Numerical Simulation Research on Output Characteristics of Tidal Turbine in Time-varying Flow

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***Abstract*— In real ocean environment, direction and velocity of the tidal stream change frequently, therefore the output characteristic of the tidal turbines would be affected. Case study on a 50kW tidal turbine was carried out by numerical simulation. Based on the measured hydrological data of a certain observation point in the sea area of Zhaitang Island, the output of the turbine under time-varying flow conditions was analyzed by CFD to determine the turbine's optimum installation orientation. Result of simulation of a tidal periodicity (15 days) showed that the power output of tidal turbine may be influenced by the change in the velocity and direction of tide and its installation orientation. The maximum power output would be reached if the turbine was installed facing the direction of about 62° (WGS-84) in current observation point, which was about 2500kWh in a tidal periodicity. Therefore, velocity asymmetry between flood and ebb tides should be fully considered to determine the installation orientation of the turbine, which provides references for the development of tidal energy in the actual marine environment.**

***Keyword* — tidal turbine; time-varying flow; measured hydrological data; numerical simulation; output characteristics**

Ⅰ. Introduction

Deviation between the directions of tidal stream and the tidal turbine may have effects on performance of the tidal turbine, in that the direction and speed of the tide stream varies with time while the turbines are generally being installed with fixed preset orientation [1]-[4]. As the studies of Budi Gunawan et al. showed that the power output of the tidal turbine was reduced by 4.5% and 17%, respectively, when the direction deviation of flow was 10° and 20° at a same constant flow velocity [5].

Relevant studies were carried out by some researchers. Tony EI Tawil et al. evaluated tidal energy resources and got the result that the change of the flow direction will affect the installation orientation of turbine for the case study of by the sea area near the Ouessant Island in France by using the far-field CFD model [2]. Nicolas Maslov et al. introduced the yaw attenuation coefficient to analyze the influence of the changes in direction and velocity of tide on tidal turbine's output and evaluated annual energy output of the turbine at two observation sites in the Brittany region of France respectively [3]. Ahmad Safwan Sakmani et al. studied on location selection of the tidal turbines based on one-week's flow velocity measuring near Pangkor Island in the Strait of Malacca [6]. Marc Mestres et al. analyzed the characteristics of tide in the Ria de Vigo region of Spain by using the 3D hydrodynamic model with Flux method, and optimized the location of a tidal power station [7]. Hao Xu et al. made a comprehensive analysis of the tidal currents at a certain site in the Zhoushan archipelago with ROMS, and selected optimal location for developing tidal energy considering the influence of flow direction around the waters [4]. Most of the above studies were related to tidal energy resources assessment or the site selecting for tidal turbines in a large-scale region, few researches about how the time-varying tides effect on the performance of tidal turbines were studied.

In order to analyze more accurately the impact of this tidal stream changing on tidal turbines, ADCP was used to measure the hydrological data of the observation point (35.6199 N, 119.9285 E) in the sea area of Zhaitang Island. Based on the measured data, performance of a 50kW turbine, placed in the observation point with different installation orientations was simulated, and the output of the turbine with different installation orientation was compared and analyzed. The optimal installation orientation of the tidal turbine can be obtained according to the simulation result for a tidal periodicity (15 days).

Ⅱ. CASE STUDY: THE SEA AREA NEAR ZHAITANG ISLAND

Zhaitang Island, Qingdao, Shandong Province with the coordinate of 35°38'N, 119°55'E, is located to the southeast of Langyatai Strait (Fig.1). The morphological characteristics of the southeastern sea area of Zhaitang Island is a large relatively flat underwater terrain with depth about 35m to 40m, tidal range in this area is up to 4.6m in spring tide and its tidal current energy is suitable for exploited by building a tidal farm. Before the tidal current energy of the area is harnessed, some pre-researches have been carried out. Li H et al. assessed the resource reserve of tidal current energy in Langyatai strait by Flux method in 2012 [8]. Shi L et al. analyzed the tidal current energy of the test field using FVCOM in 2013 [9]. Ji H et al. preliminarily made a project to build tidal Farm based on the measured data in 2014 [10]. Chen Y et al. studied the arrangement of tidal turbine based on Delft 3D in 2015 [11]. Lin J et al. made a research about the impact of eddy induced by island to the energy extracted using Delft 3D in 2017 [12]. So far, several tidal turbines have been placed in this sea area [11], and more turbines are likely to be arranged in the future. Most of the researches focused on assessment of tidal energy resources and the analysis of multi-unit arrays in a large area of the sea area, and few studies on the impact of time-varying flow on the performance of tidal turbines were found.

