Similarity Model Development of Spar Floating Wind Turbine for Vibration Experimental Study

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Abstract. As the fixed foundation wind turbine no longer meets the design and cost requirements in deep sea power plant, and the offshore floating wind turbine (FOWT) suitable has been developed rapidly. The spar FOWT model is established in ANSYS-AQWA, and the influences of spectral peak frequency and incident angle for irregular waves on the vibration responses of FOWT are studied under five load cases. Under the guidance of similar theory, 1/150 scaled model has been simulated under typical load cases. The results show that the peak frequency of the spectrum has a significant effect on the vibration responses of FOWT, the incident angle also has a slight effect. By comparing the maximum and standard deviation (SD) of the tower top fore-aft displacement (TTDspFA) with the physical model and the experimental model, the minimum errors are 3.60% and 3.56%, respectively. This work will lay a foundation for experimental study on vibration of the floating wind turbine.

1. Introduction
As the main method of utilizing wind energy, wind power generation has become one of the commercialized power generation methods in new energy technology [1]. Offshore wind power has become an important direction for the development of the global wind power industry due to its unparalleled advantages in onshore wind power. Offshore wind farms are far from residential areas on land, which can eliminate the impact on the lives of land residents during operation, and can install larger-scale wind turbines to form wind farms, and fully convert offshore wind energy into electrical energy [2-3]. Therefore, the research on FOWT has important practical significance.

At present, Sultania et al. [4] used numerical simulation methods to study the motion responses performance of the spar floating wind turbine platform under extreme marine environment. Jonkman et al. [5] developed HydroDyn, a hydrodynamic calculation module embedded in FAST, established a fully coupled calculation model for FOWT, and analysed the dynamic response characteristics of 5MW barge floating wind turbines under different wind and wave loads.

Nielsen et al. [6] studied the motion responses of the spar floating wind turbine platform system by combining numerical simulation and 1/47 scale model method. Utsunomiya et al. [7-8] further studied the motion responses of the floating wind turbine system under wave load by using the methods of 1/22.5 and 1/100 model experiments. Ishihara et al. [9] conducted a wind-wave experiment on a semi-submersible floating system using a 1/150 scale model to effectively verify the motion response performance of the platform system.

The influences of spectral peak frequency and incident angle for irregular waves on the vibration responses of FOWT are studied in this paper. For the experimental work, 1/150 scaled model has been simulated. The content of this paper is as follows: spar FOWT model is introduced in section 2. The
influences of wave load on FOWT vibration responses are introduced in section 3. The similarity theory is introduced in section 4. The simulation comparison results of the physical model and the experimental model are in section 5. The last section presents the conclusions of these simulations.

2. Floating offshore wind turbine model
At present, four types of design schemes for floating-based wind turbine support platforms are adopted: the spar floating platform of the European Hywind project, Tension Leg Platform developed by the National Renewable Energy Laboratory and MIT, Barge floating platform and the Dutch three-float structure, etc. [10]. Compared with the other three platforms, the spar floating platform has obvious comprehensive advantages in terms of load performance, cost, and structural form. It seems to be the most suitable support way for deep waters [11]. The spar FOWT is selected as the research object in this paper, and the wind turbine parameters are shown in Table 1 [12-13].

Table 1. Parameters of spar FOWT.

| Parameter                              | Parameter value |
|----------------------------------------|-----------------|
| Rating                                 | 5MW             |
| Rotor Orientation, Configuration       | Upwind, Three blades |
| Rotor, Hub Diameter                    | 126m, 3m        |
| Hub Height                             | 90m             |
| Cut-In, Rated, Cut-Out Wind Speed      | 3m/s, 11.4m/s, 25m/s |
| Rotor Mass                             | 110000kg        |
| Nacelle Mass                           | 240000kg        |
| Tower Mass                             | 347460kg        |
| Platform Mass (Including Ballast)      | 7466330kg       |
| Coordinate Location of Overall CM      | (-0.25m, 0, -78.7m) |

The rigid-body platform DOFs include translational surge, sway, and heave motions and rotational roll, pitch, and yaw motions. Positive surge is defined along the positive X-axis, sway is along the Y-axis, and heave is along the Z-axis. Positive roll is defined about the positive X-axis, pitch is about the Y-axis, and yaw is about the Z-axis. The illustrations of structural model and finite element model are shown in Figure 1.

Figure 1. Illustration of spar FOWT: (a) structural model and (b) finite element model.
3. Influences of wave load on FOWT vibration responses

The marine environment at the former Stevenson Weather Station (located at 61° 20’ N latitude, 0° 0’ E longitude) is extremely harsh. This reference site is chosen for its fairly extreme wind and wave conditions, with the implication that if the results of the loads analysis are favourable, the floating wind turbine system under consideration will be applicable at almost any site around the world [14]. Five typical load cases are shown in Table 2. The load cases 1-5 represent the cut-in wind speed, below rated speed, rated speed, higher than rated speed and cut-out speed, respectively [14].

| Load case number | 1   | 2   | 3   | 4   | 5   |
|------------------|-----|-----|-----|-----|-----|
| Hub-height mean wind speed/(m/s) | 4   | 8   | 12  | 18  | 24  |
| Significant wave height/m          | 1.7 | 2   | 2.6 | 4.0 | 5.6 |

The influences of wave spectrum peak frequency and incident angle on wind turbine vibration responses are studied in this section. The three spectral peak frequencies are 0.034Hz, 0.08Hz and 0.12Hz, where 0.034Hz is the critical natural frequency of the wind turbine platform. When the FOWT is working in the marine environment, the external environmental load is random, and the direction of the waves cannot be predicted. Several wave incident angles of 0°, 30°, 60° and 90° are selected for analysis at the wave spectrum peak frequency of 0.034Hz. The NPD wind spectrum is selected to simulate wind, and the Jonswap spectrum is selected to simulate irregular waves.

