Effect of Tip Clearance on Hydraulic Performance of Water-Jet Pump

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Abstract. The k-ω Shear Stress Transport (SST) turbulence model is adopted to study the hydrodynamic performance of the water-jet axial pump which is applied in Unmanned Surface Vehicle (USV). The numerical simulation of the whole passage of the water-jet pump is carried out for four different tip clearance with δ = 0.3 mm, δ = 0.8 mm, δ = 1 mm and δ = 1.4 mm. And the results, in term of external characteristics and internal flow field, show that, due to the tip leakage flow, the leakage vortex is formed behind the blade after the fluid flows over the impeller blades. Moreover, with the expansion of tip clearance, the head and efficiency of the water-jet pump will be affected, and this impact is weakened with the increase of the flow rate. Finally, the suggestion of structure optimization of water-jet pump can be made.

1. Introduction
USV is a kind of small-scale surface platform which can carry out multiple Tasks (e.g. Target detection) by itself and autonomous voyage. It can undertake terrain investigation, Search and Rescue Service, Surveillance and Reconnaissance etc. With the development of USV, the water-jet propulsion technology is gradually applied in the propelling of the USV. For example, “Jinghai No. 1” USV (designed by the Shanghai University Research Institute of USV Engineering and Donghai Navigation Safety Administration in 2013) and “Haiteng No. 1” USV (designed by Dalian Maritime University) both adopted the water jet propulsion technology [1]. In order to improve the speed and stability of USV, it is necessary to optimize the performance of the water-jet pump.

In the water-jet pump, when there is a tip clearance, under the action of the pressure differential, there will be a tip leakage flow in the tip clearance of the blade, resulting in the performance degradation of the water-jet pump. Therefore, tip clearance is one of the important factors that affect the performance of the water-jet axial flow pump.

Many studies have been engaged on the effect of tip clearance in recent years. Li Yaojun et al. [2] used the large eddy simulation method and the sliding mesh technique to simulate the axial flow pump with unsteady calculation, and analyzed the influence of the tip clearance on the pump external characteristics, the leakage vortex shape and the pressure fluctuation at the outer edge of blade. Zhang De-sheng et al. [3] carried out numerical analysis of an axial flow pump, found the cause and characteristic of the leakage vortex and the influencing factors of the tip leakage flow, which reveals the flow characteristics of the leakage vortex in the tip of the axial flow pump. Zhao Yu et al. [4] do experiments in a closed cavitation tunnel to observe the unsteady cavitating flows in a hydrofoil tip
leakage region, during which high speed camera was used to capture the cavitation patterns. Then he proposed a cavitating vortex model to describe the development of vortex cavitation.

In addition, some scholars have brought above research methods in the field of structure optimization of the water-jet axial flow pump. HAN Ji-ang et al. [5] analyzed the cavitation characteristics of the water-jet pump and its affected process under different conditions of tip clearance. The study found that the critical net positive suction head (NPSH) of the pump and the cavitation area on the suction surface of the blade have a positive correlation with tip clearance. Wang Jianing [6] optimized the anti-cavitation performance of water-jet pump by analyzing the effect of tip clearance on the cavitation characteristics.

However, the previous studies on effect of tip clearance are mainly concentrated on the ordinary land axial pump, only a few studies focus on the effect of tip clearance in the field of water-jet pump. In other words, our knowledge of detailed characteristics and performance affected by tip clearance in water-jet pump is not widely studied. The aim of this paper is to explore the effect of tip clearance on the performance of water-jet pump and gain suggestions of structural optimization for water-jet pump used in USV by analyzing external characteristics, internal flow field under different tip clearance conditions.

2. Geometry and grid

2.1. Parameter selection and modeling of water-jet pump

The water-jet pump studied in this paper is designed for the propulsion unit of an USV. The USV is 7.5 m long and 2.4 m wide. Based on the basic design theory of pump [7] and power requirements of USV, the water-jet pump is designed. This paper selects flow (Q) 10 kg/s, speed (n) 1000 rpm and the head (H) 5 m as the design condition.

Determine the specific speed of the water-jet pump at design condition, then the number of blades and the hub ratio can be obtained. Based on the previous calculation, streamline method can help get the blade diameter and relevant parameters. The model of impeller and blades are shown in Figure 1, and the overall model is shown in Figure 2.