According to measured hydrological data from the observation site, as shown in Fig.2, the tidal currents dominantly flow in a NE-SW direction. Tidal speed of flood is a bit larger than that of ebb and the direction of the flood and ebb tide is about 57°(237°) and 67°(247°). Referring to the rose map of the tide, five possible installation orientation (57°, 62°, 67°, 72°and 77°) were chosen for installing the tidal turbine. The 50kW tidal turbine starts at a flow velocity of 0.4m/s-0.5m/s according to the practical operation. As it can be seen from Fig.3 that the percentage of velocity of tide less than 0.4m/s-0.5m/s is only about 25%, the turbine can operate for most of the time theoretically.

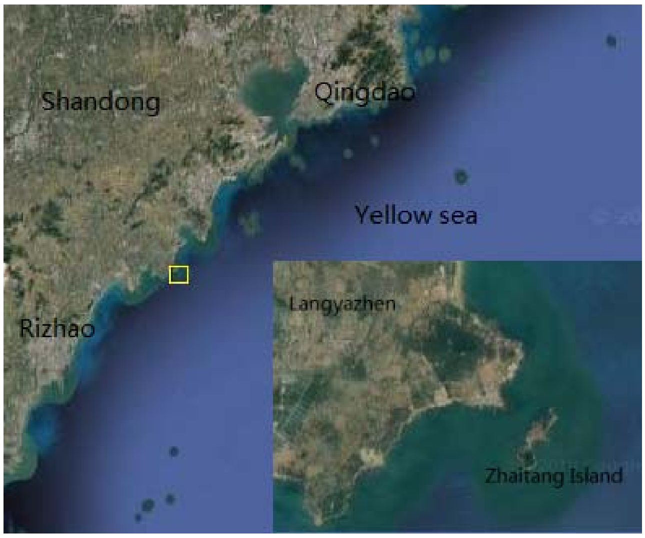

Fig. 1 Location of Zhaitang Island

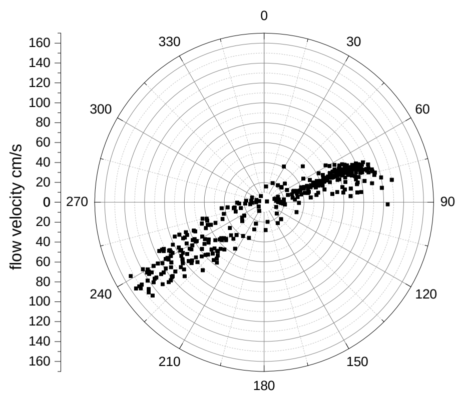

Fig.2 Rose plot of one tidal periodicity in observation point

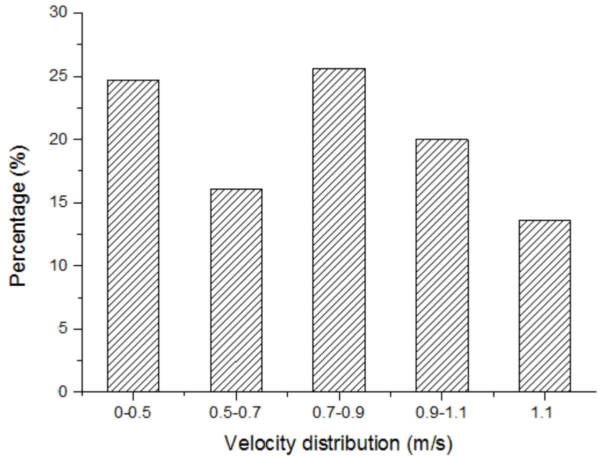

Fig.3 Velocity distribution statistics in one tidal periodicity at the observation point

III. MODELLING AND NUMERICAL SIMULATION

A. 50kW Tidal Turbine

The 50kW turbine being studied was developed by Ocean University of China. It has been put into operation in this sea area in 2013. It consists of a horizontal axis tidal turbine and a seabed seated support structure [13]. The hub center of the tidal turbine is about 12.5m above the sea bottom, as shown in Fig.4. Pitch-adjusting technology is used for the turbine's blades to adapt to the reciprocating tidal flow. The blades could be controlled to rotate 180° to adapt to the changed flow direction when the tidal flow reversed.

The hydrofoil of the blades of the rotor, which is the core component of the tidal turbine, is NACA63-8XX. In order to get a credible result, a model of the rotor with the same hydrofoil was built for the simulation. The three dimensional model and the parameters of the rotor are shown in Fig. 5 and Table Ⅰ, respectively. Impact of the support structure on the performance of the tidal turbine was not taking into account in this study for its effect on the result of the simulation is negligible.

