Research on tip clearance leakage flow field characteristics of tidal energy hydroelectric unit based on NACA0009 hydrofoil

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Abstract: In the rotor passage of tidal energy hydroelectric unit, there is a tip leakage problem between rotor and runner chamber. In order to research the flow characteristics of tidal energy hydroelectric units and explore the control method of tip leakage, based on the experimental data of NACA0009 hydrofoil, the SST-CC turbulence model was used for numerical simulation and compared with the experimental results. The characteristics of tip leakage flow and vortex were analysed under different hydrofoil shapes and gap widths. The results show that the rounded hydrofoil can effectively control the generation of tip separation vortex, but the rectangular hydrofoil has higher vortices coefficient and lower pressure coefficient in the downstream section; the tip leakage amount will increase with the increase of gap width; the tip vortex intensity will increase first and then decrease, and cavitation may occur when the vortices is maximum. The results can provide reference for studying the control method of tidal energy hydraulic machinery clearance leakage.

1. Introduction

Axial flow hydraulic machinery is widely used in important civil economy fields such as agricultural engineering, hydraulic engineering and ship hydraulic propulsion[1][2]. In order to avoid friction, there is a gap between the rotating parts and the fixed parts, and cause flow losses [3]. The process of tip leakage flow is accompanied by shocks, secondary flows, vortices phenomena, and these factors will make tip leakage flow more complex [4]. Moreover, because the test operation is difficult, some problems of tip leakage flow remain unresolved.

As a simplified model of rotating machinery, three-dimensional hydrofoils are less difficult to operate in experimental research, which lays a foundation for the test research on the tip leakage of rotating machinery. Yamamoto [5] measured the tip internal flow in the endwall area of a turbine cascade. The results show that the leakage flow vector has a great relationship with the incident Angle and gap size, and affects tip hydrofoil and passage vortexes formed at the blade tip tail simultaneously. Kang[6][7] made an analysis of the vortex structure at the tip clearance based on the experimental data of compressor cascades, and proposed a method that could accurately determine the vortex trajectory, vortex core radius and vorticity. Masahiro et al.[8] observed the leakage vortex cavitation phenomenon at the tip clearance of oscillating hydrofoil, and the results showed that when the oscillation frequency was reduced, the delay between the steady and unsteady results of leakage vortex cavitation increased.
and the maximum cavitation volume decreased. Palafox et al. [9] used PIV technology to measure the flow field of a turbine rotor, obtained the flow parameters in the channel, and clarified the interaction relationship between leakage vortex and passage vortex. Dreyer et al. [10] measured the velocity field of NACA0009 hydrofoil under different conditions through SPIV technology, observed the trajectory of vortex core and flow variation of tip leakage vortex, and pointed out that there was a certain tip value that makes vortex intensity maximum and the possibility of cavitation higher.

In this study, the characteristics of three-dimensional hydrofoil clearance flow field are researched by numerical simulation. The optimal turbulence model was determined. The applicability of different vortex identification methods to clearance leakage vortex was compared, and the effects of different hydrofoil shapes, gap width and Angle of attack on the clearance flow field were analysed. The flow field characteristics and leakage vortex peculiarity under different gap widths are defined.

2. Calculation modal and numerical methodology

2.1. Calculation model

Referencing the experiment of Dreyer [10], NACA0009 hydrofoil was taken as the research object and placed in the water area (0.15×0.15×0.75m³). The hydrofoil chord length is 0.11m, the maximum thickness is 9.9mm, and the total span length is 150mm. There is a certain gap between hydrofoil and water area, and the gap width ranges from τ=0.1~2. The hydrofoil attack Angle is 10°. Two sections of z/c =±0.2 were selected as the research object in the downstream of the hydrofoil. Figure 1 is the schematic diagram of the three-dimensional hydrofoil and calculation domain.

![Figure 1. Schematic diagram of computational model](image)

2.2. Mesh generation and boundary condition setting

Figure 2 show the structured grid of the computational domain. The mesh independence was verified when the gap width is τ=1, and the SST-CC turbulence model was used for calculation. As shown in figure 3 (Q=1×10⁶s⁻² isosurface), the leakage vortex shape remained basically unchanged when the number of grids increased to 6.31 million, so 6.31 million was selected as the total number of grid.

![Figure 2. Structured mesh diagram](image)

![Figure 3. τ=1 leakage vortex form with different mesh numbers](image)

The boundary conditions are set as the inlet velocity Vin=10m/s, the outlet static pressure is 1atm, the wall surfaces are set as no-slip wall, the turbulence intensity is set as 1%. The calculation results show that the leakage vortex length at τ=1 is obviously longer than τ= 0.2, and the tip leakage vortex path at τ=1 is closer to the hydrofoil suction surface. And, the separation vortex region of rectangular
hydrofoil at $\tau=1$ is larger than the experimental value. The calculated results of the SST-CC turbulence model are the most close to the experimental results, and the leakage vortex can extend to the farther downstream position.

