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Study of the hydrodynamic derivatives of vertical-axis tidal current turbines in surge motion

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ABSTRACT

Both the particle velocity of waves and the response of floating platforms influence hydrodynamic loads of floating tidal current turbines. In this paper, the influence of surge motion on vertical-axis turbines was studied; numerical simulation results were validated by experimental results. Based on numerical simulation results, a double trigonometric function was developed to fit the time history curves of hydrodynamic derivatives because of the dual frequency characteristics of vertical-axis turbines. Then least squares method was used to solve hydrodynamic derivatives of force coefficient. The results showed that in the working condition, surge motion results in the periodic variation of peak value of instantaneous hydrodynamic loads and that maximum loads on the turbine increased, which is bad for structural strength of the turbine. Under small surge motion, hydrodynamic loads on the vertical-axis turbines are linearly related to surge motion velocity and acceleration. Under stable conditions, damping coefficient in surge motion is not dependent on the amplitude, phase and frequency of surge motion but is related to the tip speed ratio, phase angle of the blade. The research results are beneficial to the design of mooring systems and are significant for forecasting the motion response characteristics of floating tidal current power stations.

1. Introduction

Oceans cover more than 70% of the earth's surface and offer a huge energy resource that can be harnessed for the production of electricity and/or fresh water [1–3]. Ocean energy is available in many forms, including tidal, wave, tidal current, thermal, salinity gradients and biomass [4]. Tidal current energy has received increasing amounts of attention from researchers for the development of tidal current energy.

The tidal current energy is converted to electrical energy by a tidal current turbine, which is a key component of the tidal current power system. Tidal current turbines can be classified as horizontal-axis turbines (HATs) and vertical-axis turbines (VATs). Compared with horizontal axis turbines, the latter may have some advantages [5]. Vertical axis turbines can reach higher torque at a lower tip speed ratio and lower current velocity range, which makes VATs favourable in weak current conditions. The platform of tidal current power station (TCPS) is used to support turbines, generators and other equipment, and the staffs also works on the platform. Therefore, the selection of support platform for TCPS is very important. According to the different types of TCPS, platforms can be classified as sea-bed mounted/gravity based systems, pile mounted systems and floating moored systems. The sea-bed system is suitable for shallow water, where the effects from wind and wave are minimal. However, the generator is under water, which requires high sealing technology, and maintenance is not convenient [6]. The pile mounted system is applied for deep water (30–60 m), and the structure is very firm. This type of system is limited by geological conditions; for example, if the sea-bed is too hard to drill, the pile mounted system cannot be used. The advantages of the floating moored system are [7] its easy installation, essentially, the system is towed to and then moored at the site; easy removal if a major repair task is needed or if relocation is necessary; and simpler routine maintenance because it is mostly conducted near or above the surface. In addition, the environment around the

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Nomenclature

Symbols

U	tidal current flow speed
u	surge velocity
ω_T	rotation speed of turbine
ω	surge frequency
ξ_0	surge amplitude
D	diameter of turbine
c	chord of blade
Z	number of blades
C_{fx}	trust coefficient of turbine
θ	the azimuth of $1^{\#}$ blade
θ_0	initial azimuth of $1^{\#}$ blade
λ	tip speed ratio
ψ	phase of hydrodynamic coefficient

site of the power station is one of the factors that affect the design of the platform system. At sites where sea conditions are deeper and the sea-bed is mostly stone, the floating system is preferable. Therefore, the floating power station with a vertical axis turbine is studied in this paper.

The floating platform suffers from wave movement, and the motion of the floating platform influences the vertical axis turbine. In contrast, the rotation movement of the vertical axis turbine would increase the movement of the floating platform. The two movements are coupled, which is very complex. The hydrodynamic performance of the vertical axis turbine with the floating platform depends on the current speed and the wave response motion of the tidal current power station. Six degrees of freedom response motion of the vertical axis turbine should be considered, so it is important to study the relationship between the variation loads on the turbine and the movement of the floating platform. Without considering the wave diffraction response and the radiation response, the speed of water particles in waves and the movement response of the turbine are considered as the variety of the relative movement speed between the turbine and the incoming current speed. In this case, the hydrodynamics performance of the tidal current power station is simplified as a hydrodynamics problem of the tidal current turbine in the dynamic incoming current. Generally, the 6 DOF motion equations are employed to solve the wave response motion of a floating body. In the 6 DOF motion equations, the hydrodynamic forces acting on the floating body are divided into three parts [8–10], which are the added mass forces, damping forces and exciting forces. The added mass coefficients, damping coefficients and exciting forces coefficients of a floating body can be solved by panel methods based on potential theory [11,12]. Then, the hydrodynamic forces are decoupled from the wave response motion.

