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The impact of pitch motion of a platform on the aerodynamic performance of a floating vertical axis wind turbine

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ABSTRACT

The flow-field around the offshore floating vertical axis wind turbines (OF-VAWTs) are affected by the six-degrees of freedom (6-DOF) movement of the platforms. Understanding the impact of a certain DOF motion on the aerodynamics is beneficial to the design of wind turbines. In this paper, the aerodynamics and performance of a scale OF-VAWT in pitch motion are investigated. The computational fluid dynamics (CFD) method with the turbulence model of improved delayed detached eddy simulation (IDDES) and the overset mesh technique are employed to analyze the characteristics of pitch motion of wind turbines. The CFD model is verified by the experimental data from available literature when the turbine has no-pitch motion. Then, the aerodynamic forces, power, and wake of an OF-VAWT in periodical pitch motion are analyzed. Because of the varying wave loads, an unsteady aerodynamic analysis considering the pitch motion with different periods and amplitudes is performed. The results show that the pitch motion can improve the power output of the OF-VAWTs, and enlarge the variation ranges of aerodynamic force coefficients. Meanwhile, the graphs of the vortex structure show that the complex flow interaction emerges around the rotor blades. Additionally, the power coefficient and the instantaneous aerodynamic forces coefficients sensitively change with different pitching periods and pitching amplitudes.

1. Introduction

In recent years, the demands of renewable energy have become increasingly urgent due to the energy crisis and climate warming. As a kind of promising renewable and sustainable energy, wind energy has attracted a lot of attention [1]. Additionally, the wind turbines that can convert the wind energy into electricity have also achieved great development [2]. Nowadays, Multi-megawatt offshore floating wind turbines (OFWTs) have been constructed due to the limited space on land [2]. Meanwhile, compared with the traditional onshore wind turbines, the wind turbines installed offshore can get greater inflow wind speed and weaker turbulence [3]. Archer and Jacobson pointed out that the average wind speeds acting on the offshore wind farm could be 90% greater than that on land [4]. Therefore, OFWTs are regarded as one of the most promising renewable energy devices due to the vast area and the superior wind resources of the sea [2–5].

OFWTs are installed on floating structures, which mainly include spar platforms, tension leg platforms and semi-submersible platforms [5]. The floating platforms are usually attached to the mooring lines, so as to keep the platforms stable under environmental loads as far as possible. Although the mooring lines can restrict the motions of the platforms, it is difficult to keep the platforms absolutely steady due to the actions of the stochastic wave force [3]. The platforms will have excessive motion in the six-degrees of freedom (6-DOF) under the wind and ocean wave loads. As show in Fig. 1, the 6-DOF motions include three rotational components and three translational components [6]. According to Borg et al. [5], the Catenary moorings can only restrict the 'Horizontal' DOF, including yaw rotation, surge, and sway translations, while the Tensioned moorings can restrict all the 6-DOF motions. The platform motions can affect the aerodynamics of the rotor, and the varying aerodynamic forces will in turn influence the platform movements. Hence, the aerodynamic characteristics of the OFWTs

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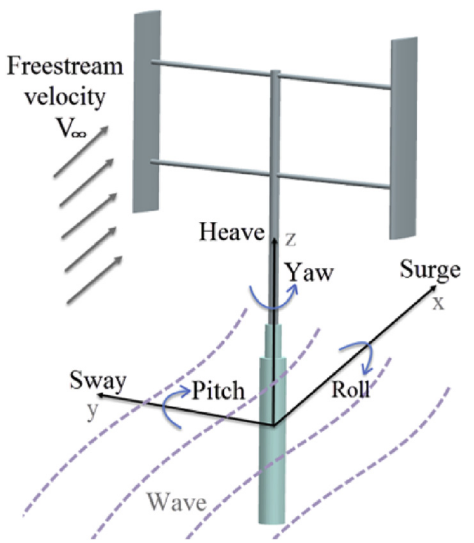

Fig. 1. Degrees of freedom (DOF) for an offshore floating VAWT platform.

become more complex than those of the onshore wind turbines, and it is crucial to study the aerodynamics of the rotor both coupling with the 6-DOF motions and under a single DOF motion of the platforms.

Wind turbines mainly include two categories: vertical axis wind turbines (VAWTs) and horizontal axis wind turbines (HAWTs) [7]. There were some publications studying the aerodynamics of the offshore floating HAWTs (OF-HAWTs) [8–11]. For instance, Tran and Kim [3] employed the unsteady computational fluid dynamics (CFD) method with the dynamic mesh techniques to study the aerodynamics of an OF-HAWT under the pitching motion of platform. Farrugia et al. [8] investigated the aerodynamics and performance of a model OF-HAWT by wind tunnel experiment. Vaal et al. [9] used the blade element momentum (BEM) with a quasi-steady wake model to study the rotor thrust and induced velocity of an OF-HAWTs under surge motion. Micallef and Sant [11] adopted an axisymmetric actuator disc (AD) method combined with the CFD method to investigate the performance of an OF-HAWT suffering the varying loads. However, there were few studies focusing on the aerodynamic performance of the offshore floating VAWTs (OF-VAWTs) along each of the 6-DOF motions of the platforms.