In order to study the influences of wave spectrum peak frequency, it is assumed that the incident wave angle and the wind direction are both 0°. Figure 2 shows the influences of different spectrum peak frequencies on the FOWT vibration responses under five load cases. The SD of the TTDspFA and the SD of the platform heave displacement (PFDspH) are used as the evaluation criteria.

![Figure 2. Effects of wave spectrum peak frequency on spar FOWT vibration responses: (a) SD of TTDspFA and (b) SD of PFDspH.](image)

Figure 2 illustrates TTDspFA and PFDspH gradually increase as the marine environment becomes more and more severe. When the peak frequency of the spectrum is 0.12 Hz, PFDspH does not change obviously. The vibration responses of the FOWT are greatest when the spectral peak frequency is 0.034 Hz because 0.034 Hz is close to the critical natural frequency of the FOWT.

![Figure 3. Effects of wave incident angles on spar FOWT vibration responses: (a) SD of TTDspFA (b) SD of TTDspLR and (c) SD of PFDspH.](image)
Figure 3 gives the influences of different incident angles on FOWT vibration response under five load cases. Figure 3 shows that the vibration responses of FOWT will increase as the working conditions become more and more severe, the incident angles of 60° and 0° have great effects on TTDspFA and PFDspH, respectively. Under normal load cases, 90° incident angle has a greater impact on TTDspLR, while TTRspLR increases significantly at 30° incident angle as the working conditions become worse.

4. Similarity theory
In marine engineering, the similarity theory refers to a certain similarity relationship that the experimental model and the physical model should satisfy. We usually choose appropriate similarity criteria according to specific experimental research objects.

The ratio of the linear scales of the experimental model and the physical model is constant, and the corresponding angles are equal, as shown in Eq. (1).

\[
\frac{L_s}{L_m} = \frac{B_s}{B_m} = \frac{D_s}{D_m} = \lambda, \quad \frac{\alpha_s}{\alpha_m} = 1
\]

where \(\lambda\) is the scale ratio, \(L_s, B_s, D_s, \alpha_s\) and \(L_m, B_m, D_m, \alpha_m\) are the length, width, draught and included angle of physical model and experimental model respectively.

The marine engineering model experiment is mainly to study the structure's movement under the wind and wave conditions, where gravity and inertial force are the main factors that determine its force. Therefore, the most common method of scaling the model is to use Froude's scaling law, the scaling factor is defined by the Froude-number (Fr). In addition, the structure has periodic motion on the waves. The physical model and the experimental model must keep the Strouhal-number (St) equal, as shown in Eq. (2).

\[
\frac{V_s}{\sqrt{gL_s}} = \frac{V_m}{\sqrt{gL_m}} = \frac{V_s T_s}{L_s} = \frac{V_m T_m}{L_m}
\]

where \(V_s, L_s, T_s\) and \(V_m, L_m, T_m\) are the characteristic velocity, characteristic line scale and period of the physical model and the experimental model, respectively.

Marine engineering model experiment is usually conducted in freshwater tank, but the actual working environment is the marine environment. Therefore, in the water tank experiment, the density of the fluid needs to be corrected, and the ratio of seawater to freshwater is \(\gamma\) (\(\gamma=1.025\)). For future experiment preparation, the scale ratio is selected as 150, and the experimental model is calculated by the physical model and scale ratio. The main experimental model design parameters are shown in Table 3.

| Parameter                        | Scaled ratios | Experimental model |
|----------------------------------|---------------|--------------------|
| Rotor, Hub Diameter              | \(\lambda\)   | 0.8m, 0.02m        |
| Hub Height                       | \(\lambda\)   | 0.6m               |
| Rotor Mass                       | \(\gamma \lambda^3\) | 0.032kg           |
| Nacelle Mass                     | \(\gamma \lambda^3\) | 0.069kg           |
| Tower Mass                       | \(\gamma \lambda^3\) | 0.101kg           |
| Platform Mass (Including Ballast)| \(\gamma \lambda^3\) | 2.158kg           |
| Coordinate Location of Overall CM| \(\lambda\)   | (-0.00167m, 0, -0.525m) |

According to the conversion relationships given above, the relationships between various physical quantities such as stiffness, weight per unit length, elastic coefficient, restoring force coefficient, and wind coefficient can be further calculated.

