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Hydrodynamic analysis of horizontal-axis tidal current turbine with rolling and surging coupled motions

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ABSTRACT

The hydrodynamic performance of a turbine with multi-degree of freedom (rotation, rolling, surging) coupled motion in the unbounded uniform flow is analysed by the sliding and dynamic meshes. The effects of the turbine's hydrodynamic load has been studied and illustrated considering the coupled motion of rotation, rolling and surging. Numerical results shows that: 1) the effects of the hydrodynamic load is mainly caused by the surging motion, namely, the instantaneous values of the axial load and power coefficients generate fluctuation with a frequency that is the same as that of the surging and an amplitude that similarly increases in parallel. The effect of the rolling motion on hydrodynamic load will be reflected when its frequency is greater than that of the surging; 2) the calculation formulas of the turbine's axial load and power coefficients has been obtained. The results of the hydrodynamic load calculated by the calculation formula and CFD numerical simulation show good agreements, which verify the calculation formulas. The results of this research can provide relevant data for the hydrodynamic analysis of turbines with multi-degree of freedom motion and verify the structural design and control of the electric output.

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1. Introduction

With the development of the worldwide economy, the demand for energy increases year by year, so more and more countries have begun to consider pursuing clean renewable energy. Among them, tidal current energy [1] does not have significant variation between years and seasons. It also has many other advantages, including its sustainability and predictability and its large energy density, and it does not occupy any land area, so it is viewed very favourably. According to the relationship between the turbine rotation axis and the direction of inflow, tidal current turbines can be divided into vertical-axis turbines and horizontal-axis turbines. The horizontal-axis turbine [2–6] has attracted much attention because of its advantages, such as that the change in the load in the flow field is not very large, and the output of power is stable.

Scholars at home and abroad have carried out a large number of experiments on the horizontal-axis tidal current turbine that can be divided into two broad categories as follows: experiments in which the effects of waves are considered and those in which the effects of waves are not considered. In 2006, the effects of the wing section, taper and hub pitch angle on the power coefficient and cavitation number were studied by Batten [7]. The study found that the phenomenon of cavitation can be minimized or even avoided by selecting an appropriate hub pitch angle or wing section with a higher camber. In 2007, Bahaj [8] tested a three-bladed tidal energy turbine with a diameter of 0.8 m and profile NACA63-8xx in a cavitation tunnel and towing tank. In the cavitation tunnel experiment, the hub pitch angle of the turbine was set to 15–30°, and the flow velocity, to 0.8–2 m/s. In the towing tank experiment, the tip-immersion of the turbine was set to 0.19D to 0.55D (D is the diameter of the turbine), and the yaw angle, to 0–30° from the axis. It was observed that the power coefficient of the turbine reaches its peak when the hub pitch angle is 20°. The power coefficient decreases by 10–15% when the tip-immersion changes from 0.55D to 0.19D because of the influence of the free surface. In 2010, Maganga [9] tested a three-bladed turbine with a diameter of 0.7 m in a closed circulation water channel. The turbulence levels of inflow ranged from 8% to 25%; the yaw angle was −10 to 20°; and the depth below the free surface was 0.94D, 1.37D and 2.04D. The experiment determined that when the inflow has a high turbulence level, the efficiency and thrust coefficient decrease by

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Nomenclature

Symbols

U	Tidal current flow speed (unit: m/s)
u	Swaying velocity (unit: m/s)
ω_T	Rotation speed of turbine (unit: rad/s)
Z_{zd}	Surging displacement (unit: m)
ω_{zd}	Surging frequency (unit: rad/s)
A_{zd}	Surging amplitude (unit: m)
θ_{hy}	Rolling angle (unit: degree)
ω_{hy}	Rolling frequency (unit: rad/s)
A_{hy}	Rolling amplitude (unit: degree)
D	Diameter of turbine (unit: m)
R	Radius of turbine (unit: m)
N	Number of blades
F_Z	Axial force (unit: N)
M_{hy}	Roll moment (unit: N/m)
M_Z	Axial torque (unit: N/m)
ρ	Density of the inflow water (unit: kg/m^3)
ε	initial phase (unit: rad)

approximately 9%, and the performance of the turbine decreases significantly with a large yaw angle. These experiments did not consider the effect of waves and mainly studied the effects of the wing section, inflow yaw angle and free surface on the horizontal-axis tidal current turbine hydrodynamic performance. They also did not study the influence on hydrodynamic performance when the turbine generates a swaying movement.