There are several advantages of the OF-VAWTs compared to the OF-HAWTs, such as better floating stability, simpler blade profile, lower gravity fatigue loads, and lower investment [5,6,12]. In light of this, it is important to develop the OF-VAWTs. Meanwhile, investigating the effects of a certain DOF on the aerodynamics of the OF-VAWTs can help to understand the wake characteristics, optimize the design of platforms, and improve the rotor's power coefficient [13]. Chowdhury et al. [14] studied the aerodynamics of a VAWT in upright and titled conditions using the CFD method with the shear stress transport (SST) k-ω model. They found that the power coefficient was greater in the titled condition than that in the upright condition, and the stream of wake shifted downward in the titled condition. Orlandi et al. [15] investigated the performance of a VAWT in skewed flows by adopting the CFD method with the SST k-ω model. They also found that the power of the VAWTs increased in the skewed flows. Although both the studies of Chowdhury et al. [14] and Orlandi et al. [15] showed the aerodynamic performance of a VAWT in the certain angles of pitch motion, they could not demonstrate how the aerodynamic forces and the wake-to-blade interaction change with time. Hence, a study considering the instantaneous variation of aerodynamics for the OF-VAWTs is required to show the overall aerodynamic performance under a certain DOF motion.

The CFD method has been commonly used to simulate the aerodynamics of VAWTs in the past studies [16–19], indicating that was a reliable method to analyze the VAWTs. Compared with the Momentum model and Vortex model, the CFD method can obtain more detailed information about the flow fields. Particularly, the three-dimensional (3D) model is able to provide more precise simulation results [20]. Since the amount of calculations of the direct numerical simulation (DNS) is huge, there is a need to choose a suitable turbulence model so as to balance the accuracy and efficiency of the simulation results. Reynolds-averaged Navier-Stokes (RANS) model is widely used in the simulation of the aerodynamics of the VAWTs [21]. However, the performance of the RANS model is worse than that of the large eddy simulation (LES) in the condition of the wide range of flow separations. Although LES is a high-fidelity method, it still requires a large amount of computational cost. Therefore, one of the hybrid methods, so-called the detached eddy simulation (DES), is recommended, which combines the RANS model with the LES [22]. The DES model has been applied to solve the aerodynamics problems of the HAWTs [23,24], and shows a good performance. Because of the intrinsic property, the DES model can solve the aerodynamics of VAWTs under large scale flow separation. Therein, the improved delayed detached eddy simulation (IDDES) is one of the DES models that can deal with both moderate and large scale flow separations [25], and has a better performance in analyzing the aerodynamics of wind turbines [26].

The most present literature focused on the aerodynamic performance of the bottom-fixed VAWTs [19,27–30], and some concerned the aerodynamics of the VAWTs in titled figure and skewed flow [14,15]. These studies could not reflect the time-dependent aerodynamics and blade-vortices interaction of the OF-VAWTs in a certain DOF motion. Almost no one pays attention to the time-dependent aerodynamic performance of floating VAWTs in pitch motion. Hence, the present paper is aimed to investigate the detailed aerodynamics and performance of an OF-VAWT in pitch motion by using the CFD method with the IDDES model. Then, the overset mesh combined with a user defined function is adopted to simulate the aerodynamics of the rotor with periodical pitch motion. The Cartesian grid is employed to generate the whole mesh topology for its advantages in overset mesh and local grid refinement. Due to lack of experiments about the OF-VAWT in pitch motion, experimental data about a VAWT with no-pitch motion (bottom-fixed) from available literature is used to test the validity of the present model. In this work, the aerodynamic forces, vortex structure of wake, and performance are studied so as to assess the changes induced by pitch motion. Meanwhile, a variety of environment loads may lead to the movement of the rotor in possible pitching frequencies and amplitudes. The aerodynamic forces and performance of an OF-VAWT in different pitching frequencies and amplitudes are also studied so as to better understand some regularities of the dynamic changes.

2. Numerical method

In the present study, the aerodynamic performance of an OF-VAWT is simulated by the CFD method with the turbulence model of IDDES. The overset mesh technique is used to realize the pitch motion of the rotor, and the Cartesian grids and prism boundary layer cells are employed to generate the mesh topology. The finite-volume-method (FVM)-based commercial software, STAR-CCM+ (CD-adapco Group, USA) [31] is used for all the simulations.