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Experimental Research on Energy Extraction Characteristics for Half-rotating Impeller Tidal Turbine

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Abstract. The half-rotating impeller tidal turbine (HRITT) is a new type of vertical shaft tidal current turbine with lift and resistance performance. The experimental prototype and the experimental platform of the HRITT were designed and simulation experiments was carried out to analyze the energy extraction performance of the HRITT under various flow velocity and loads. The results of the experiment indicated that the platform was stable as well as reliable. The HRITT not only had good dynamic characteristics at low inflow velocity, but also had high efficiency that its maximum coefficient of energy extraction could increase to 45%. The flow velocity had little influence on the maximum efficiency of the HRITT.

1. Introduction

Tidal current energy has became a research hotspot of renewable energy development due to its advantages of high energy density, strong predictability and non-pollution. As the primary device for power flow energy conversion, hydraulic turbine has been widely developed in the world[1]. As one of them, vertical shaft tidal turbine is favored by researchers, because its power generation device can be arranged on the surface of water, good self-starting performance and simple blade structure [2].

There are two main types of vertical shaft tidal current turbines, including pure resistance type turbine with Savonius type rotor [3] and pure lift type turbines with Darrieus type rotor [4]. The pure resistance type turbine has low coefficient of energy extraction, while the pure lift type turbine has poor self-starting performance. Vimal Patel [5] chooses to install an end plate on the blade to prevent fluid outflow, so as to increase the pressure on the concave surface of the blade, which improves the coefficient of energy extraction of the resistance turbine to 20%. Herman zeiner-gundersen [6] develops a new type of lift-turbine with the blade position-variable, which enhances the characteristics of self-start. It is seen that both of them have their advantages and disadvantages in vertical shaft turbines. In combination with the characteristics of lift and resistance type turbines, Bian Peixiang [7] proposes a combined lift-resistance turbine, which enhances the self-start performance of the turbine at low speed and improves its maximum coefficient of energy extraction to 38%. However, this kind of turbine is only a combination of structure, and not seen on the mechanism of integration. While the flow rate of most sea areas are less than 1m/s in China [8], the rated flow rate of the most vertical shaft turbines are mostly above 2m/s. Therefore, it is great practical significance to develop a new type hydraulic turbine that can integrate lift type turbine with high coefficient of energy extraction and good self-starting performance of resistance type turbine.

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Based on the characteristics of animal motion, half-rotating mechanism is put forward by the bionic machinery research team of Anhui university of technology [9]. It has been applied to similar-flapping wing flight [10] and ship propulsion [11], both of which have achieved favorable experimental results. In view of the good hydrodynamic performance of half-rotating mechanism with fluid, it was applied to the field of power generation. On the basis of the early CFD simulation calculation [12], a new prototype of the HRITT was designed and the experiment was carried to analyze the energy extraction characteristics. It provided experimental support for the commercial application and promotion of the turbine.

2. Basic principal and the prototype of HRITT

Working principle of the half-rotating mechanism is shown in Figure 1, and the HRITT evolves from the half-rotating mechanism. The diameter of the rotating gear is twice that of the fixed gear. When the crank rotates at angular speed ω , the half-rotating rod rotates at angular speed ω /2 in the same direction.



Figure 1. Working principle of the half-rotating

When the half-rotating mechanism was applied in the fluid field, the crank was extended into the rotating arm and two rotating gears were equipped on both ends of the rotating arm, meanwhile the half-rotating rod was replaced by the blade, then the half-rotating impeller was derived as shown in Figure 2.



Figure 2. Working principle of the HRITT

Taking the midpoint of the rotating arm O as the coordinate origin, the rectangular coordinate system was established as shown in the figure 2. When the incoming flow with velocity U_0 appeared from the Y axis direction, the rotating arm driven by the two blades rotated around O point with angular velocity ω under the action of hydrodynamic force, and in the meantime the two blades rotated around its center axis of rotation with velocity $\omega/2$ through the gears, chains, or other transmission, so as to realize the rotating arm rotated one circle meanwhile blade rotated half a circle. Blade relative flow velocity V was the vector sum of the velocity of the incoming flow U_0 and the blade itself V_0 .

When the fluid flowed through the two blades, it could produce resistance F_D and lift F_L at the same time. Therefore, the asymmetric rotation of blade made it effective use of the lift and resistance. In order to ensure the best operation of the turbine, convection device should be equipped for the HRITT so that flow direction had the certain requirement. According to the operation principle of the half-rotating impeller, the prototype of the HRITT was designed and manufactured, as shown in figure 3.



Figure 3. The prototype of HRITT

The prototype was mainly composed of rotating arm, blade, rotating-wheel shaft (output shaft), transmission gear and frame. The rotating arm was fixedly connected with the output shaft and could rotate around the central axis of the output shaft. In addition, the blade 1 and blade 2 were mutually perpendicular and connected to the two ends of the rotating arm respectively through the bearing. In order to improve the running stability and strength of the blades, the rotating arm was designed as the upper and lower structure. Considering the problem of rust prevention, the turbine blades, rotating arm and output shaft were all made of stainless steel, and the frame was assembled with hard aluminum alloy profiles. After the main structure and parameters of the prototype were designed as shown in table 1.

		1		
Blade number	Rotating arm	Blade span	Chord length	Blade
Ν	R(m)	L(m)	C(m)	thickness
				D(m)
2	0.085	0.9	0.2	0.003

Table 1. Structural parameters of the prototype

3. Experimental platform and experimental scheme

3.1. Experimental platform

As shown in figure 4, the experimental platform was designed to investigate the hydrodynamic performance of the HRITT.



