A study on the dynamic response of a semi-submersible floating offshore wind turbine system Part 1: A water tank test

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ABSTRACT: A new semi-submersible floating structure was proposed on which three wind turbine towers would be installed. This paper presented the dynamic behaviors of the 1/150 scaled rigid model experiments in a water tank. A free vibration test was conducted in still water to obtain the natural periods for verifying the numerical model and modeling the damping ratio of the vertical motion in the part 2 of this study. To evaluate the dynamic behavior of the floater, regular wave tests were conducted with the wave heights 2,4,8cm, wave periods range 0.6~3.0s and the responses of floater were measured by using an optical system. The observed surges varied linearly with the wave height in the ranges of periods far from the natural period. However, the surges normalized by wave height had peaks around the natural period, and decreased significantly when wave heights increased. To investigate the effect of the wind turbines to the floater, collinear wave and wind tests were also conducted in the same wave condition, wind speed was set at 2 and 4m/s corresponding the operating and survival case of wind turbine, respectively. The observed surges showed that the peak responses of the floater decrease in the operating condition due to the aerodynamic damping from wind turbine, but there was little effect in the survival condition.

KEYWORDS: Floating offshore wind turbine system, semi-submersible floater, water tank test, hydrodynamic damping, aerodynamic damping

1 INTRODUCTION

Wind energy is widely recognized as a useful renewable energy to reduce the greenhouse gas emissions, to satisfy the increasing energy need and to increase the security of energy supplies. At the end of 2005 in Japan, total amount of installed wind energy capacity reached to 1,078MW. The official government target for wind energy is 3,000MW in 2010. A large portion of wind energy potential in Japan is located at rural area, where demand is low, the grids are weak, and the limitation in integrating wind energy to the grids exists. However, there is no limitation of integration of wind energy to the gird near urban areas, but the onshore resource is limited and little land is left for large wind farms. Offshore wind energy development is found to be an important role in overcoming this situation.

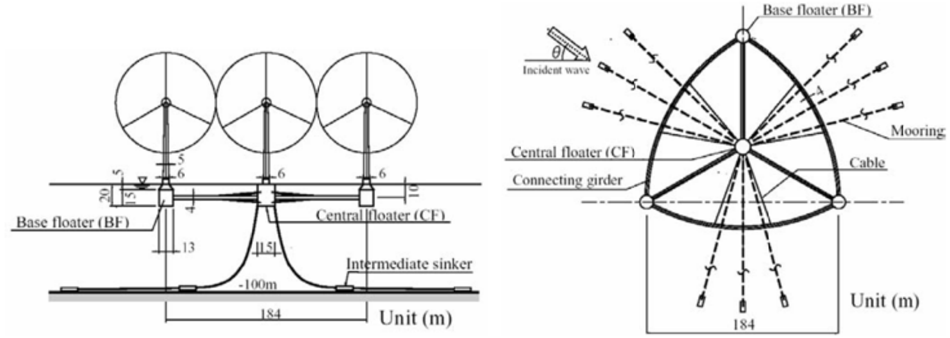
Ishihara et al. [1] investigated the offshore wind energy potential in the Kanto area, and concluded that the annual wind speed offshore is over 7m/s in some regions. Moreover, when the economic and social criteria were considered, the available potential became 94TWh/year, accounting for 32% of the annual demand of Tokyo Electric Power Company. But only 0.4TWh per year would be exploited in areas where water depth was under 20m, where the bottom-mounted foundation can be adapted. On the other hand, 60% of the total available potential is located in areas where water depth is between 20 and 200m. This implies that floating offshore wind energy should be developed to exploit offshore wind energy in this area.

The floating offshore wind energy offers the obvious advantages of no land usage and a probably more reliable wind resource. Although the floating wind turbine technologies have been derived from well-known floater concepts in oil & gas industry such as semi-submersible, spar or tension leg platform, they required to reduce the cost for mass production, not need to consider the safety factor of human station, and to achieve the stability of the floater for reduction of the turbine and tower loading. After FLOAT project [2], several concepts of the floating wind turbine systems [3-6] have been proposed, but few water tank tests have been performed to investigate the dynamic behaviors of the floater and the interaction between wind turbines and floater.

In the part 1 of this study, a new semi-submersible floating structure was proposed. The basic design concept was focused on reducing of construction cost and achieving of stability in order to reduce the loads on wind turbine and its tower. A water tank test was carried out in consideration with the operating and survival conditions to investigate the dynamic responses of the proposed semi-submersible floating offshore wind turbine system. The responses of the floater were measured in regular wave and collinear wave and wind conditions. The variations of dynamic responses with the wave heights, wave periods and wind speeds were investigated to clarify the effect of hydrodynamic damping and the effect of wind turbines to floater.

