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Vortex suppression of the tip leakage flow over a NACA0009 hydrofoil via a passive jet induced by the double-control-hole

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ABSTRACT

Tip leakage vortex (TLV) frequently occurring in bladed energy conversion machines may induce flow loss as well as cavitation. The double-curved-hole (DC hole) structures located at the 10%–25% chord near the leading edge of the foil are adopted to induce a passive jet thus suppressing the tip leakage vortex structures in this paper. The control effects and the control mechanisms of three DC hole positions are illustrated by numerical analyses based on the rotation-curvature corrected shear stress transport (SST) $k-\omega$ turbulence model and the Zwart-Gerber-Belamri (ZGB) cavitation model. The results demonstrate that the passive jet from the DC hole could divide the TLV into several parts and induce new vortical structures. The newborn vortical structures can be classified into three types: weakened tip leakage vortex (WTLV), newborn secondary tip leakage vortex (NSTLV) and hole separation vortex (HSV). The control effects for different tip clearance are greatly related to the DC hole location. Once the DC hole locates near the merger point of the tip leakage vortex and the tip separation vortex, it could achieve the best control effects. Besides, TLV core pressure could be improved thus suppressing the local cavitation, and the lift-drag ratio for different inlet velocities can be slightly reduced.

1. Introduction

Ocean hydropower is one of the most reliable and sustainable energy sources in the world. The energy performance is closely related to the flow characteristics of hydraulic machinery (Li et al., 2017; Luo et al., 2015; Prasad et al., 2014). The gap between the rotor and the stator is inevitable, such as in compressors, turbines and pumps. The tip leakage vortex (TLV) and tip separation vortex (TSV) that appear in the tip region could cause energy loss, noise, and cavitation phenomenon (Xiao et al., 2001; Gopalan et al., 2002; Zhang et al., 2015a). Many studies have demonstrated that the gap size has a crucial effect on the TLV, and the efficiency declines obviously with increasing gap size in hydraulic machinery (Kim and Chun, 2007; Yu et al., 2019). Meanwhile, the size and strength of TLV increase with the gap size (You et al., 2006; Pogorelov et al., 2016; Decaix et al., 2015). Therefore, researchers have performed numerous experimental and numerical investigations of the evolution of TLV as well as the flow mechanism in the gap region (Liu et al., 2020; Xi et al., 2021). Decaix et al., 2015, 2016, 2018 captured the flow trajectory of TLV around a hydrofoil with tip clearance, using the shear stress transport (SST) $k-\omega$ model (Menter, 2009). They found cavitation could make the TLV trajectory closer to the suction side

compared with the non-cavitation case and cause a misalignment between the high vorticity region and the cavitating region. Smirnov and Menter (2009) developed a SST-CC model by adding a rotation-curvature correction (CC) term into the original SST $k-\omega$ model. The improved model was proven to be able to enhance the prediction accurateness of the TLV evolution (Arolla and Durbin, 2014; Guo et al., 2018). In consideration of the influence of the angular momentum on the vortex cavitation, the modified cavitation model is used to investigate the TLV cavitation (Guo et al., 2019; Zhao et al., 2016). Dreyer et al., 2014a, 2014b experimentally investigated the flow mechanism and flow pattern of TLV cavitation around a hydrofoil, considering the influences of different attack angles, gap sizes, and inlet velocity. Their results illustrated the smaller clearance could pull the TLV away from the hydrofoil more, and TLV cavitation could alter the vortex trajectory as well as the wandering amplitude. The effects of TLV on different cavitation patterns have been analyzed, such as horseshoe vortex cavitation, sheet cavitation, tip separation vortex cavitation, and perpendicular cavitation vortex (PCV) (Ji et al., 2013; Bai et al., 2018; Cheng et al., 2019, 2020). It is suggested that TLV interact with the mainstream at the trailing edge of the blade to form PCV (Tan et al., 2015; Zhang et al., 2015b).

