Flow Field Characteristics of 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. In order to explore the hydrodynamic characteristics of HRITT, the CFD method was used to analyze its flow field characteristics and dynamic performance. XFlow software was used to analyze the variation of velocity, vorticity, pressure and wake in the flow field of the half-rotating impeller, and the flow field characteristics of the device were expounded. The distribution of wake vortices and the attenuation law of wake velocity in a half-rotating impeller were analyzed, and the arrangement distance between the front and rear units was explored. According to the characteristics of the flow field, the variation law of torque coefficient and water utilization ratio were analyzed. It was found that the maximum water utilization ratio of HRITT is 34.7%, and the fluctuation of torque coefficient is small. The above results show that HRITT has unique flow field characteristics and good dynamic characteristics.

1. Introduction
As a kind of renewable energy with high energy density, strong predictability and abundant reserves, tidal current energy has broad development prospects and great development value [1]. At present, hydraulic turbines are the main devices for developing tidal energy. The blades provide tangential force to drive the impeller to rotate and convert the kinetic energy of tidal current into mechanical energy. The main research methods include flow tube method, vortex method and CFD method, among which CFD method can obtain more instantaneous flow field information.

Scholars have done a lot of research on the hydrodynamic characteristics of tidal turbines. Jo Chulhee [2] used CFD method to study the performance of tidal turbines, pressure distribution on blades and the streamline variation of the device; Li Ye [3-4] studied the effect of rotating direction and blade angle of attack on the performance of hydraulic turbines by eddy method; Lee JuHyu [5] tested a three-blade horizontal-axis tidal current turbine and simulated its power characteristics by BEM and CFD methods respectively; Stallard T [6] tested a three-blade horizontal-axis tidal current turbine in a flume at the University of Manchester and recorded the recovery of the downstream flow wake; Harrison M E and Myers L E [7-10] used porous media to simulate hydro-turbine, and studied the variation of wake field of tidal energy turbine by experiment and CFD method; GOUDE A[11] respectively simulated the vertical axis turbine group, drew the curves of efficiency and tip speed ratio of different arrangement forms of turbine group, and put forward suggestions for multi-unit turbine arrangement.
Based on the characteristics of animal motion, the bionic machinery research team of Anhui University of Technology put forward a half-rotating mechanism [12], which can produce asymmetric motion, and applied it to the design and research of tidal turbine. A new type of vertical shaft tidal energy turbine with lift and resistance performance was put forward. In order to explore the hydrodynamic characteristics of HRITT, the CFD method was used to obtain the flow velocity, pressure, vorticity and wake around the blade by using the hydrodynamic simulation software XFlow. It provides a theoretical basis for the performance analysis and optimization of the HRITT.

2. Working principle of HRITT

The HRITT was mainly composed of rotating arm, blade and driving mechanism. Figure 1 shows working principle diagram and Prototype model of the HRITT.

![Figure 1. Half-rotating impeller tidal turbine](image)

Working principle of half rotating impeller was shown in Figure 1(a), the rotating arm rotates around axis O. The rotating axes of blade 1 and blade 2 were hinged at the ends of the rotating arm A and B respectively. The blades can rotate around points A and B respectively. The two blades had same size and the initial installation phase difference was 90 degrees. When the incoming flow with velocity \( U \) appeared from the Y direction, the two blades drove the rotating arm together to rotate around O point with angular velocity \( \omega \) under the action of hydrodynamic force. Through the transmission mechanism, the two blades rotated around A and B points with angular velocity \( \omega/2 \) respectively, and the kinetic energy of the flow was converted into mechanical energy. During the operation of the unit, the blade had a large angle of attack in the downstream area (right side of Y axis) and stayed in the stall state of flow separation. The differential pressure drag was much greater than the lift force and the differential pressure drag \( F_D \) driving device operated. It had the working characteristics of a resistance turbine. When the blade was at the right angle of attack in the countercurrent zone (left side of Y axis), the lift \( F_L \) was greater than the drag \( F_D \), in which the lift \( F_L \) operated as a positive driving device and had the working characteristics of a lift turbine. Therefore, the device was vertical shaft tidal energy turbine with lift and resistance performance which had resistance as the main drive.

