

Article

Influence of T-Shape Tip Clearance on Energy Performance and Broadband Noise for a NACA0009 Hydrofoil

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Received: 28 September 2019; Accepted: 24 October 2019; Published: 25 October 2019



Abstract: In the present paper, the effect of the proposed T-shape tip on the energy performance, flow patterns and broadband noise sources of a NACA0009 hydrofoil with tip clearance is investigated. The vortex induced by the gap is simulated by means of the SST $k-\omega$ turbulence model, and then, the noise generated by dipoles and quadrupoles is analyzed by using the Curle acoustic analogy and Proudman acoustic analogy, respectively. The numerical simulation results agree well with the experimental measurements. Results indicate that three tip shapes, including the half pressure side T-shape model (MPT), the half suction side T-shape model (MST) and the T-shape model (MT), have complex influence on energy performance of the foil. Only the MST model can promote the energy performance of the hydrofoil at all inlet velocities, with the maximum ratio of lift coefficient to drag coefficient increasing by 4.26%. In addition, the ratio of lift coefficient to drag coefficient for MT obviously increases when the inlet velocity is 7.5 m/s, 10 m/s, 12.5 m/s and 15 m/s, and the maximum promotion is 15.21% at 7.5 m/s. The T-shape tip can effectively suppress the tip clearance leakage vortex, which makes the vortex area decrease with a maximum drop of 5.02%. Furthermore, the MPT and MT have good suppression effect on the hydrofoil dipole noise, and reduce the maximum Curle Acoustic Power (AP) of the foil with 2.64% and 3.03%, respectively. The MST model obviously reduces the isosurface area of the Proudman AP by 6.55% for 55 dB.

Keywords: T-shape tip; NACA0009; tip clearance; tip leakage vortex; noise

1. Introduction

Hydraulic machineries are widely used in modern submarines and warships, such as pumps, duct propulsors and waterjet propulsors, which have attracted the attention of researchers on a worldwide scale [1–5]. However, due to the limitation of the impeller structure, there is inevitably a gap between the rotating blades and the fixed impeller chamber [6,7]. The tip leakage flow (TLF) and tip leakage vortex (TLV) is induced by the existence of the gap, which results in pressure drop and energy loss, and then leads to cavitation, erosion, vibration and noise [8–12]. The radiated noise from these hydraulic machineries will harm the worker health and can be easily detected by the enemy sonar systems. Therefore, the internal mechanism among TLF, energy loss and radiated noise is waiting to be explored.

In the past decades, considerable experimental investigations have been conducted on the tip leakage flow, cavitation and noise mechanism. Wu et al. [13,14] experimentally investigated the cavitation within the gap of a waterjet pump. The results indicated that the TLF along the aft side of the blade was strong enough to cause sheet cavitation in the gap starting from the pressure side corner.

Moreover, Zhang et al. [15,16] carried out an experimental investigation in an axial flow pump; the results on TLV cloud cavitation revealed that it keeps a stable triangular flow structure from the leading edge to 80% of the length of the chord, while the cavitation shape becomes unstable near the trailing edge. For the fundamental research, Dreyer et al. [17] experimentally studied the influence of the tip size on the TLV formation and cavitation of a NACA0009 hydrofoil. This work is a classic example that is often used to verify the validation of the Computational Fluid Dynamics (CFD) computation of the tip clearance. Recently, Gopalan et al. [18] conducted experimental work upon the impact of gap width on internal flow mechanism, cavitation formation, corresponding bubble dynamics and induced noise. The results showed that the bubbles will grow up in the vortex core, and deform and break into multiple bubbles, which resulted in a noise peak value. By changing the shape and size of bubbles, its cavitation radiation noise can be effectively suppressed.

In addition to experimental measurements, the numerical method is of great significance for the study of TLF and its induced cavitation. Liu et al. [19] analyzed the vortex features and pressure fluctuation within a mixed flow pump; results showed that the TLV can be divided into the primary TLV, secondary TLV, entangled TLV and dispersed TLV. Hao et al. [20] compared the impact of unsymmetrical and symmetrical gaps on the changes of radial force and cavitation within the mixed flow pump. Results indicated that the unsymmetrical tip clearance is inapplicable for reducing cavitation performance, and its existence influenced the magnitude and direction of the radial force as cavitation developed. Liu et al. [21] investigated the TLV evolution with time in a mixed flow pump, and the TLV split, developed and merged under different stages. Results showed that the varied pressure at blade junction aggravated TLV fluctuation. Guo et al. [22] studied the impact of foil tip shape and size on the flow characteristics and energy performance for a NACA0009 hydrofoil. Results showed that the sharp tip mitigated the TLV loss, and the separation of the boundary layer increased the velocity gradient. Okita et al. [23] focused on the cavitation evolution induced by the tip clearance of an inducer; the flow detail was captured by adopting a detached eddy simulation model. Zhang et al. [24] concentrated on energy performance and flow features within multiphase pump; results showed that the pressure maximum and the area of vortex were enhanced as the gap size increased. Decaix et al. [25,26] simulated the TLV between blade tip and the wall of water tunnel; results revealed that the vortex trajectory approached the suction side, which would aggravated the wall erosion.

The above references show that despite the fact that tip clearance is small, the interaction between TLV and main flow in the blade passage, the boundary layer near the wall and the wake near blade will form a complex vortex structure. Additionally, it will cause cavitation, vibration and noise, which seriously affect the operation stability of hydraulic machineries. Consequently, it is necessary to put forward some effective control measures.

