Investigation of the groove effect on the tip leakage vortex flow

Zhaodan Fei¹, Rui Zhang², Hui Xu¹,² and Tong Mu¹

¹ College of Water Conservancy and Hydropower Engineering, Hohai University, 1 Xikang Road, Nanjing, 210098, China
² College of Agricultural Science and Engineering, Hohai University, 1 Xikang Road, Nanjing, 210098, China

E-mail: gulie1984@163.com

Abstract. The groove effect on the tip leakage vortex around a NACA0009 hydrofoil was studied by numerical method. The results show that, as the groove angle is 45°, the groove could enhance the turbulence kinetic energy around the TLV, weaken the TLV strength and improve the pressure in the TLV core, resulting in an efficient suppression effect on the TLV cavitating flow. When the groove angle is 0° and 45°, the groove could decrease the tip leakage flow rate and the TLV gets lower and moves away from the tip gap. As the groove angle is 90° and 135°, the tip leakage flow rate gets larger, and the TLV gets higher and closer to the tip gap.

1. Introduction
Tip leakage vortex (TLV) is a common phenomenon in the hydraulic machinery. It can promote the vortex cavitation which is very harmful to the hydraulic machinery. It can drop the hydraulic performances, cause the noise and vibration, and even can generate the cavitation erosion. Therefore, it is necessary to investigate the TLV flow and the TLV cavitation. Decaix et al. [1] used both RANS and LES computations to simulate the TLV and found both computations can predict the tip vortex well and proposed a law matching the vortex trajectory. Guo et al. [2] investigated the TLV flow field and performance of a hydrofoil under the effect of different shape of tip gap geometries and found the cases with the round tip edge has a lower risk of clearance cavitation inside the gap. Gao et al. [3] investigated TLV flow and loss mechanisms under the influence of the pivoting axis and found the interactions between the flow around the pivoting axis and the tip leakage flow in the vane tip rear part were strong, leading to a low-pressure region on the tip endwall. Recently, researchers are going to pay more attention to the way to control the TLV and its cavitating flow. Chen et al. [4] studied the effect of axial casing grooves on the performance and flow structures in the tip region of an axial low speed fan rotor experimentally and found grooves can reduce the stall flow rate. Liu and Tan [5] used a C groove to suppress the TLV for a NACA0009 hydrofoil and found C groove can suppress the vortex area, and improve the lift drag ratio of foil.

In this paper, the TLV flow of a three-dimensional NACA0009 hydrofoil with a typical tip gap size was investigated under the non-cavitation condition and cavitation condition by the RANS method. A specific groove structure was put forward to controlling TLV and its cavitating flow. The groove was set on the wall near the tip gap region and four different groove cases were used to evaluate the groove
effect on the TLV and its cavitating flow. The TLV cavitating flow, the TLV trajectory and the TLV flow characteristics were investigated compared with the results of the non-groove case.

2. Physical model and computational method

2.1. Physical model

Referred to experiments of Dreyer et al. [6], a three-dimensional NACA0009 hydrofoil with a typical tip gap was used to simulate the TLV flow as shown in figure 1(a)-(c). The hydrofoil is truncated at $C=0.1$ m and the hydrofoil tip side is rounded by a radius of 1 mm. The main parameters of the water tunnel and hydrofoil are listed in table 1.

As for the groove, the groove is attached to the wall near the tip gap as shown in figure 1(c)-(d). The groove is located from $z/C=-0.52$ to 0.52, and both the width and depth are 2 mm, and the instance between the adjacent grooves is 4 mm. Four different groove cases in the groove angle are simulated to compare with the non-groove case, and the groove angle $a_{gre}=0^\circ$, $45^\circ$, $90^\circ$, and $135^\circ$.

![Figure 1. Physical model of the computational domain.](image)

| Water tunnel | Hydrofoil          |
|--------------|--------------------|
| Length $L$   | Chord length $C$   |
| 0.75 m       | 0.1 m              |
| Width $a$    | Maximum height $h_{max}$ |
| 0.1 m        | 9.9 mm             |
| Height $b$   | Tip gap size $\delta$ |
| 0.1 m        | 2 mm               |
| -            | Incident angle $\alpha$ |
| -            | 10$^\circ$         |

2.2. Boundary setup and mesh arrangement

The boundary conditions are referred to the experiments [6]. The inlet is set as a uniform streamwise velocity of $W_\infty=10$ m/s with low turbulence intensity (below 1%), and the outlet is set as a static pressure. All the solid walls are set as the no-slip boundary.
The structural hexahedral mesh is generated to discretize the computation domain. The O-grid method and local mesh refinement method are used, as shown in figure 2(a). The mesh near the hydrofoil is shown in figure 2(b). Based on the mesh independency validation implemented by Guo et al. [2]. The mesh number is about 4.8 million and the related mesh numbers for the groove cases are about 5.2 million.