The prototype model was shown in Figure 1(b). The output shaft corresponded to the center O of the spindle in Figure 1(a), and the output shaft, rotating arm and column are fixed and the central axis coincided, and the three are connected to the frame through bearings. Through the gear transmission mechanism installed on the rotating arm, the motion relationship between the rotor and the blade was realized.

3. Establishment of hydrodynamic analysis model

The hydrodynamic analysis model of half-rotating impeller was established in XFlow. The main parameters of the impeller were shown in Table 1. The simplified model is shown in Figure 2.
Table 1. Main parameters of half-rotating impeller

| Rotating arm R(m) | Chord length C(m) | Blade span L(m) | Blade thickness D(m) |
|-------------------|-------------------|-----------------|---------------------|
| 0.225             | 0.476             | 2.101           | 0.010               |

Figure 2. Simplified model of half-rotating impeller

The vertical direction is the blade’s spanwise, and the horizontal direction is the blade’s chordwise. Firstly, the motion equations of the rotating arm and blade were set up in the XFlow motion module according to the motion law of the half-rotating mechanism. Then the flow field parameters were set in the environment module and the hydrodynamic calculation was started.

4. Analysis of hydrodynamic characteristics

Assuming the inflow velocity \( U = 1 \) m/s, the hydrodynamic simulation of the half-rotating impeller in different rotating speeds was carried out in XFlow. Then the middle section of the blade was selected as the observation surface in the post-processing module. The velocity, pressure and vorticity around the blade are analyzed and the flow field characteristics are summarized. The variation of the tail flow field around the half-rotating impeller was observed in a volumetric field. Combining with the flow field characteristics, the torque coefficient and the Conversion efficiency were analyzed.

4.1. Analysis of flow field characteristics

The flow field of the half-rotating impeller under this working condition with \( U = 1 \) m/s and \( \omega = 2.26 \) rad/s was analyzed. From the structural relationship of half-rotating impeller, it can be seen that the rotating arm rotates one cycle and the impeller undergoes two motion cycles. Therefore, the flow field of the rotating arm in the range of 0–180 degrees was analyzed only.

4.1.1. Velocity distribution. As shown in Figure 3, the half-rotating impeller rotated counterclockwise with the flow direction from bottom to top. In the initial state of the second cycle, the blade 1 was in a horizontal position and the blade 2 was in a vertical position.
As can be seen from Figure 3, the initial angle of attack of blade 1 was 90 degrees, and the blade was in the state of lift stall with flow separation. With the rotating arm, the angle of attack between the blade and the incoming flow were decreasing gradually. The blade broke away from the state of lift stall when the rotating arm angle was 140 degrees, and the blade was in the state of flow separation and additional lift induced by attached eddy current at 140-180 degrees.

The initial angle of attack of blade 2 was 0 degrees, and the angle of attack of blade increased with the rotation of rotating arm within 0~20 degrees. The flow separation occurred at the front end of blade, and the attached eddy current was generated at the end of blade, which moved along the blade chord direction on the inflow surface of blade. The blade was in a state of flow and attachment during 20~60 degrees, and the vortex generated in the upper stage still sticked to the blade surface and moved backward along the chord direction. The boundary layer at the front end of the backflow surface of the blade produce a countercurrent in the range of 60 to 120 degrees, and then the flow separated to produce eddy current. The blade was in the state of lift stall with flow separation between 120 and 180 degrees, and a resident vortex was gradually formed at the front end.

