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The effects of yawing motion with different frequencies on the hydrodynamic performance of floating vertical-axis tidal current turbines

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ABSTRACT

Under real sea conditions, the hydrodynamic performance of floating vertical-axis tidal current turbines is affected by waves and currents. The wave circular frequency is a significant factor in determining the frequencies of the wave-induced motion responses of turbines. In this study, the ANSYS-CFX software (manufacturer: ANSYS Inc., Pittsburgh, Pennsylvania, United States) is used to analyse the hydrodynamic performance of a vertical-axis turbine for different yawing frequencies and to study how the yawing frequencies affect the main hydrodynamic coefficients of the turbine, including the power coefficient, thrust coefficient, lateral force coefficient, and yawing moment coefficient. The time-varying curves obtained from the CFX software are fitted using the least-squares method; the damping and added mass coefficients are then calculated to analyse the influence of different yawing frequencies. The simulation results demonstrate that when analysing non-yawing turbines rotating under constant inflow, the main hydrodynamic coefficient time-varying curves of yawing turbines exhibit an additional fluctuation. Furthermore, the amplitude is positively correlated with the yawing frequency, and the oscillation amplitudes also increase with increasing yawing frequency; however, the average values of the hydrodynamic coefficients (except the power coefficient) are only weakly influenced by yawing motion. The power coefficient under yawing motion is lower than that under non-yawing motion, which means that yawing motion will cause the annual energy production of a turbine to decrease. The fitting results show that the damping term and the added mass term exert effects of the same level on the loads and moments of vertical-axis turbines under yawing motion. The results of this study can facilitate the study of the motion response of floating vertical-axis tidal current turbine systems in waves.

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1. Introduction

Today, traditional fossil fuel energy is the main source of energy throughout the world; however, based on current mining trends, fossil fuel reserves will become depleted within the next few years. Therefore, an increasing number of countries have begun to develop clean and renewable energy resources [1]. Tidal current energy [2] represents a type of marine renewable energy that has recently garnered interest because of its sustainability, high energy density and predictability.

Tidal current turbines are the main area of development in the field of tidal current energy generation [3–5]. Turbines can be classified as either vertical-axis turbines or horizontal-axis turbines depending on the relative orientation of the main shaft and the flow direction. Tidal current power station platforms support turbines, generators, other equipment and personnel. In deep waters, floating moored systems [6] are the best platforms for tidal current turbines because of their advantages in terms of maintenance, removal and installation. However, the floating platforms for floating tidal current power stations experience motion in six degrees of freedom induced by waves and currents. The hydrodynamic performance of turbines thus exhibits significant variations.

Research on the wave-induced hydrodynamic forces on and coefficients for floating structures continues to expand. Marine floating structures are produced in a variety of styles; however, most are too complicated for their hydrodynamic performance subject to waves and currents to be directly studied. Therefore, simple structures (such as cylinders and spheres) are used to study this problem. Yeung et al. [7] chose to study the hydrodynamic

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problem of a floating circular cylinder in finite-depth water by matching the eigenfunctions of the interior and exterior problems. Their paper addressed three types of radiation problems: heave, sway, and roll; then, the added mass and damping coefficients were introduced. The results were compared to study the hydrodynamic performance and revealed that the heave-added mass is logarithmic singular and that the damping coefficient approaches a constant value in the low-frequency limit. Lopes et al. [8] studied the hydrodynamic coefficients of a submerged pulsating sphere in finite-depth water based on a study by Linton. The results showed that close to the resonance frequency, both the added mass and damping coefficients for the pulsating oscillation mode are much larger than those for the heave or sway modes and that the water depth affects the damping coefficient only in the low-frequency range. The hydrodynamic performances of cylinders, spheres, and other simple structures have been studied by several researchers, including [9–11]. These researchers have applied the multipole method, eigenfunctions and other approaches to solve the hydrodynamic problems presented by simple geometries in waves and currents.