2.3. Numerical method and validation
Considering the local rotation characteristics and curvature effects of the TLV flow, a rotation-curvature corrected SST (SST-CC) turbulence model is used to simulate the time-averaged turbulent flow. The Zwart-Gerber-Belamri (ZGB) cavitation model [7] is used to simulate the cavitating flow. The computations are conducted using the commercial CFD code of ANSYS CFX. Convergence is specified as RMS residuals of $10^{-5}$.

Figure 3 shows the TLV flow for the non-groove case. For the computational simulation, the TLV flow is displayed by the iso-surface of $Q$-criterion ($Q=1.5\times10^6$ s$^{-2}$) under the non-cavitation condition and it is displayed by the iso-surface of $\alpha_v=0.1$ under the cavitation condition. Figure 4 shows the axial and circumferential velocity distributions at the downstream section of $z/C=1.0$. It can be seen that the TLV flow both under the non-cavitation condition and the cavitation condition agrees well with the results of the experiment, which means that the computation method can be used in further research.
3. Results and Analysis

3.1. TLV cavitating flow

The TLV cavitating flow for all the groove cases displayed by the iso-surface of $\alpha_v=0.1$ is shown in figure 5. For the non-groove case, as shown in figure 3(c), the TLV cavitating flow could extend to $z/C=0.3$. Compared with the non-groove case, when the groove angle $\alpha_{gre}=0^\circ$ and $45^\circ$, the groove can shorten TLV cavitating flow. For these two groove cases, the TLV cavitating flow could extend to $z/C=0.1$, especially when the groove angle $\alpha_{gre}=45^\circ$, the TLV cavitating flow is much thinner. For the groove case of $\alpha_{gre}=90^\circ$, the TLV cavitating flow could extend to $z/C=0.2$. It should be noticed that for the groove case of $\alpha_{gre}=135^\circ$, the TLV cavitating flow extends to $z/C=0.4$ which is longer than that for the non-groove case. For this groove case, the groove can lengthen the TLV cavitating flow, so it should be avoided to be used to suppress the TLV cavitating flow. Above all, it is obvious that when the groove angle $\alpha_{gre}=45^\circ$, the TLV cavitating flow is significantly suppressed. When the groove angle $\alpha_{gre}=135^\circ$, the TLV cavitating flow is extended, i.e. the groove could worsen the TLV cavitating flow.
3.2. TLV trajectory

Figure 6 shows the TLV trajectory in different cases. As shown in figure 6, the TLV trajectory is similar under the non-cavitation condition and cavitation condition. For the spanwise position, compared with the results of the non-groove case, the TLV core is further away from the tip gap for the groove case of $\alpha_{\text{gre}}=0^\circ$ and $45^\circ$ than that for the non-groove case, and it is closer to the tip gap for the groove case of $\alpha_{\text{gre}}=90^\circ$ and $135^\circ$. For the pitchwise position, compared with the results of the non-groove case, the TLV core is lower for the groove case of $\alpha_{\text{gre}}=0^\circ$ and $45^\circ$ than that for the non-groove case, and it is higher for the groove case of $\alpha_{\text{gre}}=90^\circ$ and $135^\circ$. By comparison, the TLV trajectory is the lowest for the groove case of $\alpha_{\text{gre}}=45^\circ$ and it is the highest for the groove case of $\alpha_{\text{gre}}=135^\circ$. Meanwhile, the TLV trajectory under the cavitation condition is lower than that under the non-cavitation condition, which is similar to the other researchers’ investigation (Decaix et al. [8]).

Table 2 lists the tip leakage flow rate $Q_{\text{tg}}$ and the mean pitchwise velocity at the tip gap $W_{\text{tg}}$. It can be seen that the tip leakage flow rate $Q_{\text{tg}}$ and the mean pitchwise velocity $W_{\text{tg}}$ under the cavitation condition are both less than those variables under the non-cavitation condition, which can explain why the TLV trajectory under the cavitation condition is lower than that under the non-cavitation condition. Under the cavitation condition, when the groove angle $\alpha_{\text{gre}}=45^\circ$, both the tip leakage flow rate and the...
mean pitchwise velocity are the smallest, so the TLV trajectory is also the lowest; when the groove angle $\alpha_{\text{gre}}=0^\circ$, the mean pitchwise velocity is less than that for the non-groove case, while the tip leakage flow rate is a little more than that for the non-groove case, and the TLV trajectory is still lower than that for the non-groove case; but when the groove angle $\alpha_{\text{gre}}=90^\circ$ and $135^\circ$, they are both more than those variables for the non-groove case, and the TLV trajectory is higher. Under the non-cavitation condition, the sensitivity of the TLV trajectory on the mean pitchwise velocity $W_{\text{tg}}$ decreases, and this may be because the TLV has moved far away from the tip gap. Taking the groove angle $\alpha_{\text{gre}}=90^\circ$ for instance, the TLV trajectory is higher than that for the non-groove case, even the mean pitchwise velocity $W_{\text{tg}}$ is less than that for the non-groove case. This indicates that under the non-cavitation condition, the tip leakage flow rate $Q_{\text{tg}}$ has a greater effect on the TLV trajectory than the mean pitchwise velocity $W_{\text{tg}}$.