4.1.2. Vorticity distribution As shown in Figure 4, the vortices generated by blade 1 at the left end of the blade were less intense in the range of 0 to 40 degrees and fall off directly from the tip to form a wake vortex; the vortices generated at the right end were more intense and accumulated near the tip to form a resident vortex. With the rotation of the rotating arm, the standing vortex diffused and the strength decreased gradually. The shedding vortices at the left end gradually increase in the range of 40 to 140 degrees and approached the blade gradually during the movement. The standing vortices at the right end gradually shredded and formed wake vortices. The blade was in the state of flow separation from 140 to 180 degrees. High-intensity eddy currents were produced at the left end of the blade. The eddy currents accumulated to a certain extent at the end and fell off. The shedding eddy currents attached to the back surface of the blade and moved along the blade chord. In this process, the eddy currents provided additional lift to the blade.

The backflow surface of blade 2 stayed in the state of flow attachment within 0-20 degrees and no vortices were generated. The vortices were separated and attached to the blade surface in front of the inflow surface. At 20~60 degree, there was no eddy current generated by the blade except the attachment vortex generated at the last stage. At 60~120 degrees, eddy current around inflow surface
was the produced around the blade, which was applied to the surface with gradual decrease of strength. The vortex at the back end of the blade shed off directly from the tip within 120–180 degrees, and a resident vortex with gradually increasing intensity formed on the back surface of the blade.

![Vorticity nephogram of HRITT](image)

**Figure 4.** Vorticity nephogram of HRITT

4.1.3. Pressure distribution

![Pressure distribution images](image)
As shown in Figure 5, the pressure on the inflow side of the blade was higher than that on the backflow side of the blade when the blade was in the range of 0~40 degrees and on both ends of the inflow side was higher than in middle. A higher negative pressure area was formed at the right end of the blade because of the presence of the resident vortices, and the intensity of the negative pressure area decreased continuously, the range of the negative pressure area also gradually narrowed and tended to detach. From 40~100 degrees, the pressure of backflow surface of blade 1 increased gradually because of the disturbance of the wake of the blades. Within 100~180 degrees, the pressure on the left inflow surface of the blade increased gradually, and the negative pressure area on the backflow surface moved due to the attached eddy current.

Within the range of 0 to 100 degrees of blade 2, the pressure at the front end of the blade increased continuously and the range increased gradually to the rear. The strength of the negative pressure zone formed by the eddy current decreased continuously and was far away from the blade. The pressure near the inflow side of the blade 2 increased further because the flow between the blade 1 and the blade 2 was blocked in the range of 100 to 140 degrees, and the negative pressure region increased gradually in the front of the blade 2. At 140~180 degrees, the pressure at the inflow surface of the blade began to decrease and the strength of the negative pressure area on the back surface increased continuously.

4.1.4. *Wake Vortex distribution* The wake vortex will disturb the velocity and pressure distribution in the flow field, which will affect the performance of the half-rotating impeller. The three-dimensional cloud diagram of half-rotating impeller trailing vortex was shown in Figure 6.
As shown in Figure 6, the vortices are annular at the edge of the blade. With the rotation of the rotating arm, the continuous vortices gradually detached from the blade and form wake vortices. The trailing vortex at the left end of blade 1 and the trailing vortex at the back end of blade 2 kept close in the course of motion and contact and merge gradually at 80 degrees. At 90 degrees, the trailing vortex at the left end of blade 1 began to contact with the trailing vortex at the back end of blade 2 and inserted into the trailing vortex. So that part of the trailing vortex at the back end of blade 2 attached to the inflow surface of blade 1. In 115~180 degrees, the trailing vortex generated by the rear end of blade 2 moved on the inlet surface of blade 1. At 180 degrees the distal separation of the two wake loops of blade 1 and blade 2 was combined at the proximal end. The above was the evolution process of the wake vortex in the flow changing cycle.

The process of wake evolution was the same as that of the previous period within 180~360 degrees, and the strength of the combined vortex ring produced in the last period weakens and began to break away from the new vortex ring produced in this period. At 900 degrees, the wake vortex generated by the first cycle basically dissipated.

4.1.5. Wake Velocity distribution The maximum projection length of impeller in the direction of incoming flow is D. The flow velocity collection lattices was set on the blade central section. The sensor was arranged in the radial direction with 0.1D spacing and along the flow direction with the 1D spacing. The wake velocity variation curve is shown in Figure 7.