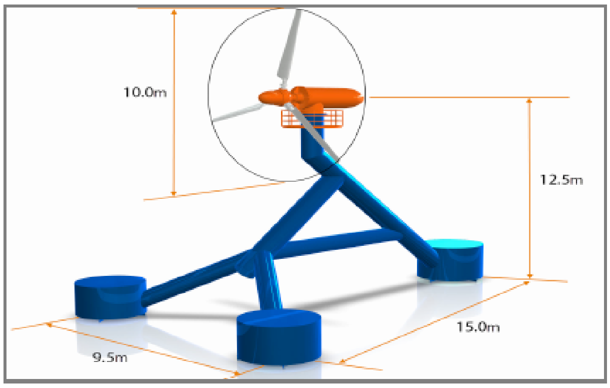

Fig.4 50kW tidal turbine

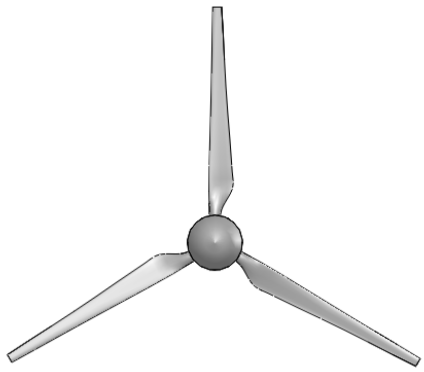

Fig.5 Three dimensional model of the tidal turbine rotor

TABLE I

TURBINE ROTOR PARAMETERS

Hydrofoil	Number of blades	Rotor diameter (m)	Hub diameter (m)
NACA63-8XX	3	10	1.2

B. Modelling, meshing and boundary conditions

Three dimensional model of the 50kW tidal turbine was built by using software Solidworks, and then imported into software Gambit to be meshed and boundary conditions were set.

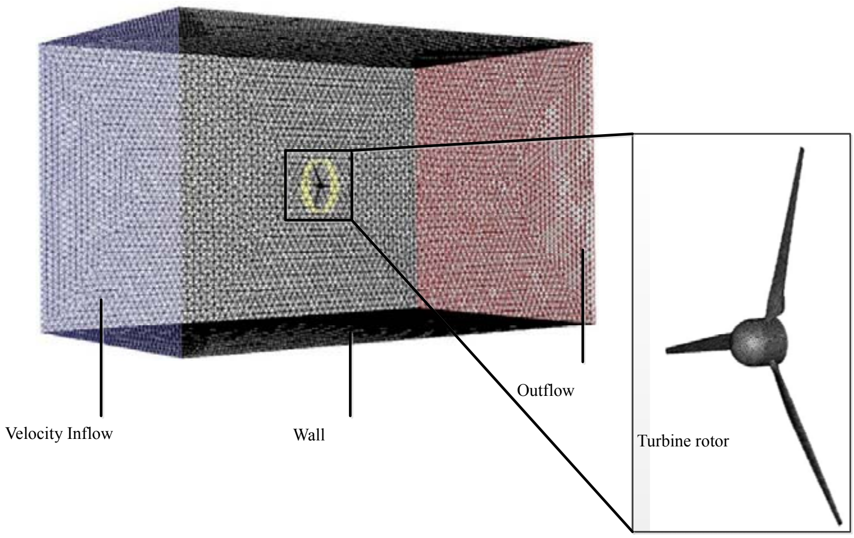

Fig.6 Meshing and boundary conditions settings

The turbine rotor was meshed by using triangular mesh for its shape is more complicated, while the rotating field domain and fluid domain were meshed by using tetrahedral unstructured grid [14]. Different axial direction of the turbine and direction of inlet flow was applied for all the five cases while the models and meshes remained the same. The calculation model is made up by the fluid domain and the rotation domain. The mutually overlapping faces between the rotation domain and the fluid domain were set as the interface, which was implemented in Fluent (CFD software). The turbine rotor is completely merged into the rotation domain, the turbine blades are set to the wall type, and both the rotation domain and the fluid domain are set to fluids. The grid and boundary conditions are set as shown in Fig. 6.

In the paper, the SST k-ω turbulence model was used in the simulation, which takes into account the advantages of the standard k-ω turbulence model and the standard k-ε turbulence model and has high accuracy and good convergence[15].

C. Verification

In CFD simulation, the number of grid elements affects the calculation accuracy. Appropriate number of grid elements should be chosen to improve the calculation accuracy and save the calculating time.