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As the TLV could cause negative influence on the system efficiency and the flow stability of the hydraulic machinery, it is urgent to control and suppress TLV and the associated TLV cavitation. Fortunately, some efforts have been done to suppress the TLV as well as its cavitation. We know the control method are usually divided into two types: active and passive methods (Souri and Mojra, 2021). As the TLV always start around 20–30% chord close to the suction side of the blade tip (Wu et al., 2011), there are few available places to place the control actuator. So, researchers commonly adopt the passive control methods. Chang et al. (2011) proposed tip vortex cavitation suppression by active mass injection. Their results showed that the optimal levels of mass injection reduced the inception cavitation number from 3.5 to 1.9 (a reduction of 45%). Timoshevskiy et al. (2018) experimentally investigated the method of manipulating cavitation by a wall jet on a 2D hydrofoil, and they found that the wall jet can effectively manipulate cavitation. Liu and Tan, 2018, 2020a suggested the method of C groove in the tip to suppress vortex and cavitation for a hydrofoil, The C groove is close to the leading edge of the tip, and the exit of C groove is nearly perpendicularly to the primary TLV, and they found the C groove can decrease the vortex area under all geometric conditions. Amini et al. (2019) observed in their experiment that the maximum tangential velocity of the tip vortex falls to almost half of the baseline and the vortex core size increases significantly (by almost 70%) for the most effective winglet in the tip. These effects are accompanied by a visible reduction in the axial velocity at the vortex core leading to further mitigation of tip vortex cavitation. Fei et al.'s (Fei et al., 2019) numerical results showed that the groove could affect the tip leakage vortex cavitating flow. The groove enhances the interaction between the tip leakage flow and main flow, and then it affects the cavitation of the tip leakage vortex. Guo et al. (2016) numerically investigated the effect of round tip and sharp tip on the flow field and performance of a hydrofoil. In addition, a novel method of T shape tip is proposed to improve energy performance and suppress TLV, the results showed that the T shape tip remarkably suppresses the flow separation around the pressure side tip corner and decreases the pressure gradient and reduce the TLV area in the tip (Lei et al., 2017; Liu and Tan, 2020b).

From the above, the methods of TLV suppression need further researches. The objective of this paper is to put forward a new strategy on TLV suppression. Referring to the experiment of Dreyer et al. (2014b), a double-curved-hole (DC hole) structure is proposed to suppress the TLV. The vortical structures, dynamic performance of the foil as well as the control mechanism will be discussed in detail in this paper.

2. Methodology

2.1. Physical model

Fig. 1 shows the schematic diagram of the computational domain which is referred to the experiment of Dreyer et al., 2014a, 2014b. The NACA0009 hydrofoil is chosen as the object of which the chord is $C = 100$ mm, and the span is $b = 146$ – 148 mm, with the maximum thickness

Fig. 1. Computational model.

$h = 9.9$ mm. The length of the flow channel is $7.5C$, and the width is $1.5C$. The tip clearance size δ is normalized by h , leading to a non-dimensional variable $\tau = \delta/h$. Three typical conditions with $\tau = 0.2$, $\tau = 0.3$, and $\tau = 0.4$ will be discussed in this paper.

As shown in Fig. 2, the DC hole (a combined structure of two holes) is close to the leading edge (LE) of the foil. The passive jet induced by the pressure difference between the pressure side (PS) and the suction side (SS), could interact with the TLV, thus modifying the TLV structures as well as the pressure. The distance of the DC hole from the top surface of the foil tip is 1 mm, and the height of the hole is 2 mm. From the inlet to the outlet of the DC hole, it gradually contracts, thereby causing an increase in the velocity of the jet flow. The hole closer to the leading edge is named H1, and the adjacent one is named H2. The detailed geometry parameters of the hole is shown in Fig. 2 (b). The points labelled A, B, C, D and E are on the foil chord ($AB = CD = 2$ mm, $BC = 3$ mm), and the point E is located at the foil leading edge. The length of L_{AE} is used to control the position of the DC hole. Once L_{AE} is determined, the position of the DC hole is determined. The side outline of the DC hole is formed by a B-spline curve. M0 is the original case, means no control. M1, M2, and M3 are the different position schemes. The three model schemes and the DC hole geometry parameters are shown in Table 1.