2 FLOATING OFFSHORE WIND TURBINE SYSTEM

The floating offshore wind turbine systems can be divided into two groups, the single turbine systems and the multi turbine systems. The advantage of the multi turbine systems are less motion due to the low thrust height to floater ratio and common mooring system for a set of turbines. However, they have disadvantages of high loads by current and wave, and the turbine wakes. The single turbine systems have opposite characteristics. The semi-submersible floater has a number of advantages due to the floating structure below the water surface, including reduced wave loads and response motion.



(a) Front-view (b) Plane view

Figure 1. Proposed floating offshore wind turbine system

In this study a slightly bowed triangular semi-submersible floating offshore wind turbine system as shown in Figure 1 was proposed. Floating structure consisted of three base floaters to support three wind turbines (BF), one central floater (CF), connecting girders that connected these floaters, and mooring cables with three mooring chains. BF was made of a composite structure from steel and concrete, and connecting girders were made of steel in which the ballasts were installed to cancel the buoyancy of the floater. Furthermore, connecting girders and CF were connected with cables to tether the platform to the central floater to increase stability. In order to reduce the wave induced motion, natural periods of the floater were extended as long as possible by suppressing the restoring stiffness in 6-degrees-of-freedom. To achieve it, intermediate sinker was introduced to suppress stiffness of mooring in surge, sway and yaw direction. Furthermore, the tapered BF was designed to reduce the hydrodynamic restoring stiffness in heave, roll and pitch direction. As the result, the natural period for each degree of freedom was longer than 25 seconds. In addition, turbines with the hub height at 70m, for the 92m diameter rotor, and was rated at 2.4MW at 12.5m/s hub wind speed, would be positioned at each of the BFs. The final platform design had 23,200ton displacement and weight of 16,000ton.

3 METEOROLOGICAL AND OCEANOGRAPHIC CONDITION

For the design condition of the floating offshore wind turbine system, it is necessary to consider the combination of 7 parameters from meteorological and oceanographic conditions, i.e. wind speed, wind direction, wave height, wave direction, wave period, current speed and current direction. The figure 2 shows an example of wind, wave and current direction that were observed at one site in Japan. Since the prevailing directions of winds corresponded to those of wave and current satisfactorily, a wind, wave and current directions were supposed to be collinear in this study.

To estimate the significant wave height, the equation (1) approximated by the SMB formula [7] was proposed, in which the fetch F was assumed as a function of wind speed as follow.

$$H_{1/3} = \max\left[1.5, H_{SMB}(U_{10})\right] \tag{1}$$

$$H_{SMB(U_{10})} = \frac{0.3\left[1-\left\{1+0.004\sqrt{gF(U_{10})/U_{10}^2}\right\}\right]}{g}U_{10}^2 \tag{2}$$

$$F(U_{10}) = 0.059U_{10}^3 - 2.4U_{10}^2 + 33U_{10} + 49 \tag{3}$$

where $H_{1/3}$ is significant wave height, H_{SMB} is significant wave height by SMB formula, U_{10} is hourly mean wind speed at 10m above the sea surface, F is the fetch in kilometer and g is the gravity acceleration.

In addition, the significant wave period $T_{1/3}$ was approximated as a function of significant wave height and expressed by the equation (4). This equation is based on full-developed JONSWAP spectrum and is adapted in the rules and guidelines of Germanischer Lloyd Wind Energie (GL) [8].

$$T_{1/3} = 14\sqrt{H_{1/3}/g} \tag{4}$$

Figure 3 demonstrates the predicted significant wave heights and wave periods as well as those obtained from the statistical database of winds and waves around Japan edited by Tsujimoto et al [9]. In this sea, the wave height shows constant value of 1.5m when the wind speed is lower than 10m/s.

Table 1 Design conditions of the floating offshore wind turbine system

	Maximum operating	Maximum survival
Hub height wind speed (m/s)	25	50
Significant wave height (m)	7.1	12.0
Significant wave period (s)	9.8	13.4
Current speed (m/s)	1.8	1.8

The design conditions of the floating offshore wind turbine system were calculated using the above equation and summarized in Table 1. Here, the hub height maximum wind speeds were 25m/s and 50m/s for the operating and survival conditions, respectively, and current speeds were assumed to be 1.8m/s in both case.