Through the verification of the grid independence of the calculation models for five different number of grid elements, Table Ⅱ shows the results with different grid resolutions. It can be seen from Table Ⅱ that the calculation results converged for the number of grid elements more than 3.05 million. This indicates that further increasing of the grid resolution would not improve the results significantly. Considering the economy of time consumption, the grid with 3.05 million elements was chosen for the following simulations.

TABLE Ⅱ

RESULTS OF TORQUE AND THRUST FOR MESH VERIFICATION

Approx. number of grid elements (million)	**Torque (N·m)**	**Thrust (N)**
1	6744.43	30329.29
1.8	7561.11	30526.24
3.05	8494.32	30985.65
4	9029.38	31043.29
4.9	9042.38	30918.35

Ⅳ. Results and Analysis

The CFD software is used to calculate the turbine's production in time-varying flow conditions. It is assumed in the calculation process that the fluid in the flow field is viscous and incompressible [16]. The continuity equation and momentum equation of the flow field are:

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad (1)$$

$$\frac{\partial(\rho u_j)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\mu \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right] \qquad (2)$$

Where u_i and u_j are velocity components (m/s); x_i and x_j are position coordinate components; P is fluid pressure (Pa); μ is hydrodynamic viscosity coefficient.

Tidal turbine converts the kinetic energy of the reciprocating motion of the tidal current into mechanical energy, and then converts mechanical energy into electrical energy output during running [17]. The energy extracted by a tidal turbine is converted into usable power from the torque applied to the rotor [11]. The expression is as follows:

$$P = \frac{1}{2} C_P \rho A U_\infty^3 \qquad (3)$$

Where P is turbine power (W); C_P is power coefficient; ρ is seawater density (kg/m^3); U_∞ is tidal velocity (m/s). A is the sweep area of rotor (m^2); The power of the turbine can also be expressed as the relationship between the rotational angular speed ω of the rotor and the rotor torque [16]:

$$P = \omega T_a \qquad (4)$$

A. Research on Effects of Velocity and Direction of Tidal Flow on Output of Tidal Turbines

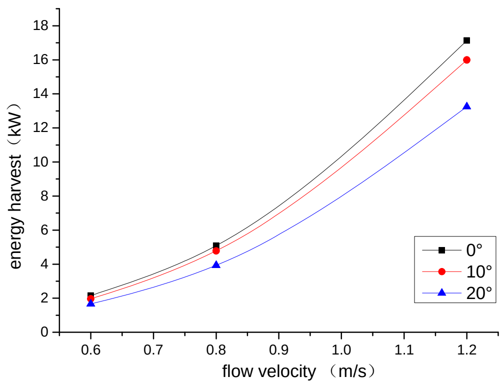

Fig.7 Comparison and Analysis of Turbine Power Effect When Changing Flow Velocity and Flow Direction

A comparative study of the variable deviation angle at constant velocity and variable velocity at constant deviation angle is conducted. As shown in Fig.7, output of the tidal turbine decreased 6% and 22.6% respectively for the cases of the angles between the axial of the turbine and flow direction are 10°and 20° while the speed of the flow kept constant, which is approximately consistent with the results of Budi Gunawan et al. with the fixed velocity [5]. Power attenuations of the turbine were about 70% and 87% when the flow velocities were reduced from 1.2m/s to 0.8m/s and 0.6m/s, respectively, with the fixed installation orientation. Change in velocity or direction of flow would affect the power output of the turbine, especially the simultaneously changes.

B. Analysis of electric power production in Different Installation Orientation

The distribution of electric energy produced by the tidal turbine at 62° install orientation at a relatively large velocity in one day is shown in Fig.8. From Fig.8 we can see that the tidal turbine cannot generate electric power in about 6 hours because of the too low flow velocity.

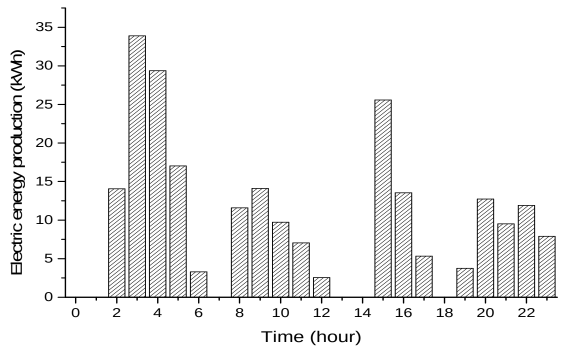

Fig. 8 Daily electricity production at 62°installation angle

In order to explore the statistical law that the time-varying flow affects the energy extraction of the tidal turbine in a long period, a numerical simulation of the energy extraction was conducted and analyzed based the measured data at observation point in a tidal periodicity (15 days). The detailed electric power production of 50kW tidal turbine in different installation orientation is shown in Fig. 9. The comparison results of the tidal turbine' electric power production in different installation orientation is also shown in Fig. 10.