Table 2. The tip leakage flow rate $Q_{\text{tg}}$ and the mean pitchwise velocity $W_{\text{tg}}$ at the tip gap.

| Cases     | Under non-cavitation condition | Under cavitation condition |
|-----------|-------------------------------|----------------------------|
|           | $Q_{\text{tg}}/Q_{\infty}$  | $W_{\text{tg}}/W_{\infty}$ | $Q_{\text{tg}}/Q_{\infty}$ | $W_{\text{tg}}/W_{\infty}$ |
| non-groove| 0.00801                       | 1.05249                    | 0.00710                      | 0.91527                      |
| $\alpha_{\text{gre}}=0^\circ$ | 0.00791                       | 0.94971                    | 0.00764                      | 0.89145                      |
| $\alpha_{\text{gre}}=45^\circ$ | 0.00739                       | 0.82034                    | 0.00571                      | 0.62390                      |
| $\alpha_{\text{gre}}=90^\circ$ | 0.01014                       | 1.03014                    | 0.00958                      | 0.97650                      |
| $\alpha_{\text{gre}}=135^\circ$ | 0.01021                       | 1.01173                    | 0.00941                      | 0.96464                      |

3.3. TLV flow characteristics

Figure 7 shows the variation of the vorticity coefficient $C_\omega$ in the TLV core center. The curve of the $C_\omega$ under the non-cavitation condition is shown in figure 7(a), and the curve of the $C_\omega$ under the cavitation condition is shown in figure 7(b). Peng et al. [9] found that cavitation could decrease the vortex strength comparing with the case without cavitation. Under the non-cavitation condition, the vorticity coefficient $C_\omega$ can reflect the strength of the TLV. As shown in figure 7(a), when the groove angle $\alpha_{\text{gre}}=45^\circ$, the TLV flow is suppressed effectively. While when the groove angle $\alpha_{\text{gre}}=135^\circ$, the suppression effect of the groove is very poor and even the groove can worsen the TLV. Under the cavitation condition, as mentioned above, in the region where the cavitation appears, the lower the vorticity coefficient $C_\omega$ is, the stronger the cavitation is. As shown in figure 7(b), in the region where the cavitation appears, the vorticity coefficient $C_\omega$ is larger in the groove case of $\alpha_{\text{gre}}=45^\circ$, and it is less in the groove case of $\alpha_{\text{gre}}=135^\circ$. In the region where the cavitation disappears, the variation trend of the vorticity coefficient $C_\omega$ restores to be like that under the non-cavitation condition. This means that the groove can mitigate the TLV cavitation and weaken the TLV flow.

![Figure 7](image_url)

(a) Under non-cavitation condition  (b) Under cavitation condition

**Figure 7.** The variation of the vorticity coefficient $C_\omega$ in the TLV core center.
Figure 8 shows the variation of the pressure coefficient $C_p$ in the cavitating TLV core center. Figure 9 shows the distributions of the turbulence kinetic energy at the downstream sections of $z/C=0$ and $z/C=0.2$ under the cavitating condition. The turbulence kinetic energy is dimensionless by $(W_\infty)^2$ and the black line means the iso-line of $\alpha_v=0.1$. As shown in figure 9, it can be seen that the turbulence kinetic energy is mainly generated from the boundary layer of the hydrofoil tip side, and the distribution of the turbulence kinetic energy indicates that the flow from the groove disturbs the TLV flow, leading to the loss of the kinetic energy around the TLV. Combined with the variation of the pressure coefficient shown in figure 8, it can be seen that for the groove case of $\alpha_{gre}=45^\circ$, the flow from the groove disturbs the TLV flow strongly, so the value of the turbulence kinetic energy is the largest and the pressure coefficient $C_p$ restores fastest, as a result, the suppression effect is the most efficient; for the groove cases of $\alpha_{gre}=0^\circ$ and $90^\circ$, although the variation of the pressure coefficient $C_p$ is similar, the value of the turbulence kinetic energy around the TLV for the groove case of $\alpha_{gre}=0^\circ$ is larger, as a result, the suppression effect is better than the groove case of $\alpha_{gre}=90^\circ$. For the groove case of $\alpha_{gre}=135^\circ$, the flow from the groove no more disturbs the TLV flow, but improves it. Compared with the non-groove case, the value of the turbulence kinetic energy is much less and the area of the low pressure coefficient $C_p$ is longer, which is more conducive to the development of the TLV cavitating flow, leading to a stronger and longer TLV cavitating flow.