Similar to the floating body, the hydrodynamic loads acting on the turbine are also dependent on the waves and the wave response motion of the floating TCPS. Generally, the hydrodynamic loads of a turbine can be solved by CFD or BEM methods [13–15]. In those methods, the loads are coupled with the motion of the turbine. In the 6 DOF motion equations, the loads should be solved step-by-step. The calculations of the loads of turbines occupy significant CPU time and lower the efficiency of the numerical analysis. If the loads on the turbine can be divided into added mass forces, damping forces and exciting forces, which are similar to those of a floating body, and if the added mass forces, damping coefficients and exciting forces can be previously determined, the solution of the 6 DOF motion equations of floating TCPS should be more efficient. Most of the hydrodynamic loads of floating TCPS are acting on the vertical axis turbine. The hydrodynamic forces acting on the vertical axis turbine in waves have two types of periodical frequency: the wave frequency and the turbine rotation frequency, which means that the hydrodynamic derivatives of floating TCPS in waves might be periodical functions and not a constant value. The hydrodynamic derivatives of the vertical axis turbines are not solved by the potential method.

In this paper, a CFD method was used to simulate the hydrodynamic performance of 2D vertical axis tidal current turbines in surge motion, and the numerical simulation results were validated by the experimental results. Based on the numerical simulation results, a double trigonometric function was developed to fit the time history curves of the hydrodynamic derivatives because of the dual frequency characteristics of vertical axis turbine. Then, a least squares method was used to solve the hydrodynamic derivatives of the force coefficient. The research results are beneficial to the design of mooring systems and are significant in the forecasting of the motion response characteristics of floating tidal current power stations and the hydrodynamics loads of turbines.

2. Mathematical model

The hydrodynamic loads on the turbine are one of the exciting sources for the wave response motion of TCPS. The load depends on the current speed, the rotating speed of the turbine, waves and the motion of the platform. When the motion of TCPS is solved in the time domain, the loads on the turbine should be recalculated at each time step, which requires the most CPU time. When the wave response motion is stable, the loads on the turbine may be expressed as an explicit function of the waves and the motion of the TCPS, which makes the solution of the motion equation of TCPS more efficient.

Suppose the following:

a. The turbine is working with constant rotating speed, and the circular frequency of the turbine is ω_T.
b. The tidal current speed U is uniform, and the flux of the tidal speed $\mathbf{u}_F$ is a small value.
c. The wave response motion of TCPS is stable.
d. The diameter of the turbine is smaller than wavelength, and the wave-making induced by turbine can be omitted.
e. The axis of the turbine is vertical to the calm surface, and the blades of the turbine are straight. The flow field at each turbine section is similar and can be treated as a 2D flow field.

For each section of the turbine at $z = -h$, the flux of the relative speed between the turbine and water is

$$\mathbf{u} = (\mathbf{u}_F + \nabla\phi - \mathbf{u}_T)_{z=-h} \tag{1}$$

where $\mathbf{u}_F$ is the tidal current speed, $\nabla\phi$ is the induced velocity by waves and $\mathbf{u}_T$ is the wave response motion of the TCPS. The hydrodynamic loads of each turbine section are determined by the horizontal relative velocity, so the vertical velocity component in Eq. (1) is omitted.

The hydrodynamic force acting on the turbine section with unit height is separated as

$$\begin{aligned}\mathbf{F} = {} & \mathbf{F}_0(U, \omega_T, D, \rho, c, Z, \theta, \mu) + \mathbf{N}(U, \omega_T, D, \rho, c, Z, \theta, \mu)\cdot\mathbf{u} \\ & + \mathbf{M}(U, \omega_T, D, \rho, c, Z, \theta, \mu)\cdot\dot{\mathbf{u}}\end{aligned} \tag{2}$$

$\mathbf{F}_0$ is the hydrodynamic force on the turbine in uniform flow with calm water, $\mathbf{N}$ is the damping matrix and $\mathbf{M}$ is the added mass