Design of half-rotating impeller tidal turbine and its energy-capturing characteristics

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Abstract. Based on characteristics of the half-rotating mechanism, a new type of vertical axis turbine with characteristic of lift-drag combination was proposed, which named the half-rotating impeller tidal turbine (HRITT). The turbine was composed of rotary mechanism, alignment mechanism and support mechanism. The mechanism design and manufacture of the HRITT were completed and underwater operation experiments were carried out to verify the rationality of mechanism design and its good self-starting performance. Through the hydrodynamic simulation of the impeller by Xflow, the changes of pressure and velocity around the blades in the flow field were analyzed, which proved the feasibility of the operation and energy-capturing characteristics of lift-drag combination of the HRITT.

1. Introduction
Water resource is a kind of renewable and clean energy with huge reserves, whose development and utilization have attracted more and more attention[1]. Turbines are power machines that convert the kinetic energy of flowing water into mechanical energy which are divided into two categories: horizontal-axis turbine and vertical-axis turbine[2]. In Seong Hwang investigated an new cycloidal water turbine and carried out parametric study by CFD analysis to find the optimal parameters[3]; Yang B designed the ‘Hunt turbine’ and carried out research through CFD method[4]; Fernandes A C studied a flat vertical axis turbine on improving efficiency[5]; Ye Li studied three-dimensional effects and arm effects of vertical axis tidal current turbine using a newly developed vortex method[6]; Le T Q analyzed the start-up process of vertical axis turbine with straight blade and helical blade under different loads through the Fluent software[7]; The bionic machinery team of Anhui university of technology proposed a special mechanism, named half-rotating mechanism [8], which was applied in the field of ship propeller and flapping-wing aircraft[9-10]. A special flow field between the half-rotating mechanism and fluid was found, which had a good development prospect.

A new type of half-rotating impeller tidal turbine was presented in this paper. The working principle of the HRITT was described and mechanism design and prototype manufacturing were completed. Underwater operation experiments were made to verify the rationality of mechanism design and running stability of the turbine. CFD method was used to study the flow velocity and pressure variation around the blades and to explore the energy capturing characteristics of the HRITT.

2. Working principle of the HRITT
The working principle of the HRITT was shown in figure 1. The rotating arm rotated freely around
fixed point O and two blades were articulated at both ends of the rotating arm, who could rotate around articulated points A and B respectively. The rotating arm and blades were connected by transmission mechanism. When the rotating arm rotated at angular velocity $\omega$, two blades would rotate in the same direction around point A and point B respectively at angular velocity $\omega/2$. The extension line of blades at any position always intersected at the fixed point P.

![Figure 1. Working principle of the HRITT.](image1)

![Figure 2. Motion analysis of a single blade.](image2)

Motion analysis of the HRITT with a single blade during a period was shown in figure 2. $V_0$ and $U_0$ meant the inflow velocity and blade's linear velocity respectively, and $U_1$ meant the blade velocity relative to inflow velocity. During the operation of the device, the angle $\alpha$ (attack angle) between the blade and the relative velocity was larger when the blade moved in the area (down tidal area) where the blade moved on the left side of the Y axis. The drag force acting on the blade by the incoming flow was much greater than lift force. At this time, the drag force was the main driving force $F$; On the contrary, when the blade moved in some regions on the left side of the Y axis (the countertidal area), the lift force was greater than drag force, then the lift force was the main driving force $F$. Therefore, the HRITT was a kind of vertical shaft turbine with characteristics of lift-drag combination.

3. Mechanism design of the HRITT
Mechanism of the HRITT was designed according to the working principle. The half-rotating motion between blades and arm was realized by using synchronous belt drive with transmission ratio of 2:1. A alignment device was designed to realize the alignment function of the HRITT. The preliminary design of the HRITT structure consisted of three parts: rotary mechanism, alignment mechanism and support mechanism, whose detailed structure was shown in Figure 3.

![Figure 3. Structural sketch of the HRITT.](image3)

3.1. Design of rotary mechanism
Rotary mechanism was the core structure of the HRITT, whose function was to capture and convert
energy. The rotating mechanism mainly consisted of upper rotating arm, lower rotating arm, impeller, fixed column and primary transmission system. The upper and lower rotating arms were connected by fixed column to form a rotating frame like a shape of ‘Gong’, which was connected with the supporting mechanism by the alignment arm. Two blades were symmetrically mounted at both ends of the rotating arm and connected by the primary transmission system. The installation phase difference between two blades was 90 degrees. The primary transmission system consisted of large and small synchronous pulleys, tensioners and synchronous belt. The large synchronous pulley was fixed with blade and small synchronous pulley was fixed with the upper alignment arm. The tooth number ratio of the large and small synchronous pulley was 2:1. The small synchronous pulley stayed fixed and the rotating arms rotated around it while the large synchronous pulleys rotated with the blades. The primary output shaft, which was fixed on upper rotating arm, transmitted energy to the secondary output shaft through the transmission system.