![Figure 1. The model of impeller (a) and blade (b)](image)

![Figure 2. The overall model of water-jet pump](image)

2.2. Grid and the test of grid independence

The computational domain is divided into four parts including inlet pipe, impeller with four blades, stator part with 7 guide vanes and outlet pipe before meshed. Then structural mesh methods is used to mesh the above parts respectively in the ANSYS ICEM CFD. O-type grid refinement are used at near wall of the blades and guide vanes for more accurate simulation of the internal flow of the pump. The number of grids in the blades and the guide vanes parts is 170W and 125W, respectively. The computational domain mesh is shown in Figure 3, in which Figure 3 (a) is the grid of full passage and Figure 3 (b) is the grid of the blades and hub. The enlarged view of local mesh at the surrounding area of the blades and guide vanes is enlarged as shown in Figure 4.
Figure 3. Computational domain mesh of (a) full passage and (b) blades and hub

Figure 4. Enlarged view of mesh at the surrounding area of the (a) blades and (b) guide vanes

3 million, 5 million, 7 million, 8.5 million and 10 million grids are all tested in the simulation to find the best grid number, and make sure the accuracy and efficiency of the calculation. Compare the head in the results and verify grid independence. By comparison with the results of all above simulation, the grid of independence is verified. As shown in Figure 5, when the number of grids rises to 7 million, the change of the head is less than 1%, which means the number of grids has little influence on the result. So the final mesh consists of about 7 million grids.

Figure 5. The test of grid independence

2.3. Boundary conditions
ANSYS CFX turbomachinery module was applied for the study. During the calculations the turbulence effects were modeled by k-ω SST turbulence model. The boundary condition is pressure inlet and mass flow rate outlet. The boundary of blades and the pump shell is no slip wall. For this study, the frozen rotor is employed for the interface between stationary and rotating components, which allows the flow to recirculate across the interface freely. The rotational speed (n) is 1000 rpm and the mass flow rate are 7.5 kg/s, 10 kg/s, 12.5 kg/s, 15 kg/s and 20 kg/s, respectively.
3. Results and discussion
In this paper, four different values of tip clearance (δ) were chosen among 0.1% ~ 0.5% diameter (D), which are 0.3 mm, 0.8 mm, 1 mm and 1.4 mm respectively. Under the above five conditions, calculate the external characteristic and the flow field Characteristics for the four models, and then comparative analyze.

3.1. External characteristics comparison
The change of head and efficiency with tip clearances of the water-jet pump is shown in Figure 6.

As can be seen from Figure 6 (a), when the tip clearance is constant, the head of the water-jet pump decreases as flow increases. Among these models, the head is the largest when the tip clearance is 0.3 mm, and reduced with the increase of the tip clearance.

As can be seen from Figure 6 (b), the efficiency of the water-jet pump decreases as the flow rate increases. When the mass flow rate is 7.5 kg/s, as the tip clearance increasing from 0.3 mm to 1.4 mm, the efficiency reduces by 1.2%; but when the mass flow rate is 20 kg/s, the efficiency reduces by only 0.5% as the tip clearance increasing from 0.3 mm to 1.4 mm.

In the case of the tip clearance are 1 mm and 1.4 mm, the efficiency respectively reduce by 1.4% and 1.0% when the mass flow rate increases from 7.5 kg/s to 12.5 kg/s. However, the efficiency reduce by 0.6% and 0.3% respectively when the mass flow rate increases from 15 kg/s 20 kg/s. This shows that when the tip clearance is large, the efficiency is greatly affected by the tip clearance at the low flow rate condition, and the effect is much smaller under the large flow condition.

Therefore, taking into account the optimization of efficiency and head, the tip clearance 0.3 mm is the best option for a water-jet pump.

3.2. Analysis of pressure nephogram on blades
The pressure distribution of blades as the tip clearance is 0.3 mm, 0.8 mm, 1 mm, 1.4 mm is shown in Figure 7, in which the left side is the pressure surface and the right side is the suction surface.
Figure 7. Pressure distribution of blades

As can be seen in Figure 7, at about 40% ~ 80% radius (R) in the radial direction on the leading edge of the blades, there is a very small zone of low pressure. For the pressure surface, after the initial low pressure zone, the pressure on the blade increases rapidly along the chord (direction of the water flow), and the span is large. Then the pressure reaches the maximum at the middle of blades. This shows that the blade work increases as the area of blade contact with water increases. With the increase of the tip clearance, the area of the middle high pressure area increases, but the maximum pressure slightly reduces and the pressure gradient also reduces. It shows that, as the tip clearance increasing, the blades do less work on the flow, but the blades are uniformly forced.