2.2. Numerical method

A commercial CFD code of ANSYS CFX is used in present work with a RANS solver. In the following steady-state equations, the bar is dropped for averaged quantities, except for products of fluctuating quantities.

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_j) = 0 \quad (1)$$

$$\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left(\mu \frac{\partial u_i}{\partial x_j} - \rho \overline{u_i' u_j'} \right) + S_M \quad (2)$$

where u_i ($i = u, v, w$) is the velocity, x_i ($i = x, y, z$) is the position, t is the time, p is the pressure, μ is the dynamic viscosity, S_M is the external momentum source term. The Reynolds stresses $\rho \overline{u_i' u_j'}$ can be modified by a turbulence model. For the multiphase flow, the homogeneous (one-fluid) model allows some simplifications with an assumption that the transported quantities are the same for all phases, except for the volume fraction α . ρ is defined as the density of mixture with the following definition:

$$\rho = \alpha_v \rho_v + \alpha_l \rho_l \quad (3)$$

where the subscripts v and l represent the vapor and liquid phases respectively.

In order to accurately capture the flow trajectory around the tip clearance, the SST $k-\omega$ model is determined as the turbulence model in the present simulation. It has a good adaptability to the simulation of flow separation (Zarei et al., 2020). The SST $k-\omega$ model with a rotation-curvature correction (SST-CC) (Smirnov and Menter, 2009) is used in the current calculation owing to the rotation characteristics and curvature factors around the TLV. The SST-CC model improves the prediction of the velocity in TLV on the measured sections in downstream, and gives a good prediction of the vorticity and pressure characteristics of the TLV trajectory (Guo et al., 2018). The ZGB cavitation model (Cheng et al., 2019) is used to simulate the flow with cavitation. According to the experiments previously conducted by Dreyer et al. (2014b), the inlet velocity is set as a normal speed with low turbulence intensity, and an adjustable static pressure is used as the outlet boundary to ensure the inlet pressure p_∞ maintains at 1 bar. Additionally, for the enclosing walls, no slip and smooth walls are assumed as boundary conditions. The high-resolution scheme is selected for the advection scheme and turbulence numeric. The convergence criterion is set to root-mean-square residuals of 10^{-7} for non-cavitation and 10^{-5} for

Fig. 2. Structure of the DC hole.

Table 1

Parameters of the optimization schemes.

Case	L_{AE}	$\angle EA2 = \angle AB4$	$\angle BC6 = \angle CD8$	$\angle AB3 = \angle CD7$	BC
M1	10 mm	60°	60°	90°	3 mm
M2	15 mm	60°	60°	90°	3 mm
M3	20 mm	60°	60°	90°	3 mm

cavitation.

3. Mesh and validation

A structured hexahedral mesh is generated in the present case as shown in Fig. 3. The O-type topology and local mesh refinement are adopted because the O-type topology can generate the body-fitted grid as well as the ideal boundary layer mesh. Besides, different nodes are arranged from the foil tip to the endwall according to the tip gap size. In the case of DC hole, the mesh in the hole is also refined to capture the flow details. The mesh quality is appropriate with the value quality criterion beyond 0.67 in the ANSYS ICEM CFD. The average value of Y^+

Fig. 3. Computational domain mesh.

on the foil surface is mainly in the range of 10–20. The total number of mesh elements is 5.8–7.8 millions, referring to the mesh independency validation of Guo et al., 2016, 2018.

In order to verify the reliability of numerical results, some specific numerical parameters are compared to existing experiments conducted by Dreyer et al. (2014b), the inlet velocity is 10 m/s, and the incidence angle is 10° in the case of the tip clearance $\tau = 0.2$. The TSV and TLV trajectory is compared between the experimental result and simulated cavitation structure (vapor volume fraction $\alpha = 0.1$), as shown in the Fig. 4. The numerical results of TLV structure are in qualitatively good agreement with the experimental results. Moreover, the axial velocity contours and the circumferential velocity contours of the x-y section at the same spatial position are similar with those obtained in the experiment. The above comparison shows the accuracy and validity of the numerical results.