### 3. Analysis of flow field characteristics

#### 3.1. Characteristics of gap flow field with different hydrofoil endwall shapes

In order to clarify the effects of rectangular hydrofoil and rounded hydrofoil on tip leakage flow, the influence of right-angle and rounded hydrofoil (radius of 1mm) on clearance flow field characteristics were analysed based on NACA0009 hydrofoil. Figure 4 shows the pressure contour and streamline distributions of different hydrofoil shapes at different sections ($z/c =0.6$, $0.3$, $0$ and $-0.3$) when gap widths are $\tau=0.2$ and $\tau=1$. As we can see that the tip flow fields are similar under different hydrofoil shapes. A leakage vortex rotates clockwise in the low pressure area above the suction surface, and a separation vortex is formed at the same position, which corresponds to the vortex structure shown on the $Q$ isosurface. There is almost no separation vortex in the rounded hydrofoil, which indicates that the rounded edge can effectively reduce the separation vortex area. When $\tau=0.2$, it can be observed that a small vortex is formed at the $z/c =0.6$ section of the rounded hydrofoil, which is absorbed by the leakage vortex in the downstream. There is also a vortex structure above the suction surface of the $z/c =0$ section of the rectangular hydrofoil, which disappears in the downstream, the vortex structure has a low intensity and little influence on the flow field.

![Figure 4. Streamlines and pressure distribution of two hydrofoil shapes at different sections](image-url)
3.2. Flow field characteristics at different gap widths

Figure 6 shows the average velocity field distribution under different gap widths and the tip vortexes are shown by contour lines $Q = 10000^2$s on the two axial sections. Combined with the analysis of vortex structure, the positions and intensities of those vortex structures are different. Therefore, gap width is an important factor affecting the tip flow field. After the average velocity was decomposed, the axial velocity $V_z$ is close to 10m/s, which is basically consistent with the inlet velocit. The velocity component $V_y$ is close to 8m/s, which indicates that the jet flow at the tip is oblique.
Figure 6. Average velocity field; black line represents $Q = 10000$ s$^{-2}$ velocity isoline

The gap jet flow is generated by the pressure difference between the suction surface and the pressure surface, and the leakage vortex is formed above the suction surface by rolling from the pressure surface. Due to the small gap, tip leakage vortex rolls causing boundary layer separation and forming induced vortices at the edge wall. When the gap $\tau = 0.2$, the separation vortex is not obvious. When the gap $\tau = 1$, it can be seen that the negative vortices region also appears at the trailing edge in the suction surface of the hydrofoil, which is caused by the vortex shedding at the trailing edge of the suction surface. Due to the gap size is large and the gap jet flow does not drive the separation of the boundary layer in the process of coiling. The axial velocity of the tip leakage vortex at $\tau = 1$ is about 1.5 times of the $\tau = 0.2$. In addition, as the leakage vortex develops downstream, it is observed that the separation vortex gradually develop towards the suction side on the two planes $z/c = -0.2$ and $z/c = 0.2$.

3.3. Analysis of gap leakage flow and leakage vortex characteristics

Figure 7 shows the variation curve of the leakage amount and the average flow velocity with the gap width under different hydrofoil shapes. As can be seen from the figure, when the gap width $\tau < 2$, the maximum leakage amount is not more than 5% of the inlet flow, and the leakage amount gradually reduces with the decrease of the gap width, indicating that the clearance leakage flow can be effectively controlled with a smaller gap width. In addition, for both hydrofoil types, the growth rate of clearance leakage slows down gradually. This is because the separation vortex causes tip blockage, and the area and intensity of the separation vortex increase with the increase of the gap width, so the blockage effect is more serious. The reason why the leakage amount of rectangular hydrofoil is smaller than rounded hydrofoil is that the separation vortex intensity of rectangular hydrofoil is larger, which indicates that the separation vortex plays a certain effect in the clearance leakage flow control.
Figure 8 shows the curves of comparison between experimental and numerical of tip leakage vortex intensity under different gap widths at the downstream section \( z/c = 1 \) of different hydrofoil shapes. It can be seen from the figure that the vortex intensity increases at first and then decreases. When the gap width \( \tau = 0.7 \), the vorticity reaches the maximum, which indicates that the possibility of cavitation is the highest at this position. In addition, the vortex intensity numerical results of different hydrofoil are all lower than the experimental ones, but the rounded hydrofoil results are closer to the experimental value, while the deviation of the rectangular hydrofoil is larger than the experimental value.

4. Conclusions

In this paper, based on NACA0009 hydrofoil, the characteristics of tip leakage flow and vortices were analysed under different hydrofoil shapes and gap widths. The conclusions were as follows:

1. The leakage flow field mainly consists of tip leakage vortex, separation vortex and induced vortex. The rounded edge hydrofoil can effectively control the generation of separation vortex, and the rectangular hydrofoil had higher vortices coefficient and lower pressure coefficient.

2. The effect of vortices and velocity field on different vortex structure under different gap widths were analysed, it was found that the tip leakage amount increases with the increase of gap width. The reason is that the blocking effect of tip separation vortex is stronger.

3. The reasons for the formation of different vortex structures were clarified and the difference of clearance flow field under different gap widths was revealed. The variation trend of clearance vortex intensity increases first and then decreases, and the cavitation may occur when the vortex is maximum.

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