In 2007, Barltrop [10] studied the wave effect on the properties of a tidal current turbine. A horizontal axis turbine with three blades was tested in a towing tank, and the average values of torque and drag were measured in a regular wave. The research results show that, within the scope of a wave period, all average values of the measured parameters were the same as those without a wave, but the instantaneous value changes of the drag and torque are obvious. In 2010, Gallway [11] conducted a similar model test in the tank on a three-blade turbine with a horizontal axis. The result of this experiment was similar to that of Barltrop: the variation in the thrust was approximately 37%, and that of the torque, 35%. This means that the varying load on the blades will significantly accelerate the fatigue of the turbine, posing a challenge to the design of a full-scale tidal turbine. In 2013, Luznik [12], considering the effects of surface gravity waves, tested a three-bladed turbine with and without waves in the United States Naval Academy towing tank. The research results show that under the action of surface gravity waves, the average turbine performance did not appreciably change, but the axial load and instantaneous power of the turbine changed cyclically, and the frequency was consistent with the surface wave frequency. In 2014, Ethan [13] carried out a model test (wave and without wave) on a two-blade horizontal turbine in a towing tank. The diameter of the model was 800 mm, and the immersion depth was 1.3D and 2.25D. The resistance, torque and rotational speed were tested. The test showed that the results at the two different immersing depths were similar, and when a wave existed, the thrust and power experienced periodical changes, and the oscillation frequency was consistent with the wave frequency. Under different combinations of rotation speed and waves, the oscillations of the test power and resistance were 39% and as high as 79%, respectively. This is a phenomenon that we need to pay attention to. A surface wave was generally adopted in the test, and the effects of the surface wave on the turbine performance had a lot to do with the immersion depth of the blade tip. The turbine was fixed on a trailer or flume without any movement. However, in an actual situation of a floating tidal current power station [14], due to the effect of waves, the floating carrier would generate wave-induced movements that were generally multi-degree of freedom coupled motions, causing the turbine to undergo motion with a floating carrier. Therefore, the hydrodynamic characteristics of the turbine will be affected by the wave and turbine motion. To make the floating tidal current power station run safely and reliably, it is necessary to study the hydrodynamic characteristics of the turbine when it generates movement under the wave condition.

The hydrodynamic analysis of the horizontal-axis turbine in a wave-current field is very complicated, and it is difficult to use CFD software to simulate the wave-current field directly. Hence, we simplify the hydrodynamic problems of the horizontal-axis turbine with multi-degree freedom wave-induced movements and put forward the following two assumptions: 1) the turbine is fixed on a floating carrier with a main shaft, and the floating carrier has a slight simple harmonic motion with wave action; and 2) the inflow velocity is a constant with no influence of waves, which means that we assume that the tip-immersion depth is deep enough. Based on these assumptions, the hydrodynamic problems of the horizontal-axis turbine with wave motion can be simplified as problems of a turbine with multi-degree of freedom simple harmonic motion in a constant tidal current.

The literature [15] reports on the hydrodynamic load of a horizontal-axis turbine with coupled motion of surging and rotation, and found that the hydrodynamic load is affected by the frequency and amplitude of surging. On the basis of the literature and CFD, this paper studied the hydrodynamic load of a horizontal-axis turbine in unbounded uniform flow using sliding and dynamic meshes when it generated rotation, rolling and surging multi-degree of freedom coupled motion; analysed the result of the CFD when the turbine only generated rotation and a single degree of swaying motion (surging and rolling); an obtained the calculation formula of axial load and energy efficiency when the turbine generates rotation, rolling and surging coupled motion. The research focus on the effect laws of the turbine's hydrodynamic load under the condition of rolling and surging coupled motion of co-frequency and different frequency at a constant rotation speed. The result provides relevant data for studying the wave motion response of a floating carrier and designing the turbine structure and control system of the electrical energy.

2. The fitting formula of hydrodynamic loads on turbine

In the working condition of the horizontal-axis turbine, it is in normal operation and generates a single degree of freedom swaying movement. The hydrodynamic load of the turbine is affected by the rotation and swaying frequencies. According to the features of the turbine hydrodynamic load, we select appropriate expressions to fit the hydrodynamic load of the horizontal-axis turbine. The following will introduce a specific calculation method of the fitting formulas when the horizontal-axis turbine is in the working condition. The uniform inflow velocity is U, and the Z axis normal direction is the direction of the inflow velocity; the velocity of the turbine swaying is u; the angle of the blades' positions is $\theta(t)=\omega_T t+\varepsilon$. Set $\overline{u}_{yd}$ and $\overline{a}_{yd}$ as the dimensionless swaying velocity and acceleration, respectively; the hydrodynamic load coefficient of the turbine with swaying movement is C_{yd}. When the turbine generates micro-amplitude movement, we can divide the hydrodynamic force into a uniform current hydrodynamic force, damping resistance and added mass force, with the formula as follows

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