According to Fig. 9 and Fig. 10, the numerical simulation results in a tidal periodicity shows that the time-varying flow will affect the energy extraction of the tidal turbine, and the periodic variation of the tidal in a tidal periodicity has an evident influence on the power generation of the turbine, the highest daily energy production is about 4 times the minimum daily electricity production.

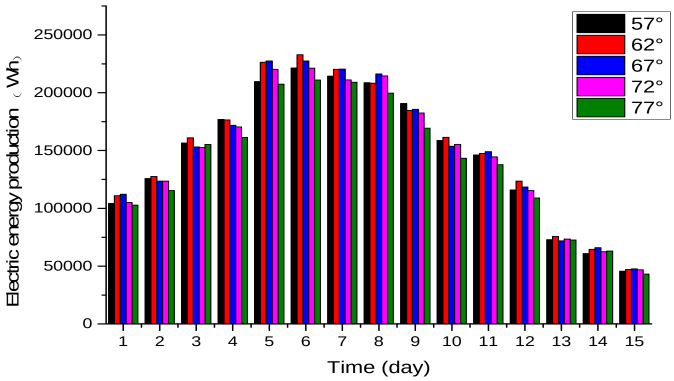

Fig.9 Electric power production in different installation orientation in observation point in one tidal periodicity (15 days)

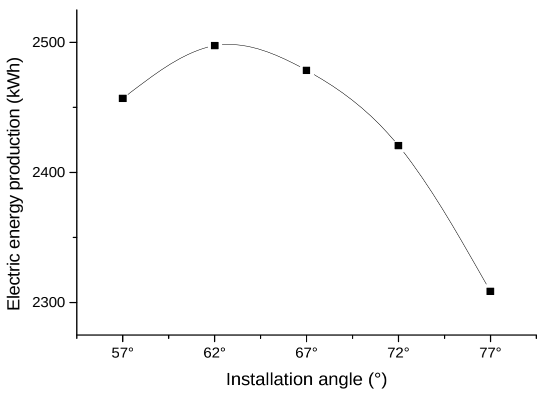

Fig.10 Comparison of electric power production in different installation orientation of one tidal periodicity in observation point

Different installation orientation will also affect the turbine's energy extraction. At the observation point, the flow directions are mainly 57° and 67° during flood and ebb, respectively. Then selecting these direction as installation orientation of the turbine, the outputs were 2456kWh and 2479kWh, respectively. However, the output was 2498kWh with 62° installation orientation. Therefore, in order to get maximize utilization of tidal energy, when selecting the orientation of a turbine in actual engineering application, not only taking the main flow direction during flood or ebb into account, but also considering the velocity asymmetry to determine the installation orientation.

C. Power generation analysis in observation point

Without influx of rivers, water level in the sea area of Zhaitang Island the measured sea level is relatively stable. Numerical analysis indicated that the tidal turbine’s power generation is about 2500kWh in the observation point in one tidal periodicity (15 days). Nevertheless, due to the influence of submarine topography, turbulence, and velocity gradient in the actual marine environment, the efficiency of the tidal turbine will be reduced, and the actual electric power production would be less than that of the numerical simulation value.

Ⅴ. CONCLUSIONS AND FUTURE WORK

In this study, a 50kW tidal turbine was analyzed by CFD under time-varying conditions based on the measured data of a certain observation point in the sea area of Zhaitang Island to predicate its power output with different installation orientation.

Time-varying flow occurs simultaneously in both velocity and direction of flow. Due to the change of time-varying flow, the respective power attenuation law could be obtained by comparing and analyzing the power output of the turbine under the two work conditions, including fixed installation orientation with time-varying velocity and fixed velocity with time-varying installation orientation. Power attenuations of the turbine were about 6% and 22.6% when the deviations between the axial direction of the turbine and the tidal current were 10° and 20°, respectively, with the fixed velocity. Power attenuations of the turbine were about 70% and 87% when the flow velocities were reduced from 1.2m/s to 0.8m/s and 0.6m/s, respectively, with the fixed installation orientation. Change in velocity or direction of flow would affect the power output of the turbine, especially the simultaneously changes.

The analysis of the turbine’s power output at five different installation orientations showed that the optimal installation orientation of the tidal turbine was 62°, which is generally close to the main flow direction during the flood and ebb. In order to develop tidal energy sufficiently and reasonably, the asymmetries of velocity and direction of flow should be considered simultaneously in the actual project. This paper provides references for determining the installation orientation of a turbine and the arrangement of turbines in the real ocean environment.

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