4. Results and discussion

4.1. Vortical structures

The TLV structures for different control schemes with different tip clearances are shown in Fig. 5. The vortices are visualized via Q criterion which is the second invariant of the velocity gradient tensor ($Q = \frac{1}{2}((\nabla \cdot \mathbf{V})^2 - \text{tr}(\nabla \mathbf{V} \nabla \mathbf{V}))$). The TLV structures under no control are shown in Fig. 5(a). It could be found the starting point of the TLV locates at about 10% of chord length from the leading edge, and the initial position of the TLV gradually shifts downstream with the increasing clearance. The tip separation vortex and the tip leakage vortex could merge together and the merger location moves downstream the foil leading edge as the clearance is increased. Besides, the swirling strength of the TLV also increases with the clearance according to the flow pattern. Fig. 5(b)–(d) show the TLV structures for different control schemes. It could be obviously seen that three DC hole schemes have fine inhibitory effects on TLV. Some special structures exist in the DC hole, and these structures could be considered as the passive jet driven by the pressure difference between the pressure and suction sides. The passive jet from the DC hole interacts with the tip leakage flow thus breaking the amalgamation of the TLV and the TSV, inducing new vortical structures, dividing the TLV into several new vortical structures and suppressing the evolution of TLV.

As the passive jet impinges perpendicularly on the TLV, the TLV is divided into weakened TLV (WTLV), newborn secondary tip leakage vortex (NSTLV) and hole separation vortex (HSV). In addition, WTLV and NSTLV have an intersection at a downstream position. Compared

the flow patterns with each other, it could be found M1 scheme has the best effects for $\tau = 0.2$ while M2 scheme and M3 schemes have the best effects for $\tau = 0.3$ and $\tau = 0.4$ respectively. Obviously, the location of the jet hole is the key factor in TLV suppression. Once the DC hole locates near the amalgamation position of the TLV and TSV, the passive jet not only inhibits the merger of TLV and TSV but also separate the TLV into WTLV and NSTLV.

4.2. Streamline

Fig. 6 shows the three dimensional streamlines starting from foil tip for $\tau = 0.2$ –0.4. For the original case M0 (Fig. 6(a)), the streamline structure of TLV is very strong and clear. For $\tau = 0.2$, the initial position of TLV is at 10% of the chord, and TLV develops with strong velocity swirling strength above the suction side. In the range of 10%–60% of the chord length, the TLV's velocity swirling strength is so high, and the vortex streamline is straight and stable. When the TLV develops into the downstream region, the velocity swirling strength is slightly reduced, and the leakage flow from the gap is involved in the TLV. The streamlines for $\tau = 0.3$ and 0.4 are similar with $\tau = 0.2$.

Fig. 6(b)–(d) show that the passive jet induced by the DC hole could significantly suppresses the entrainment process. The velocity swirling strength has been significantly reduced compared to M0 owing to the passive jet. The vortex streamlines become deformed and unstable. Approximately in the middle of the chord length, the shape and the structure of the vortex change significantly. The radius of the vortex core becomes larger, but the velocity swirling strength has a prominent decrease. As discussed above, the position of the DC hole has an important influence on the vortex streamline. We can obviously see the M1 scheme is better than the other two schemes for $\tau = 0.2$. As the gap increases, the streamline structure becomes more stable and its strength increases. The initial point of the vortex gradually moves downstream. Therefore, the more downstream DC hole solutions in M2 and M3 have a better performance. In short, compared with the original scheme, the DC hole scheme can suppress TLV.