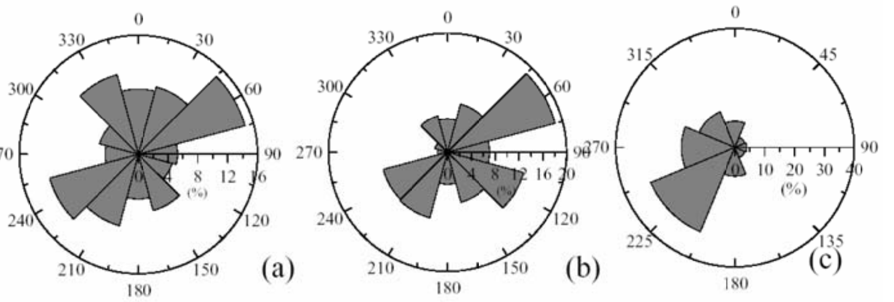


Figure 2. Oceanographic condition. (a) Wind direction, (b) Wave direction and (c) Current direction

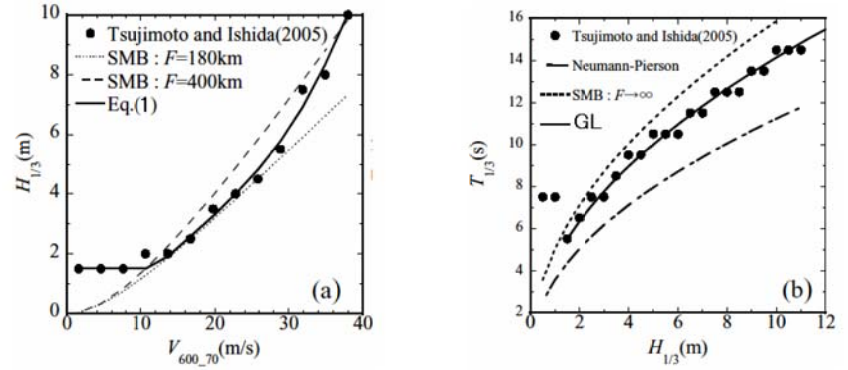


Figure 3. Wave parameters. (a) Relation between wind speed and significant wave height, (b) Relation between significant wave height and wave period

4 MODEL TEST

4.1 *Setup of experiment*

The experiments were conducted in a water tank with wind tunnel, owned by the National Maritime Research Institute, Japan [10], which is 17.6m in length, 3m in width, 1.8 m in height and 1.5m still water depth (figure 4). The wind tunnel can generate the laminar wind 1~32m/s. A flap type water generator can simulate the regular wave in the maximum wave height of 0.3m and period around 0.6~4.0s. An absorbing beach was installed at the end of the water tank to avoid unwanted wave reflections.

The proposed floater was scaled 1:150 and tests were carried out under Froude similarity law. The wave period and the velocity ratios are 1:12.2. Thus the experimental condition of wave height, the wave period and the wind speed, corresponding to the operating and survival conditions, are shown in table 2. The model structures were manufactured using acrylic. Here, cross-section of the connecting girder was modified to a square cross section from a circle in the prototype floater for the convenience of fabrication, and the tether cables were not attached. Table 3 shows specifications of the model. The model was set at the 6.6m downstream of the wave generator as shown in figure 4.

In order to investigate the dynamic behaviors, stability and the effect of wind turbine to floater, three types of rotor model as shown in Figure 5 were manufactured in this study. One was modeled by the concentrated mass at the nacelle in the experiment without wind. The second rotor was modeled using a plate with holes so that the thrust coefficient is 0.33 (U=14m/s), which is equivalent to the operating condition. The other was modeled by the equivalent slender plate, which the blades were in feathering status in the survival condition.

Mooring system was simplified by two sets of longitudinal, lateral and vertical linear springs. Here, the spring stiffness was determined by the wave motion analysis basing on a result of catenary analysis from the steady force in the survival condition, i.e. wind load on wind turbine, tidal current and wave drift force on floater. Because the stiffness of lateral and vertical linear springs were much smaller than longitudinal those, the lateral and vertical springs were ignored and the longitudinal linear springs were reproduced using very fine Kevlar wires attached to the calibrated springs.

