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Motions of a 5 MW floating VAWT evaluated by numerical simulations and model tests

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ABSTRACT

The VAWT (vertical axis wind turbine) has advantages in the development of large-scale offshore wind power. This paper presents a motion study of a 5 MW floating VAWT composed of the Φ type Darrieus wind turbine and the spar type floating foundation with heave plates. A computing code of aerodynamic loads was developed considering the dynamic stall and the floating foundation motions. The motion equations of the floating VAWT were established and solved numerically. Model tests were conducted, and the results of heave and pitch motion in test were compared with that of numerical calculation. The PRAOs (pseudo response amplitude operators) of numerical calculation are found to agree well with the experimental data with wave only conditions, and have some little discrepancies with wave and wind conditions. The surge-heave-pitch motions of the floating VAWT were analyzed. The results show that the aerodynamic forces have minimal influence on the heave motions of the floating VAWT, while they obviously increase the mean values of surge and pitch motions. The surge, heave and pitch frequencies of the floating VAWT are dominated by the wave frequencies, and the 2P (twice-per-revolution) response of pitch motions is not significant.

1. Introduction

Compared with onshore wind power, offshore wind farms have higher wind speed, less noise and visual pollution, wider space and many other advantages. In order to improve the power of the offshore wind turbine, higher wind speed will be needed, and this pushes offshore wind farms into water deeper than 50 m. The floating foundations, which normally include the spar type, tension leg platform (TLP) type, semi-submersible type and barge type, are used to support the offshore wind turbines.

According to the direction of the rotation axis in space, the wind turbines are divided into two types, the horizontal-axis wind turbine (HAWT) and the vertical-axis wind turbine (VAWT). Compared with the HAWT, the VAWTs have the advantages of a lower centre of gravity (leads to less over-turning), insensitivity to wind direction changes (allows for a large rotor size), and so on (Willy et al., 2015). Therefore, the VAWTs have more advantages in the development of large-scale offshore wind power. However, the VAWTs have disadvantages, such as low rotor power efficiency C_P and the 2P (twice-per-revolution) variation of the aerodynamic loads (Cheng et al., 2015).

A large amount of research on the floating HAWT has been carried out, such as the aerodynamics of the offshore HAWT, the motions of the wind turbine supported by different floating foundations, the coupling between aerodynamics and hydrodynamics of the floating wind turbine system (Karimirad and Moan, 2012; Zhang et al., 2013; Ramachandran et al., 2014; Ma and Hu, 2013;). Comparatively, studies on the offshore floating VAWT are rare (Collu et al., 2016). Cahay et al. (2011) put forward the concept of a 3 blades 2 MW Darrieus wind turbine installed on a semi-submersible floating foundation. Vita (2011) analyzed the feasibility of a 5 MW Darrieus type wind turbine supported by a rotating spar type floating foundation (Deepwind concept). A lot of researchers also studied the concept design, aerodynamic calculation, and so on of the Deepwind (Paulsen et al., 2015; Bedon et al., 2015; Battisti et al., 2016). Blusseau and Patel (2012) analyzed the effect of gyroscopic force on the motions of a V-type VAWT supported by a semi-submersible floating foundation in the frequency domain. Borg and Collu (2014) compared the motion responses of a 5 MW Φ-type Darrieus type wind turbine supported by different floating foundations. Cheng et al. (2015) analyzed the dynamic response of the Φ-type VAWT mounted on three different floating support foundations (spar type, submersible type, and TLP type). They found that the TLP was not a good supporting structure for the VAWT as the influences of the 2P (twice-per-revolution) aerodynamic loads were significant. Collu et al. (2016) used the FloVAWT, which uses a simple mooring system model, ignores the structural elasticity and use constant rotational speed without applying controller.

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Table 1
Comparison of the codes for the floating VAWT.

Code	Basic theories	Weaknesses
Hawc2	Aerodynamics: actuator cylinder flow theory. Hydrodynamic: Morison Equation. Viscous force of the floater: Morison formulation assuming the structure as slender body. Mooring: quasi-static approach Controller: a generator controller by external DLL	Second order wave forces were not included in hydrodynamics model
FloVAWT	Aerodynamics: double disk multi- stream tube theory. Hydrodynamic: potential theory. Viscous force of the floater: Morison formulation. Mooring: quasi-static catenary model. Controller: without rotational speed controller	The system was dealt with as rigid body, structural flexible was not considered.
Simo-Riflex-DMS	Aerodynamics: double disk multi- stream tube theory. Hydrodynamic: potential theory. Viscous force of the floater: Morison formulation. Mooring: nonlinear finite element theory. Controller: a generator controller by external DLL.	Second order wave forces were not included in hydrodynamics model

The simplified mooring model can affect the standard deviation of the motions.