4.3. Lift and drag

Table 2 shows the lift coefficient C_L of the foil for $\tau = 0.2$ and 0.4. We could observe the lift coefficient for $\tau = 0.2$ is larger than that for $\tau = 0.4$ for the same control scheme. This phenomenon is attributed to the more energy loss for the larger tip clearance. For each tip clearance, the lift coefficient always decays with the DC hole moving downstream the leading edge. This is ascribed to the pressure loss for the passive jet, and this cause may be discussed in following sections.

Fig. 4. Comparison of TLV trajectory between experiment and numerical results ($V_\infty = 10$ m/s).

Fig. 5. Vortex iso-surface visualized by $Q = 7 \times 10^6 \text{ s}^{-2}$ for different schemes ($V_\infty = 10 \text{ m/s}$).

Fig. 7 shows the lift drag ratio K (Guo et al., 2016) for different control schemes. Compared with the solution without hole structure, the lift coefficient drops by about 0.3%, and the lift drag ratio K drops by about 7%. For all inlet velocities and hole positions, the K of the foils with holes is a little lower than that of the foil without holes for two tip clearance sizes. The main reason is that the foil tip hole structure affects the pressure distribution in the tip area, thereby reducing the pressure difference of the tip at the leading edge.

4.4. Pressure and cavitation

The TLV pattern of the original foil with the tip clearance of 2 mm is defined as the original scheme M0, as shown in Fig. 8(a). The 21 red points correspond to the maximum Q value above the SS (suction side) on 21 cross sections, respectively. The first two points (A05, A075) correspond to the sections of the 5% C and 7.5% C from the foil leading edge, respectively. The points A1-A19 present the TLV trajectory from 10% C to 100% C . In this way, the trajectory of the TLV cores is given in these points.

Fig. 8(b) shows the evolution curves of pressure on the TLV cores. It can be observed that the pressure of the three suppression schemes is higher than that of the M0 scheme. It is worth noting that M1, M2, and M3 have a “V” trend that first drops and then rises at points A7, A8, and A9 respectively. Because the points A7, A8, and A9 are all intersection points of vortices after being impacted. At this point, the local pressure has a sudden rise.

The DC hole structure scheme can not only effectively break the TLV,

but also improves the vortex pressure distribution. Fig. 9 shows the pressure isosurface at 3574 Pa. The pressure distribution of the TLV of M0 is highly consistent with the structure of the TLV, and the other three schemes have an improvement effect on the distribution of the TLV low pressure area. The hole of M1 is placed at the initial point of the TLV. At this time, the suppression effect on the vortex and the improvement of the vortex low pressure area are the best. The pressure isosurface area is reduced by 53.2%. As the hole position continues to move downstream, the improvement effect of the vortex low pressure zone of M2 and M3 gradually weakens. Two holes are combined, which has a more significant effect. At the same time, according to Fig. 5, the hole jet separates the TLV into several NSTLVs, and the NSTLV develops downstream and generates an intersection. At this intersection, the local pressure has a significant decrease, as shown in Fig. 9. Fig. 10 shows the distribution of the cavitation isosurface under the condition of $\tau = 0.2$. The vapor volume fraction iso-surface area of M1, M2 and M3 is decreased by 54.6%, 35.7% and 13.4%. In other words, the DC hole could suppress the local cavitation.

4.5. Control mechanism

Fig. 11 shows the pressure and velocity vector distributions in the YZ plane located at the middle plane of the DC hole. As shown in Fig. 11(a), the pressure in the TLV core increases for three control schemes. We could see the jet generates in the DC hole due to the pressure difference between the pressure side and the suction side in the right enlarged figure. The pressure difference in hole H1 is less than that of hole H1.

Fig. 6. Three dimensional streamlines contoured by velocity swirling strength under different conditions ($V_\infty = 10$ m/s).

Table 2

Lift coefficient for different schemes ($V_\infty = 10$ m/s).