As shown in Figure 7, the wake center near the impeller had a lower velocity, and the outward spreading velocity gradually increased along the radial direction, approaching the incoming velocity generally; with the increase of the distance between the wake and the impeller, the velocity difference between the radial direction decreased and the overall velocity gradually rised back to the initial incoming velocity. Therefore, the distance between the front and rear units should be more than 10D when the parallel operation of multiple units was running to avoid affects by the wake of the front unit.
4.2. Analysis of dynamic characteristics

Torque coefficient $C_m$ can not only reflect the merits and demerits of the HRITT, but also reflect the magnitude of transient torque truly, which was the basis of the device structure analysis. Conversion efficiency $C_p$ was an important parameter to measure the hydrodynamic performance of the device. Combined with the instantaneous torque coefficient and instantaneous water energy utilization rate of the device in a moving cycle, the average torque coefficient and the average water energy utilization rate of the device at different operating speeds were analyzed.

4.2.1. Torque analysis. The instantaneous torque coefficient curves at $U = 1 \text{ m/s}$ and $\omega = 2.26 \text{ rad/s}$ and the average torque coefficient curves at different speeds were shown in Figure 8.

![Image](image_url)

Figure 8. Torque coefficient of HRITT:

As shown in Figure 8(a), the vorticity intensity on the back surface of blade 1 decreased gradually in the range of 0~40 degrees, which led to the decrease of pressure differential force on both sides of blade 1, and the increase of the angle between blade and rotating arm led to the decrease of the component of positive work on blade 1. In addition, the lift provided by blade 2 produced less torque, so the torque coefficient of the device showed a downward trend. The pressure difference on both sides of blade 1 decreased continuously in the range of 40~130 degrees. Under the influence of wake vortices from blade 2, the pressure on the inflow surface of blade 1 was less than that on the backflow surface and the pressure difference resistance increased continuously. The torque of blade 1 to the rotating arm changed from positive work to negative work. The pressure on the inflow side of blade 2 kept rising, while the pressure on the back side of blade 2 was lower under the influence of stall state, which led to a larger differential pressure on both sides of blade. Moreover, the angle between the blade force and the reverse extension line of the rotating arm decrease gradually, and the component of the positive work increased continuously, so the torque coefficient of the device was on the rise. The lift of blade 1 increased gradually; The pressure of blade 2 inflow surface gradually decreased and the torque coefficient of the device began to decrease.

From Figure 8(b), it can be seen that the average torque coefficient of the device increases from the initial static torque coefficient with the increase of rotational speed, and then decreases gradually to zero after reaching the peak value. The static torque coefficient of the device was large, which indicated that the device had good self starting performance.

4.2.2. Analysis of conversion efficiency. The instantaneous Conversion efficiency curve at $U=1 \text{ m/s}$ and $\omega=2.26 \text{ rad/s}$ and the average conversion efficiency curve at different rotational speeds were shown in Figure 9.
Figure 9. Conversion efficiency of HRITT

Figure 9(a) shows that the instantaneous power of the device was greater than zero during a period of motion, indicating that there was no negative power area in the operation process of the device, and the proportion of low efficiency area was small, indicating that the hydrodynamic performance of the device was better.

From Figure 9(b), it can be seen that the average water energy utilization ratio of the unit increases first and then decreased with the increase of rotational speed, reaching a maximum value of 34.72% when rotational speed \( \omega = 2.26 \text{ rad/s} \). Better operating parameters can be selected according to actual output requirements.

5. Conclusion

1) The half-rotating impeller blade is in the stall state of flow separation in most areas, and the pressure difference on both sides of the blade is large, which is beneficial to energy conversion.

2) The half-rotating impeller has no negative work area in the running process, which has high average effective conversion efficiency and excellent hydrodynamic performance.

3) The wake field of the device varied complex., the wake field was Symmetrically distributed along the center of the device and varied periodically. When multiple units were running, the distance between units should be controlled at about 10D.

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