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Model test research of a semisubmersible floating wind turbine with an improved deficient thrust force correction approach

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ABSTRACT

This paper investigates the model test research of a semisubmersible floating wind turbine. An improved method is proposed to correct the deficient thrust force in a Froude-scale experimental condition, which is able to simulate the rotor operational state more realistically by allowing the rotor to rotate freely with the wind. This approach also maintains tip speed ratio to some extent and overcomes previously reported negative effects produced by common correction ways. Reduced platform resonant motions in the presence of wind force are observed. Due to rotor rotation, resonant yaw and roll motions are induced even in heading wind and wave state. Tower vibration is found to be suppressed by the wind force. Multi-frequencies components are observed in the response of tower-top shear force, which is governed by the couplings of hydrodynamic loads, aerodynamic loads and tower vibration. It is also found that the dynamic response of the mooring line is mainly dominated by wave load and aerodynamic effect can be simplified as an extra constant force.

1. Introduction

Due to issues like environmental pollution, energy crisis and sustainable development, the development of wind energy industry has been boosted by the global pursuit of renewable energy. Although the commercial application of onshore wind turbines has been proved successful, the traditional land-based wind turbines are continually complained about the visual, acoustic and environmental impacts. Besides, it is technologically difficult to achieve high energy efficiency from onshore wind resource as a result of turbulent wind farm and low annual mean wind velocity. Therefore, the wind energy industry is trying to exploit the high-quality wind resource in deep water zones.

A series of floating wind turbine concepts have been proposed all over the world. Statoil launched a spar-buoy floating wind turbine project, namely the Hywind concept [1], which is the first full scale floating wind turbine that has ever been built. Roddier et al. [2] made efforts on the feasibility study of the WindFloat concept, a three–column submersible floating foundation for offshore wind turbine [3–5]. Karimirad and Michailides [6] proposed a V-shaped semisubmersible offshore wind turbine. Li et al. [7] studied the dynamic response of a spar type floating wind turbine when incorporated with a wave energy converter and two tidal turbines.

The study of floating wind turbine is multi-disciplinary, involving hydrodynamics, aerodynamics, control algorithm, modeling of structure and multi-body dynamics. Borg and Collu [8] discussed the approach of developing a coupled numerical model for floating wind turbine, considering aerodynamics, hydrodynamics, structural deflection, mooring line dynamics and control scheme. Martin [9] presented detailed information on scaling methodology, design and physical characterization of the NREL's baseline wind turbine for the application in model test. Farrugia et al. [10] studied wave motions effects on wind turbine rotor aerodynamics using lifting line method. Salehyar and Zhu [11] examined the aerodynamic dissipation effect on the wind turbine blades with a quasi-static approach and an unsteady approach, respectively. Larsen and Hanson [12] presented an improved control algorithm to overcome the negative damping caused by blade pitch control for over rated wind velocities. Odgaard et al. [13] used Pareto curves to tune a linear model predictive controller for wind turbines.

Based on the development of basic principles, simulation tools are proposed for the fully coupled analysis of floating wind

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turbines. Jonkman [14] developed a hydrodynamic module and implemented it to FAST. Skaare et al. [15] came up with a new computational tool on the basis of aerodynamic code HAWC2 and hydrodynamic, structural and control system analysis tools SIMO/RIFLEX. Li et al. [16] developed a aero-hydro dynamic code for analysis of floating wind turbine. Quallen and Xing [17] developed a simulation tool with a variable-speed generator-torque controller using CFD calculation method.

Although a series of simulation tools have been developed, the validations of these tools still rely on comparative code-to-code check analysis due to the lack of reliable model test results. The validation work based on model test method has not been adequately conducted. With the collaboration of a group of research institutes, including NREL, MAINE University and MARIN etc., projects OC3 and OC4 started the steps of validating numerical tools and also obtaining floating wind turbine's dynamic characters through the technique of basin model test [18,19]. Duan et al. [20] investigates the dynamic response of a spar-buoy floating wind turbine with model test approach. Nevertheless, few test data are open to the public and researchers usually find it difficult to validate their in-house numerical codes.

Model test technique provides not only a reliable source to validate numerical analysis codes, but also a good approach to demonstrate the dynamic characters of the floating system, especially those unable to be captured by numerical simulations. For the purpose of fully studying the dynamic response of floating wind turbine and also providing model test results for the validation of numerical codes, a model test research for a 5 MW wind turbine is conducted in Shanghai Jiao Tong University. Firstly, the set-up of the model test is presented. Identification test results are given subsequently to calibrate the floating wind turbine model and the environmental conditions. Afterwards, the experimental data for various test cases are presented to demonstrate the dynamic characters of the floating wind turbine. Finally, conclusions drawn from the model test research are presented.