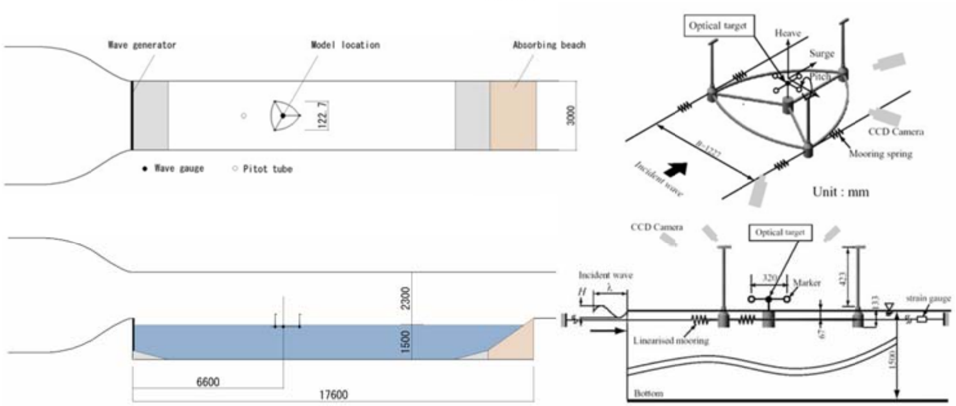


Figure 4. Water tank with wind tunnel used for testing the semi-submersible model

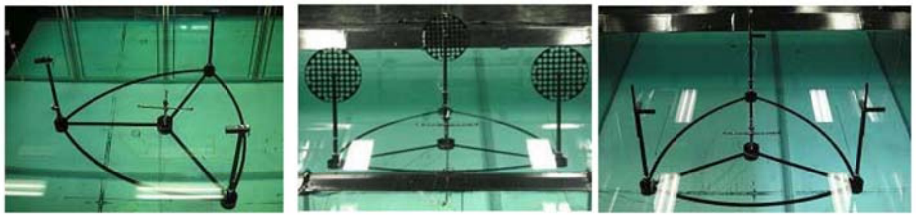


Figure 5. Experimental models (model with the rotors were modeled by the concentrated mass at the nacelles, in operating condition, in survival condition)

Table 2. Experimental conditions

Wind turbine condition	Prototype scale			1:150 scaled down form the prototype		
	Wave period (s)	Wave height (m)	Wind velocity (m/s)	Wave period (s)	Wave height (cm)	Wind Velocity (m/s)
Operating	7.4~9.8	3.9~7.1	1.4~25	0.60~0.80	2.6~4.7	1.1~2.0
Survival	13.4	12.0	50	1.09	8.0	4.1
Experimental condition	7~37	3~12	25~75	0.6~3.0	2, 4, 8	0, 2, 4

Table 3. Specifications of the experiment model

	1:150 scaled down form the prototype	Experimental model	Note
Displacement (t)	0.486×10^{-2}	0.554×10^{-2} *	Diameter of BF scaled down model: $\Phi_{1/150}$=0.0876m Experimental model: = 0.0900m
Moment of inertia Ixx, Iyy (tm^2)	0.77×10^{-3}	0.886×10^{-3}	
Center of gravity (m)	0.061	0.048	Depth from hydrodynamic surface
Height of meta-center (m)	0.189	0.152	
Water-plane area (m^2)	0.377×10^{-2}	0.377×10^{-2}	
Spring constant (kN/m)	0.196×10^{-1}	0.147×10^{-1}*	Measured by strain gauge

* Measured values

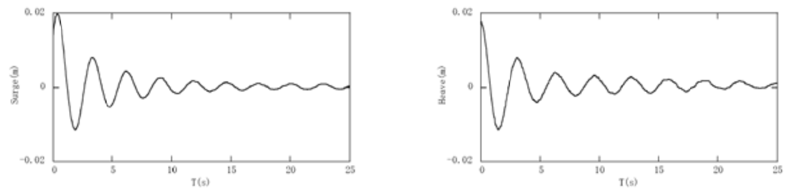
4.2 *Measurement*

The pitot tube was set at the upstream side of wind tunnel to monitor the wind speed. A wave gauge was placed in the location of the model to measure the incident wave. The optical target with five light emitting diodes were mounted on the central floater to measure the motions in six degrees of freedom by means of an optical system with three CCD cameras. Two waterproof strain gauge type load cells were used to measure the spring stiffness of mooring lines. Experimental data was recorded for 60s with the sampling frequency of 20Hz for the optical system and 1000Hz for wind speed and wave heights. The frequency component corresponding to the incident wave period were extracted from measured data by Fourier analysis.