However, real marine structures have complex geometric shapes and present substantial difficulties in attempts to solve their corresponding hydrodynamic problems using the abovementioned theories. Computational fluid dynamics (CFD) simulations and experiments have been adopted to study the hydrodynamic performance of complex marine structures, such as floating wind turbines, tidal current turbines and floating offshore platforms, in waves and currents. Carlos et al. [12] used CFD methods and conducted experiments to calculate the hydrodynamic coefficients of heave plates for semi-submersible floating offshore wind turbines. The modelled plate diameter was 1 m, which is the largest diameter for which data have been published. The added mass and damping coefficients, which are necessary for accurate time-domain simulations of a mooring design, were measured. Numerical simulations were also conducted following common industry standards; these simulation results were then compared with the experimental results. The research sought to improve the hydrodynamic design concept and benefit the offshore wind industry. Three-blade horizontal-axis tidal turbines were studied by Galloway et al. [13] in regular waves in deep water (wave height = 0.08 m, inflow velocity = 1.5 m/s). The results showed that the average parameters (thrust and torque) were identical with and without waves but that the transient values differed greatly; the fluctuations in thrust increased by 37%, and the torque increased by 35%. Milne [14] analysed a series of experimental tests of the out-of-plane bending moment response at the root of a hydrodynamic blade to planar oscillatory motion, which was selected as an idealised representation of the unsteadiness induced by waves and turbulence. They found that for attached flow, the magnitude of the unsteady hydrodynamic contribution was relatively small compared to the loads measured under steady flow. At low tip speed ratios, the loads during dynamic stall were approximately 25% greater than those under steady flow. In 2014, Zhang et al. [15] employed the CFX software to analyse the hydrodynamic performance of a turbine (D = 0.7 m, Z = 2) subjected to constant inflow when the turbine was experiencing forced vibration; the team studied how the hydrodynamic performance of the turbine was influenced by the surge frequency, surge amplitude and speed ratio. Then, they used the least-squares method to fit the time-varying axial force curves of a surging turbine. The damping and added mass coefficients were obtained using this method. Upon analysing these coefficients, Zhang et al. found that the surge phenomenon only weakly influenced the annual electricity output and that when the values of the surge frequency, surge amplitude and tip speed ratio increased, the oscillation amplitudes of the load coefficients also increased. However, surge motion had clear negative impacts on the structural strength and fatigue life of the turbine. Minimal research has been conducted on vertical-axis tidal turbines in which the hydrodynamic performance subject to waves and currents has been analysed. In 2011, the aerodynamic performance and wake dynamics of three different vertical-axis wind turbines were simulated in both normal and oblique positions by Scheurich et al. [16]; the results confirmed that a straight-bladed vertical-axis wind turbine that is operating in oblique flow can produce a higher power coefficient compared with when it is operating in normal flow. In 2015, A. Orlandi et al. [17] investigated a small-scale straight-bladed turbine in a wind tunnel with the rotational axis inclined between 0° and 15° from the vertical. They found that the power increased in skewed flows because the downwind phase of the revolution was less disturbed by the wake generated during the upwind phase. The study evaluated the influence of real motion on rotor performance. In 2015, Bedon et al. [18] used an unsteady Reynolds-averaged Navier-Stokes (URANS) CFD model to forecast the power conversion characteristics of vertical-axis wind turbine prototypes operating under tilted conditions (at tilt angles of 10° and 20°), the results showed a significant decrease in power production with increasing tilt angles. The blades used by Bedon et al. were curved, unlike the straight blades used in [16,17]. Furthermore, the range of inclination angles considered by Bedon et al. was different from that of [16,17]. These differences may have been the cause of the different performances observed for turbines operating under tilted conditions.

In summary, many studies regarding simple structures have been conducted over the past several decades. Researchers are now exploring the hydrodynamic performance of marine structures subjected to waves and currents, especially vertical-axis current turbines, for which the rotational motion around the main axis and the wave-induced motion of the floating platforms in six degrees of freedom cause significant difficulties in such studies. Accounting for the variety of possible wave frequencies, this paper studies the effects of yawing motion with different frequencies on the hydrodynamic performance of floating vertical-axis tidal current turbines. A series of simulated operating conditions under a sequence of frequencies is analysed. The time-varying hydrodynamic curves of load and torque are measured and then fitted to obtain the damping and added mass coefficients using the least-squares fitting method. This research provides a valuable reference for the analysis of the wave-induced responses of floating support structures for tidal current turbines and for the design of electricity output control mechanisms.

2. Numerical simulations

2.1. Basic modelling

The incoming flow velocity towards the turbine is represented by V, and the positive direction of the X axis is the inflow direction. The power coefficient C_P is the most important parameter for turbine energy conversion, and the thrust coefficient C_{FX}, the lateral force coefficient C_{FY}, the tangential force coefficient C_T and the normal force coefficient C_N are essential indexes for assessing the hydrodynamic performance of a turbine. The yawing moment coefficient C_M is specific to a turbine under yawing motion ($\xi = A\sin(\omega_Y t)$) (Table 1).

The following dimensionless parameters are defined:

$$\text{Thrust coefficient:} \quad C_{FX} = \frac{F_X}{0.5\rho V^2 DH} \tag{1}$$

$$\text{Lateral force coefficient:} \quad C_{FY} = \frac{F_Y}{0.5\rho V^2 DH} \tag{2}$$

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