Case	C_L	
	$\tau = 0.2$	$\tau = 0.4$
M0	1.2528	1.2154
M1	1.2483	1.2142
M2	1.2481	1.2103
M3	1.2458	1.2091

Meanwhile, the velocity magnitude in hole H2 is larger than that in hole H1. Although the jet rushes perpendicularly to the TLV, the flow direction could be modified by the upstream flow. So, local flow separations could occur near the hole thus leading to the HSVs. Besides, the low pressure in HSV could cause the pressure difference between the two holes, so part jet fluid of hole H2 flows towards hole H1. It could be clearly observed that there exists several low pressure regions downstream hole H2. This demonstrates that flow separation of the passive jet in hole H2 could separate the TLV into several parts. Combined action of the two holes could cause a stronger breaking power. In addition, as DC hole in M1 scheme is closer to the merger point of TLV and TSV, the control effects of M1 scheme are the best among the three control schemes.

Fig. 11(b) and (c) show the pressure and velocity vector distributions for $\tau = 0.3$, $\tau = 0.4$. The distribution features are analogue to those for $\tau = 0.2$. It can be seen that the location of the DC hole is a crucial factor in the control effects for different tip gaps. For $\tau = 0.3$, the M2 scheme has

the best control effect, while the M3 scheme is the best choice for $\tau = 0.4$. As discussed above, once the DC hole locates near the merger point of TLV and TSV, separation of the passive jet could separate the TSV into several NSTLVs, and weaken TSV.

5. Conclusion

In the present research, a DC hole method is proposed to suppress the TLV of a hydrofoil with a tip clearance. The control effects for several geometric and flow parameters including hole position, tip clearance size, and inlet velocity are systematically investigated. The passive jet from the DC hole can perpendicularly impinge on the TLV, and divide the TLV into several parts. The control effects are greatly related to the location of the DC hole for different tip clearance. The main conclusions can be drawn as follows:

- (1) The DC hole method can successfully suppress the development of TLV and weaken the TLV. There are newborn vortexes around the DC hole, which can be classified into three types: weakened tip leakage vortex (WTLV), newborn secondary tip leakage vortex (NSTLV) above suction side downstream hole and hole separation vortex (HSV) in tip hole outlet. Besides, the velocity swirling strength has been significantly reduced, and the vortex streamlines become deformed and unstable under control of the DC hole.
- (2) The DC hole method could greatly improve the TLV pressure distribution at the leading edge of the blade tip, inhibiting the development of the vortex core low pressure zone, and increases

Fig. 7. Variations of lift-drag ratio K with the inlet velocity.

Fig. 8. Pressure along the TLV trajectory for different control schemes ($V_\infty = 10$ m/s).

Fig. 9. Perssure defined by iso-surface of 3574 Pa for different schemes under condition of $\tau = 0.2$ ($V_\infty = 10$ m/s).

- the maximum vortex core pressure. As a result, local cavitation can be suppressed.
- (3) The hole position has the most powerful impact on the control effects. Once the DC hole locates near the merger point of TLV and TSV, the DC hole could achieve the best control effects. Among the three control schemes, M1 scheme could achieve the best control effects for $\tau = 0.2$ while M3 scheme is the best for $\tau = 0.4$.

- (4) Under different inlet velocities, the lift coefficient and the lift drag ratio of the foil are slightly reduced. But if the DC hole can effectively suppress TLV, as well as the cavitation and noise it brings, and improve the stability of the flow, it provides a solution for engineering design.

The present work has shown the advantage of the proposed DC hole method on TLV suppression and vortex pressure improvement under different conditions. However, there are still further geometric

Fig. 10. Cavitation around the foils for different DC hole positions, vapor volume fraction $\alpha = 0.1$ ($V_\infty = 10$ m/s).

Fig. 11. Pressure and velocity vector distributions on YZ plane ($V_\infty = 10$ m/s).

parameters associated with the DC hole effect, such as the size of hole and the number of holes. Moreover, the effects of the DC hole on the cavitation performance and the noise production of hydrofoils should also be studied deeply.

CRediT authorship contribution statement

Yadong Huang: Writing and methodology. **Desheng Zhang:** Supervision. **Fei Wang:** Calculation. **Guangjian Zhang:** Data processing. **B.P. M. (Bart) van Esch:** Writing revision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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