5 EXPERIMENTAL RESULTS

5.1 *Free vibration test*

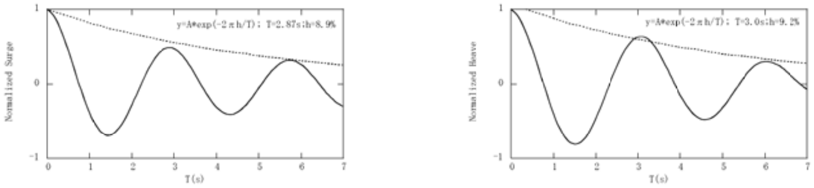
A free vibration test was conducted in still water to estimate the natural periods and damping ratios of model. Figure 6 shows time series of surge and heave in the longitudinal and vertical direction, respectively.



(a) Surge (b) Heave

Figure 6. Time series of responses from the free vibration

The Auto Correlation method was applied to remove the random components of the responses, and the time series of the responses were normalized and shown in Figure 7. The natural periods calculated from the interval peaks of the normalized responses are 2.87s and 3.00s in the surge and heave direction, respectively. The damping ratios estimated by using the power exponent function to fit the peaks on the normalized responses time series are 8.9% in the surge and 9.2% in the heave. They would be used to vertify the numerical model in the part 2 of this study.

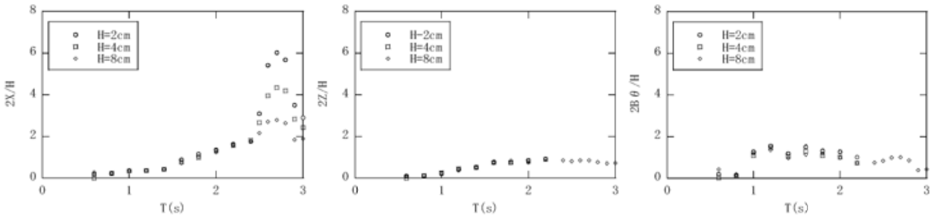


(a) Surge (b) Heave

Figure 7. Normalized responses

5.1.1 *Effect of hydrodynamic damping*

To evaluate the dynamic behaviors and the stability of the floater, the responses of model were measured without wind using the rotors modeled by the concentrated mass at the nacelle. Figure 8 presents the variations of normalized surge, heave and pitch with the wave periods. Since the observed time series of pitch disturbed significantly due to the wave reflection in the cases of the incident wave height H=2, 4cm with the wave periods over 2.2s, the data for the pitch and corresponding heave were excluded. The observed responses varied linearly with the wave height in the ranges of periods far from the natural period. However, the surges normalized by wave height had peaks around the natural period, and decreased significantly when wave heights increased. The reason is that near the resonant point, the larger wave height causes higher velocity of the floater, results in the increase of the hydrodynamic damping.

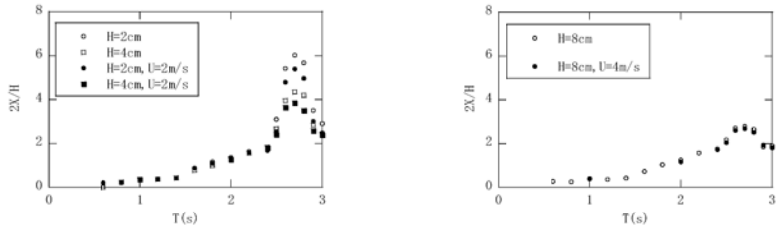


(a) Surge (b) Heave (b) Pitch

Figure 8. Variations of normalized responses of floating model with the wave periods

5.1.2 *Effect of aerodynamic damping*

The effect of the wind was evaluated by using the model with the rotor for operating and survival cases. Figure 9 shows the variation of the normalized surge with wave periods and wind velocities in the operating and survival conditions. As expected, the peak responses around the period 2.8s with wind speed U=2m/s corresponding to the operating condition are less than those without wind due to the effect of aerodynamic damping from the wind turbines to floater (Figure 9a). The effect of the aerodynamic damping is large for low wave height, that is, low hydrodynamic damping cases. However, in the survival condition (Figure 9b), there is little dependency on the wind speed. This is because the aerodynamic damping from the blade is much smaller than the hydrodynamic damping from the floater.



(a) Operating condition (b) Survival condition

Figure 9. Variations of normalized surge with the wave periods and wind velocities in the operating and survival condition.

6 SUMMARY

The dynamic behaviors of the semi-submersible floater were investigated by using a water tank with wind tunnel. The results indicate that the proposed floater gives small response during the operation and is stable enough in the survival condition. The dependency of the peak surges on the wave height was observed around the resonant points in the experiment, indicating that the hydrodynamic damping is very important. In the operating case, the wind effect on the peak surge was also observed due to the aerodynamic damping from the wind turbines, but there is little effect in the survival case, because the aerodynamic damping from the blades are much smaller than the hydrodynamic damping from the floater.

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