Figure 8. The variation of the pressure coefficient $C_p$ in the cavitating TLV core center.
4. Conclusions

(1) Groove can influence the TLV cavitating flow. When the groove angle $\alpha_{\text{gre}}=45^\circ$, the suppression effect is the best among the four groove cases, and the TLV cavitating flow is the shortest and very thin; When the groove angle $\alpha_{\text{gre}}=0^\circ$, the suppression effect is still strong, but the TLV cavitating is not as thin as that for the groove case of $\alpha_{\text{gre}}=45^\circ$; when the groove angle $\alpha_{\text{gre}}=90^\circ$, the groove effect is not very efficient and when the groove angle $\alpha_{\text{gre}}=135^\circ$, the groove could no more suppress the TLV cavitating flow, but even worsen it.

(2) Both under the non-cavitation and cavitation conditions, compared with the results of the non-groove case, for the groove case of $\alpha_{\text{gre}}=0^\circ$ and $45^\circ$, the TLV goes lower and moves away from the tip gap, the tip leakage flow rate gets less, and the TLV gets weakened. For the groove case of $\alpha_{\text{gre}}=90^\circ$ and $135^\circ$, the TLV goes higher and approaches to the tip gap, and the tip leakage flow rate gets larger, especially for the groove case of $\alpha_{\text{gre}}=135^\circ$, the TLV even gets stronger.

(3) The pressure coefficient in the cavitating TLV core center and the distributions of turbulent kinetic energy indicate that groove effect is due to the correlation between the flow from the groove and the TLV flow. When the groove angle $\alpha_{\text{gre}}=45^\circ$, the flow from the groove can disturb the TLV flow, resulting in a rapid variation of the turbulence kinetic energy around the TLV, fast restoring the pressure in the TLV core, and suppressing the TLV cavitating flow. When the groove angle $\alpha_{\text{gre}}=135^\circ$, the flow from the groove can improve the TLV flow, resulting in a small value of the turbulence kinetic energy around the TLV, slowly restoring the pressure in the TLV core, and worsen the TLV cavitating flow.

Acknowledgments

The authors are very grateful to the National Natural Science Foundation of China (Grant No.51809081), the Natural Science Foundation of Jiangsu Province (Grant No.SBK2020021992), the Fundamental Research Funds for the Central Universities (Grant Nos.B200202096 and 2019B70114), the China Postdoctoral Science Foundation (Grant No.2019M661707), the Jiangsu Planned Projects for Postdoctoral Research Funds (Grant No.2019K095) and the Postgraduate Research & Practice Innovation Program of Jiangsu Province (Grant No. SJKY19_0491).

References

[1] Decaix J, Balarac G, Dreyer M, Farhat M and Münch C 2015 RANS and LES computations of the tip-leakage vortex for different gap widths J.Turbul. 16(4) 309–41
[2] Guo Q, Zhou L and Wang Z 2016 Numerical evaluation of the clearance geometries effect on the flow field and performance of a hydrofoil Renew. Energy 99 390–7

[3] Gao J, Fu W, Wang F, Zheng Q, Yue G and Dong P 2018 Experimental and numerical investigations of tip clearance flow and loss in a variable geometry turbine cascade Proc. Inst. Mech. Eng. Part A-J. Power Energy 232(2) 157–69

[4] Chen H, Li Y, Koley S S, Doeller N and Katz J 2017 An experimental study of stall suppression and associated changes to the flow structures in the tip region of an axial low speed fan rotor by axial casing grooves J. Turbomach.-Trans. ASME 139(12) 121010

[5] Liu Y and Tan L 2018 Method of C groove on vortex suppression and energy performance improvement foe a NACA0009 hydrofoil with tip clearance in tidal energy Energy 155 448–61

[6] Dreyer M, Decaix J, Münch-Alligné C and Farhat M 2014 Mind the gap: a new insight into the tip leakage vortex using stereo-PIV Exp.Fluids 55 1849

[7] Zwart P J, Gerber A G and Belamri T 2004 A two-phase flow model for predicting cavitation dynamics ICMF 2004 Int. Conf. on Multiphase Flow (Yokohama, Japan) 152

[8] Decaix J, Dreyer M, Balarac G, Farhat M and Münch C 2018 RANS computations of a confined cavitating tip leakage vortex Eur. J. Mech. B-Fluids 67 198–210

[9] Peng X, Xu L, Liu Y, Zhang G, Cao Y, Hong F and Yan K 2017 Experimental measurement of tip vortex flow field with/without cavitation in an elliptic hydrofoil J. Hydrodyn. 29(6) 939–53