A lot of commercial software, such as Fast/Aerodyn/Hydrodyn (Jonkman and Buhl, 2007), ADAMS (Withee, 2004), Bladed (GL Garrad Hassan, 2012), 3Dfloat (Myhr et al., 2011), Simo/ Riflex /Hawc2 (Nielsen et al., 2006), was widely used in calculating the floating HAWT. Some design codes (Berg, 1983; Strickland et al., 1980; Paraschivoiu, 1982) were also developed for the fixed VAWT. However, the published codes for the floating VAWT are not sufficient, and most of these published codes were developed by the research institutes, including the FloVAWT code presented by Cranfield University (Collu et al., 2013), the enhanced Hawc2 code presented by Technical University of Denmark (Vita, 2011), Simo-Riflex-DMS code presented by Norwegian University of Science and Technology (Wang et al., 2014), and a rigid-flexible coupling code presented by Sandia National Labs (Owens et al., 2013). Comparison analysis of the codes of the floating HAWT were presented by Borg et al. (2014), here we give the comparison analysis of the codes of floating VAWT, as shown in Table 1.

To the best knowledge of the author, the study on the dynamics of floating VAWT, coupling aerodynamics –hydrodynamics-mooring dynamics-structural dynamics, and control dynamic aspects, is still needed. In this paper, a new floating VAWT was studied. The truss spar type foundation was used to support the VAWT, it had shorter length than the existent spar type foundation (Cheng et al., 2015; Paulsen et al., 2015; Bedon et al., 2015; Battisti et al., 2016), and had lighter weight than the existent semi-submersible type foundation (Collu et al., 2016). A computing code for the aerodynamic forces was developed considering the dynamic stall and motions of the floating foundation in this paper. The motion equations of the floating VAWT were established considering the nonlinear coupling between heave and pitch, and the motion performances were studied.

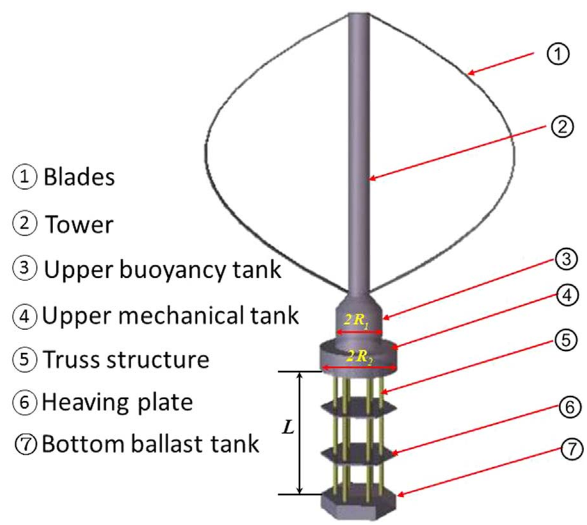

Fig. 1. The floating VAWT.

Table 2
Parameters of the wind turbine.

Items	Values
Rated power	5 (MW)
Rated rotor speed	5.26 (rpm)
Rated wind speed	14.0 (m/s)
Cut-in wind speed	5.0 (m/s)
Cut-out wind speed	25.0 (m/s)
External radius of the tower	6.3 (m)
The thickness of the tower	0.02 (m)
Height of blade	129.56 (m)
Maximum blade radius	64 (m)
Mass of blades	$3.08 \times 1\ 0^5$ (kg)
Mass of tower	4.02×10^5 (kg)

2. Parameters of the floating VAWT

The 5 MW floating VAWT was designed conceptually, as shown in Fig. 1. The rotor was fixed to the tower, and the tower was connected to the power generator that installed in the upper mechanical tank. The floating platform did not rotate, and the rotor was rotating driven by the wind force. The control devices were installed in the upper mechanical tank to brake the rotor. The detailed mechanical transmission was not available at this stage, and the aim of this paper was to study the dynamics of the whole floating VAWT.

The wind turbine was a Φ-Darrieus type wind turbine proposed by Vita (2011), with suggested the main technology parameters as shown in Table 2. The supporting structure was a spar type floating foundation, composed of an upper buoyancy tank, upper mechanical tank, truss structures, heave plates, bottom ballast tank and four groups of mooring lines that are distributed uniformly (90° between each group). The buoyancy tank was used to provide buoyancy and restoring force. The upper mechanical tank was used to install the power generation and control devices. The truss structures were composed of six vertical poles to connect the upper mechanical tank and the bottom ballast tank. Heave plates increased the heave damping and reduce the heave motion of the floating VAWT system. The bottom ballast tank was used to adjust the centre of gravity of the floating VAWT system. The upper buoyancy tank and upper mechanical tank were cylindrical, and the