3.2. Design of alignment mechanism
The main function of alignment mechanism was to adjust rotary mechanism when the direction of incoming flow changed. It was mainly composed of upper alignment arm, lower alignment arm and secondary transmission mechanism. The upper alignment arm was used for the installation of fixed wheel in primary transmission system (small synchronous pulley) and secondary transmission system. The secondary transmission mechanism connected the primary output shaft and the secondary output shaft by synchronous belt transmission, which ensured the power could be transmitted to the secondary output shaft through the transmission system continually. When the direction of incoming flow changed, the force acting on the alignment arm produced a horizontal component force which was perpendicular to alignment arm, so the function of automatic alignment could realize.

3.3. Design of supporting mechanism
Supporting mechanism was mainly composed of body and a fixed base. The body was the main frame of the supporting mechanism, which was used to support, install and fix the whole HRITT. The rotary mechanism and alignment mechanism were installed on the support mechanism through two collinear fixed bases, which was connected through bearings, to realize the relative rotation between the rotary mechanism and the supporting mechanism.

4. Prototype manufacture and underwater experiment of the HRITT
According to the design scheme mentioned above, the HRITT was manufactured which was shown in figure 4. Aluminum alloy and stainless steel were selected as the processing materials to prevent rust from destroying the prototype. Main structural parameters of the HRITT were shown in Table 1.

| Structural parameters                  | Size (m)  |
|---------------------------------------|-----------|
| Rotary radius of impeller             | 0.23      |
| Blade size (chord×elongation×thickness)| 0.2×0.6×0.003 |
| Length of alignment arm               | 0.2       |

A simplified experimental scheme was adopted to carry out underwater experiments. Depending on the ship to drive the prototype forward, the action by incoming flow on prototype was simulated. A supporting float ball was fixed on both sides of the prototype, and a power generating device with a light bulb were installed with the secondary output shaft of the HRITT to facilitate the observation of the operation and energy output, which was shown in figure 5.
Through underwater experiments, it was observed that the prototype could start up and run smoothly at the inflow speed of about 0.4m/s with the light bulb luminous, which indicated that the HRITT could run and output energy continuously. This experiment verified the rationality of the HRITT and found that the prototype had good self-starting performance.

5. Analysis of energy capturing characteristic of the HRITT

The underwater operation experiment had validated the rationality of the design scheme. In order to further explore the energy capturing characteristic of the HRITT, a three-dimensional simplified model of the HRITT was established by UG and imported into Xflow, which was simulated to analyze the flow field changes and energy capturing characteristics near the blade.

The flow field area's size was 8m×4m×4m which was shown in figure 6. In the initial state, the blade's longer side was parallel to the Y axis and the shorter one was parallel to the Z axis in the flow field. The phase difference between blade 2 and blade 1 was 90 degrees. The inflow direction was along negative direction of the X-axis and the velocity was 1 m/s. Under the action of incoming flow, the half-rotating impeller rotated counterclockwise around the Y-axis direction and the blade was constrained to do half-rotating motion by the constraint of moving equation. After setting the relevant parameters, the calculation was started and the simulation results were processed through the post-processing module.

In one motion cycle, the blade motion law in the first half cycle was exactly identical with that in the second half cycle. Therefore, the energy capturing characteristics of the HRITT were analyzed by using the velocity vector and pressure nephogram of the fluid around the blade in the first half cycle, which was shown in Table 2.

| Azimuth | Velocity vector nephogram | Pressure nephogram |
|---------|----------------------------|--------------------|
| Color bar | Velocity (m·s⁻¹) | Static pressure (Pa) |
| 0 | 0.25 | -1500 |
| 0.75 | 600 |

Table 2. Velocity vector and pressure nephogram of flow field in different directions.
| Angle  | Image 1 | Image 2 |
|--------|---------|---------|
| 0° (180°) | ![Image](image1) | ![Image](image2) |
| 20° (200°) | ![Image](image3) | ![Image](image4) |
| 40° (220°) | ![Image](image5) | ![Image](image6) |
| 60° (240°) | ![Image](image7) | ![Image](image8) |
| 80° (260°) | ![Image](image9) | ![Image](image10) |
| 100° (280°) | ![Image](image11) | ![Image](image12) |
The blade was in the state of flow-separation, and the drag of the blade generated by pressure difference was larger in the range of -80-160° which was shown in table 2. Positive work was done to the blade in the range of -80-40° and 100-160° and negative work was done in the range of 40-100°. The blade's front end was attached by eddy continuously, which induced additional lift to do positive work on the impeller in the range of 160-200°; In the range of 200-280°, the blade was in the state of flow-attachment and speed of the inner face was faster, which generated lift doing positive work. Therefore, the blades belonged to lift type in the range of 160-280° and drag type in the range of -80-40° and 100-160°. For the half-rotating impeller with double-blades, when one blade was in the low efficiency zone, the other blade was in the high efficiency zone, which ensured that the half-rotating impeller could run continuously. Therefore, the HRITT was a kind of vertical tidal turbine with unique energy capturing characteristic of lift-drag combination.

6. Conclusion
A new kind of half-rotating impeller tidal turbine was designed and physical prototype was manufactured; Good self-starting performance and smooth operation were verified by underwater experiment; Good hydrodynamic performance of the HRITT was analyzed by method of numerical simulation which found that the HRITT had the characteristic of lift-drag combination.

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