing to this area. The inset graph displays a box plot with two sets: "Spar" and "Semi", providing a visual comparison of yaw motion.