Water area 2. Floating-body 3.Experimental ship
Hydraulic turbine 5.Torque-speed sensor 6. Magnetic powder loader
Figure 4. Schematic diagram of experimental platform

The experimental platform consisted of experimental ship and experimental system, which was manufactured as shown in figure 5.



(a) Experimental ship

(b) Test system

Figure 5. Experiment platform

To simulate incoming flows at various speeds, the speed-regulating propeller was installed to the experimental ship. Furthermore, the velocity is controlled within 0-1.2m/s, and Acoustic Doppler Velocimeter(ADV) was used to measure the velocity and flow direction. As shown in Figure 3(b), the test system mainly consisted of Data Acquisition Card(DAQ Card), Torque-speed sensor, Magnetic powder loader and current meter. The dynamic torque speed sensor was adopt to measure the torque and speed , and the load (the load is the output torque) was controlled by the magnetic powder loader. Avoiding the side wake flow generated by the experimental ship interfering with the flow field of the turbine, not only should the distance between the two pontoons on the experimental test platform be greater than 1.5m, but also the water-area should be deeper than 1.4m. In order to eliminate the wake flow interference and ensure that the incoming flow direction was always perpendicular to the turbine, the tidal turbine was located on the side of the bow and the experiment was carried out in a forward push mode. And therefore, the convection device wasn't installed on the test platform of this experiment.

3.2. Experimental test scheme

3.2.1. Definition of Coefficient of performance. The average output power of the turbine can be expressed as

$$\overline{P} = \frac{1}{t} \int_0^t \frac{2\pi \cdot M \cdot n}{60} dt = \frac{\pi}{30} \cdot M \cdot \overline{n}$$
(1)

Where, \overline{p} is the average output power (w) of the turbine, \overline{n} is the average output shaft speed

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(r/min), and M is the output torque (N·M).

The average input power of incoming flow is the sum of the total energy flowing through the swept area of the impeller in unit time,

$$\overline{P_0} = \frac{1}{2} \rho \cdot \mathbf{S} \cdot v^3 \tag{2}$$

According to the running equation [12] of the blade of the half-rotating mechanism, the swept area of the HRITT is written as

$$S = (2R + \frac{C}{2} + \frac{C^2}{32R})L$$
 (3)

Where, $\overline{P_0}$ is incoming stream input power (w), and ρ is water density (kg/m³). S is HRITT swept area (m²), and v is incoming stream velocity (m/s). R is the crank length (m) of the turbine. C is the chord length (m) of the blade, and L is the blade spreading length (m).

The coefficient of energy extraction of the turbine is the ratio of the output power to the input power of the incoming stream.Coefficient of energy extraction is defined as

$$C_{\rm p} = \frac{P}{P_0} = \frac{\pi \cdot M \cdot n}{15\rho S v^3} = \frac{32\pi \cdot M \cdot n}{15\rho v^3 (64R + 16C + C^2/R)L}$$
(4)

3.2.2. Experimental scheme. The experiment was carried out in the condition that the broad water area was tranquil without wind and waves to satisfy the actual running state well.Conversion efficiency test, according to formula (4), when the structural size of the turbine had been determined, the coefficients of energy extraction (C_p) could be obtained by measuring the output parameters, such as velocity, torque and rotational speed. Especially, the output parameters of the turbine were measured after the ship was running steadily.

4. Experimental data processing and result analysis

4.1. Data processing

The incoming flow velocity was measured by Acoustic Doppler Velocimeter (ADV), and both the sampling frequency of current meter and torque-speed sensor were set as 15HZ. In order to ensure the stability and reliability of the collected data, the effective time of single sampling was longer than 60s. The center filtering method was used for data processing, because the flow velocity may be affected by the vibration of the ship. According to the equation (4), the average coefficient of performance was calculated.

4.2. Analysis of conversion efficiency

From Figure 6, with the condition of different flow velocity and loads(M), the average coefficient of energy extraction of HRITT presented a parabolic variation trend of first increasing and then decreasing.



Figure 6. Coefficient of energy extraction of HRITT

In this experiment, parameter correction was made for the results of the previous CFD analysis[12]. The half-rotating impeller hydraulic turbine had a high energy extraction efficiency, and the Coefficient of energy extraction was up to 45%, which was 25% higher than the general vertical axis hydraulic turbine [13]. Particularly, the coefficient of energy extraction of the HRITT increased slowly with the load, but when it reached the peak, the coefficient energy extraction started to decline rapidly with a small incremental loads. The flow velocity had little influence on the maximum coefficient of energy extraction. Under different incoming flow velocities, there was an optimal load at the highest Coefficient of energy extraction point for the HRITT. In the actual application, the load could be adjusted according to the magnitude of the incoming flow velocity to ensure the best operation of the HRITT.

5. Conclusion

1) The vertical axis water turbine test platform with simple and feasible was designed and fabricated, which ran steadily and operated easily. At the flow velocity below 1.2m/s, experimental tests on the hydrodynamic performance of various types of the tidal turbines could be conducted.

2) The half-rotating impeller tidal turbine (HRITT) still had great energy extraction performance under the condition of low flow velocity, and the maximum coefficient of energy extraction(C_p) of HRITT could reach 45%, which was 25% higher than the general vertical shaft hydraulic turbine.

3) The flow velocity had less influence on the optimal coefficient of energy extraction. From study, there was an optimal load at different inflow velocities. Therefore, the power generation load could be adjusted according to the magnitude of incoming flow velocity in practical application, so that the HRITT was in the optimal energy extraction condition.

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