In the four different models, the pressure gradient on the blade is basically along the direction of water flow. However, the pressure gradient distributes along the radial direction at the outer edge of the blade on suction surface, indicating that there is a radial flow near the outer edge of blade, named tip leakage flow. Tip leakage flow does not contribute to the increase in outlet pressure, which leads to the reduction of the head. This is one of the reasons why the tip clearance has an impact on performance of water-jet pump.

3.3. Analysis of the pressure cloud and velocity vector of the axial section at 50% chord length
The pressure distribution of the axial section at 50% chord length of the blade for three kinds of models with the tip clearance of 0.3 mm, 0.8 mm and 1.4 mm are shown in Figure 8, Figure 9 and Figure 10 respectively.
The leakage vortex core and the pressure difference between the front and back of the blade can be clearly observed in Figure 8, Figure 9 and Figure 10. With the increase of the tip clearance, the pressure difference between the front and the back of the blade reduce, the area of leakage vortex becomes larger, pressure of the vortex center decreases as well. Although the leakage vortex core is not obvious in figures when tip clearance is 0.3 mm, there has been an obvious leakage vortex when tip clearance is 0.8 mm and 1.4 mm.

Under the low flow rate condition (a) and design condition (b), comparing with Figure 9, the pressure difference between the front and the back of black is higher, the size of leakage vortex is larger and the pressure in the leakage vortex core is higher in the Figure 10. So it can be seen, the tip clearance has a great influence on the pressure difference between the front and the back of the blade and leakage vortex.

Under the large rate condition (c), the pressure difference between the front and the back of blade, and the size and pressure of the leakage vortex in Figure 9 and Figure 10 are almost the same. This phenomenon shows that the influence of the tip clearance on tip leakage flow and leakage vortex is the biggest under low flow rate condition. Tip clearance has less effect on the internal flow field of water-jet pump with the increase of the flow rate.
Figure 11 shows the velocity vectors on the axial section at 50% chord length of the blade for three models under design conditions. The tip leakage flow can be observed in this figure. Combining Figure 8, 9, 10, and 11, it can be seen that water flows into the tip clearance and form tip leakage flow due to the pressure difference between the front and back of blades. Then the main flow rolls up the tip leakage flow and then leakage vortex generates.

From Figure 11 (a) and Figure 8, it can be seen when tip clearance is 0.3 mm, there is little tip leakage flow or leakage vortex. It is because that the tip clearance is so small that the fluid at the clearance is greatly affected by the viscosity of the near wall, and the tip leakage flow has little influence on main flow which results in little leakage vortex. With the increase of the tip leakage, the leakage vortex is more obvious, and the entrainment is graver. It can be seen from Figure 11 that, the leakage vortex has a great disturbance to the flow and thus produces a large flow loss, so that the pressure at the leakage vortex rapidly decreases and greatly reduces the work of the blade on the fluid.

It is concluded that, with the tip clearance of impeller blade increases, the tip leakage flow increases, thus, head and efficiency of water-jet pump will reduce.

4. Conclusion
To sum up, for different tip clearance, this paper identifies external characteristic curves and internal flow field distribution of water-jet pump which is used in USV. First, the water-jet pump is designed and modeled. Then structured grids were generated in model and O-type grid refinement is used at near wall of the blades and guide vanes. Numerical simulation is calculated in four different tip clearance (0.3 mm, 0.8 mm, 1 mm, 1.4 mm) by k-ω SST turbulence model. Then obtain the external characteristics and internal flow field. Through comparative analysis, conclusions are drawn as follows:

(1) The tip clearance has little effect on the pressure distribution of blade suction surface, while it has a great effect on pressure distribution of blade press surface.
(2) Through analysis of pressure distribution and velocity vector, it can be seen leakage vortex caused by tip leakage flow results in poor performance of the water-jet pump.
(3) The tip clearance will affect the head and efficiency of the water-jet pump, but this effect will be decreased as the flow rate increases.

From the above conclusion, in the design process of water-jet pump, it is suggested that tip clearance should be designed small enough under the engineering condition.

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