2. Model test set-up

To fully understand the response mechanism of floating wind turbine under hydrodynamic and aerodynamic excitations, a large-scale model test program is launched in the Deepwater Offshore Basin at Shanghai Jiao Tong University. The water basin, equipped with advanced wave-generating system, current-generating system, wind-generating system and other testing facilities, is 50 m in length, 40 m in width and 10 m in depth. The model test is conducted at a Froude scale of 1:50. The water depth is set as 4 m corresponding to the full-scale depth of 200 m. As shown in Fig. 1, the OC4-DeepCwind concept [21] is used in the test. Nevertheless, some modifications for the floating foundation and the mooring system are made due to the restrictions caused by turbine model manufacturing and installation of data measurement devices.

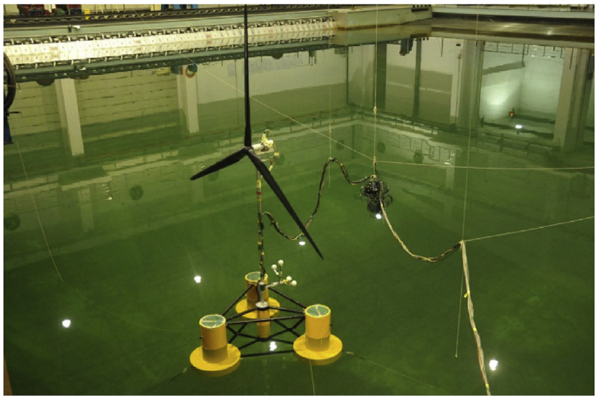

Fig. 1. Model of semisubmersible floating wind turbine.

2.1. Scaling methodology and deficient thrust force correction approach

Both hydrodynamics and aerodynamics should be regarded as dominating factors in the model test research of a floating wind turbine. Froude number similitude is typically employed in water basin test to ensure the relationship between inertial and gravitational wave forces. Meanwhile, Reynolds number similarity is more common in wind tunnel test as it preserves the relationship between viscous and inertial forces of incident flow. It is ideal to maintain Froude number and Reynolds number similitude simultaneously in the test. From a practical perspective of view, however, it is impossible to achieve such a goal. Therefore, a priority of the two scaling schemes should be selected. In a water basin test, a Froude-scaled model is able to cover most of the crucial properties which govern the dynamic responses of a floating body in waves. It is straightforward to employ the hydrodynamic view and maintain the Froude number in the test program. Therefore, both the floating wind turbine model and the incident waves are scaled with Froude number similitude in the model test.

As Froude scale method is applied in the model test, the Reynolds number similitude is no longer satisfied and the aerodynamic performance of the wind turbine will change. To demonstrate Reynolds number effect, XFOIL [22] is used to calculate the lift coefficient C_L and drag coefficient C_D of the blade airfoil at full scale ($\mathrm{Re} = 1.15 \times 10^7$) and model scale ($\mathrm{Re} = 3.25 \times 10^4$), respectively (see Fig. 2). The results show that C_L is reduced whereas C_D is increased at the model scale compared with prototype design. The thrust force coefficient C_T is subsequently computed with FAST [23] and the results are displayed in Fig. 3. Apparently, the model scale thrust force is much lower than the prototype value if no correction approach is applied.

Most correction methods are based on increasing the model scale wind speed while utilizing an electric motor to drive the rotor. In this way, rotor speed can be exactly tuned and the designed thrust force is obtained by increasing wind speed massively. However, the TSR is no longer maintained, which ensures that the system excitation resulting from rotor imbalance or aerodynamic interaction with the tower will possess the correct frequency [24]. This type of correction method may also lead to undesirable force on the tower and the platform hull above water surface since the wind speed is significantly increased [9]. Besides, the generator is not simulated properly as it drives the rotor rather than being driven by the rotor. In the test program, we introduce an improved approach to acquire the designed thrust force and better simulate the generator operation state. Instead of being driven by an electric motor, the rotor is purely driven by the wind. The electric motor is merely used to represent the wind turbine generator. By adjusting the wind speed gradually, the thrust force acting on the rotor is recorded. The adjusting of rotor speed is achieved by an appropriate selection of the motor among several available motors with different resistance properties. In this way, the TSR can be tuned although not exactly. After a series of tests, the most favorable motor is selected and the measured relationships between thrust force, wind speed, rotor speed and TSR are outlined in Table 1. It should be noted that the relationships in Table 1 will differ when a different motor is used.

The improved correction method possesses several advantages over common ways. It is capable of simulating operation state of the rotor realistically. In model test, the relative wind speed keeps