5. Comparisons of physical model and experimental model
By comparing the relative errors of the maximum and SD of TTDspFA, the accuracy of the scale model is verified, as shown in Eq. (3).

$$
\sigma_x = \frac{X_b - X_a \times \lambda}{X_b} \times 100% \\
\sigma_s = \frac{S_b - S_a \times \lambda}{S_b} \times 100%
$$

(3)

where $X_b, S_b$ are the maximum and SD of the TTDspFA of the physical model respectively, $X_a, S_a$ are the maximum and SD of TTDspFA of the experimental model, and $\lambda$ is the scaled ratio.

### Table 4. Relative errors of the maximum of TTDspFA.

| Load case number | 1   | 2   | 3   | 4   | 5   |
|------------------|-----|-----|-----|-----|-----|
| Physical model displacements(m) | 10.16 | 11.36 | 13.89 | 20.61 | 29.00 |
| Similar conversion values(m)   | 9.75 | 10.95 | 13.2 | 19.35 | 25.95 |
| Relative errors               | 4.00% | 3.60% | 4.97% | 6.11% | 10.50% |

### Table 5. Relative errors of the SD of TTDspFA.

| Load case number | 1 | 2 | 3 | 4 | 5 |
|------------------|---|---|---|---|---|
| Physical model displacements(m) | 3.09 | 3.43 | 4.15 | 6.02 | 8.19 |
| Similar conversion values(m)   | 2.98 | 3.29 | 3.95 | 5.66 | 7.42 |
| Relative errors               | 3.56% | 4.08% | 4.82% | 5.98% | 9.40% |

Table 4-5 show that the relative errors between the physical model and the experimental model basically increases with increasing wind and wave loads. While the overall relative errors are small and can basically meet the experimental requirements.

### 6. Conclusions

The influences of wave spectrum peak frequency and incident angle on the vibration response of spar FOWT are studied in this investigation, and the accuracy of the next experimental model is verified. The main conclusions are as follows:

1) The peak frequency of the wave spectrum has a significant influence on the vibration responses of FOWT. The FOWT will have a large vibration response when the peak frequency of the spectrum is close to the critical natural frequency of the wind turbine.

2) The incident angle has a certain influence on the dynamic response of the wind turbine. The incident angles of 60° and 0° have great effects on TTDspFA and PFDspH, respectively.

3) By comparing the maximum and SD of TTDspFA with the physical model and the experimental model, the minimum errors are 3.60% and 3.56%, respectively.

### References

[1] Cumali L, Hüseyin A, Rasim B. The Current Status of Wind Energy in Turkey and in the World[J]. Energy Policy, 2011, 39(2): 961-967.

[2] Breton SP, MoeG. Status, Plans and Technologies for offshore Wind Turbines in Europe and North America[J]. Renewable Energy, 2009, 34(3): 646-654.

[3] Snyder B, Kaiser MJ. Ecological and Economic Cost-Benefit Analysis of offshore Wind Energy[J]. Renewable Energy, 2009, 34(6): 1567-1578.

[4] A. Sultania, L. Manuel. Extreme Loads on a Spar Buoy-Supported Floating Offshore Wind Turbine. AIAA 2010-2738.

[5] Jonkman J M, Buhl, J M. Loads analysis of a floating offshore wind turbine using fully coupled simulation[R]. National Renewable Energy Lab. Golden, CO, 2007.
[6] F. G. Nielsen, T. D. Hanson and B. Skaare. Integrated Dynamic Analysis of Floating Offshore Wind Turbines. Proceedings of OMAE2006 25th International Conference on Offshore Mechanics and Arctic Engineering, Hamburg, Germany, 2006.

[7] T. Utsunomiya, Eitaro Nishida. Wave Response Experiment on SPAR-type Floating Bodies for Offshore Wind Turbine. Proceedings of the Nineteenth International Offshore and Polar Engineering Conference Osaka, Japan, 2009.

[8] T. Utsunomiya, T. Sato, et al. Experimental validation for motion of a SPAR-type floating offshore wind turbine using 1-22.5 scale model. International Conference on Ocean, Offshore and Arctic Engineering, Honolulu, Hawaii, USA, May 31-June 5, 2009.

[9] T. Ishihara, P. V. Phuc, et al. A study on the dynamic response of a semi-submersible floating offshore wind turbine system Part 1: A water tank test. The Twelfth International Conference on Wind Engineering, Cairns, Australia, 2007.

[10] Karimirad M. Floating Offshore Wind Turbines[M]. Offshore Energy Structures. Springer International Publishing, 2014:53-76.

[11] Dinh V N, Basu B. On the modeling of spar-type floating offshore wind turbines[J]. Key Engineering Materials, 2013: 636-643.

[12] Jonkman J. Definition of the Floating System for Phase IV of OC3[R]. Golden, National Renewable Energy Laboratory, 2010.

[13] Jonkman J. Definition of a 5-MW Reference Wind Turbine for Offshore System Development[R]. Golden, National Renewable Energy Laboratory, 2009.

[14] Jonkman M J. Dynamics Modeling and Loads Analysis of an Offshore Floating Wind Turbine[R]. Golden, CO, USA: National Renewable Energy Laboratory, 2007: NREL/TP-500-41958.