To suppress the TLF and cavitation, many scholars have studied the influence of tip shape and size on TLV or cavitation. Gearhart et al. [27] experimentally studied the effects of the gap width, boundary layer near the wall and blade load on TLF. Moreover, Laborde et al. [28] revealed that the tip geometry was of great significance on the cavitation and flow patterns. As the clearance edge becomes round on the pressure side, the optimal tip scheme can eliminate cavitation. Recently, Liu et al. [29] presented interesting work: the C groove method can reduce the TLV formation and enhance energy performance within a NACA0009 hydrofoil. Under all conditions, the C groove method exhibited the ability of promoting energy performance and suppressing TLV. As for the 0.2 and 0.4 tip clearance, the maximum of vortex area was decreased by 66.55% and 67.94%, respectively. In summary, several effective methods suppressing TLV and improving the energy performance have been proposed. However, there is not yet a reliable and effective method on suppressing broadband noise.

The objective of the present work is to examine the influence of the proposed T-shape tip on the energy performance, flow patterns and broadband noise sources in a NACA0009 hydrofoil. The main content of the present paper is as follows. Firstly, the research background is introduced and a new designed T-shape tip is proposed. Then the comparison between computational results and

experimental data is conducted in order to establish the foundation of the subsequent simulation work. Finally, the energy performance, the detailed flow features in T-shape tip and the broadband noise characteristics are systemically analyzed.

2. Research Object and T-Shape Tip

2.1. Physical Model of NACA0009 Hydrofoil

A NACA0009 hydrofoil [17] with tip clearance (Figure 1) is assumed to have a truncated chord of $c = 0.1$ m, maximum thickness of $h = 0.0099$ m and span of $b = 0.15$ m. The gap size δ , normalized by the maximum thickness h , is 0.2, and the incidence angle is 10° . The fluid density is 997 kg/m^3 and the inlet pressure is 1 bar.

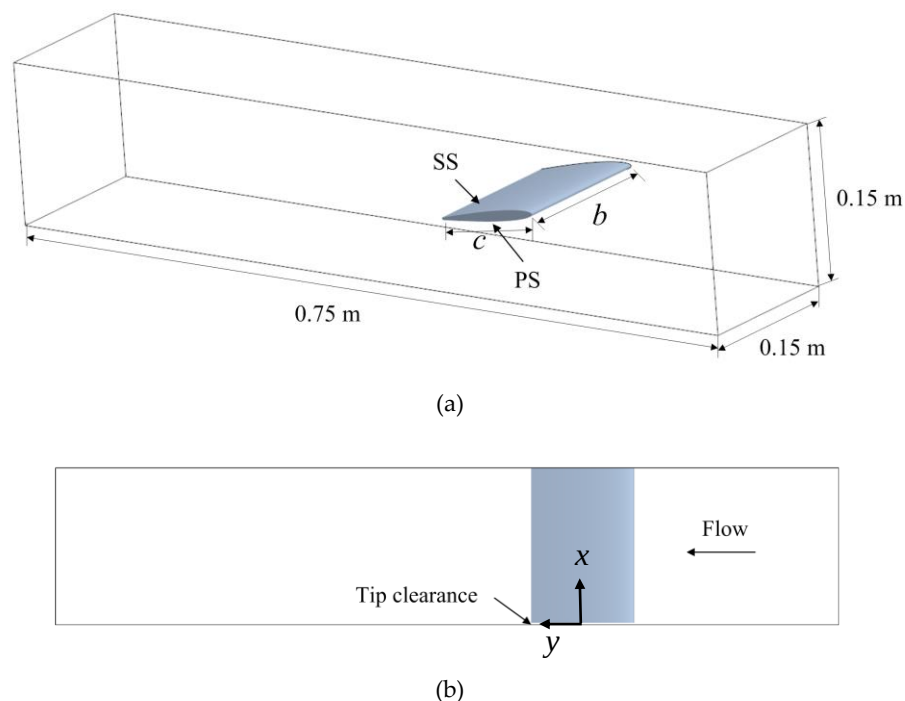


Figure 1. Physical model of NACA0009 hydrofoil. (a) Isometric view. (b) The gap.

2.2. T-Shape Tips

As shown in Figure 2, the new proposed T-shaped tip is formed by gradually increasing the thickness from point A to the tip, and the foil profile is symmetrical. The distance between A and the foil end is the tip clearance δ . At point A, the foil thickness equals the original blade thickness t_0 , and the maximum thickness of the foil end is t_m increasing by $0.3t_0$. Figure 3 illustrates the original tip and three types of T-shape tips, including half pressure side T-shape (MPT), half suction side T-shape (MST) and T-shape (MT). The control curves of the MPT, MST and MT are straight lines.

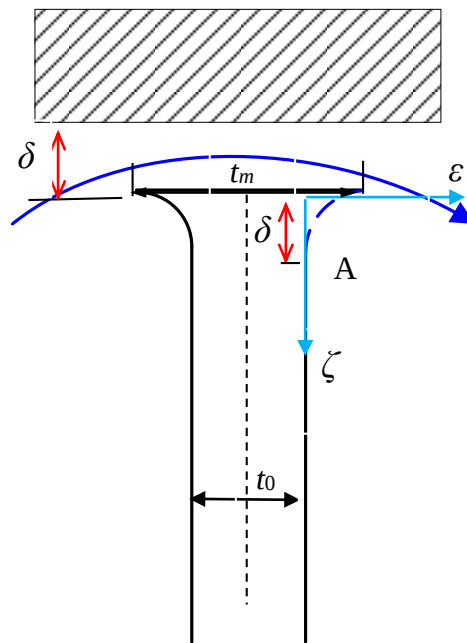


Figure 2. Sketch map of T-shape tip.

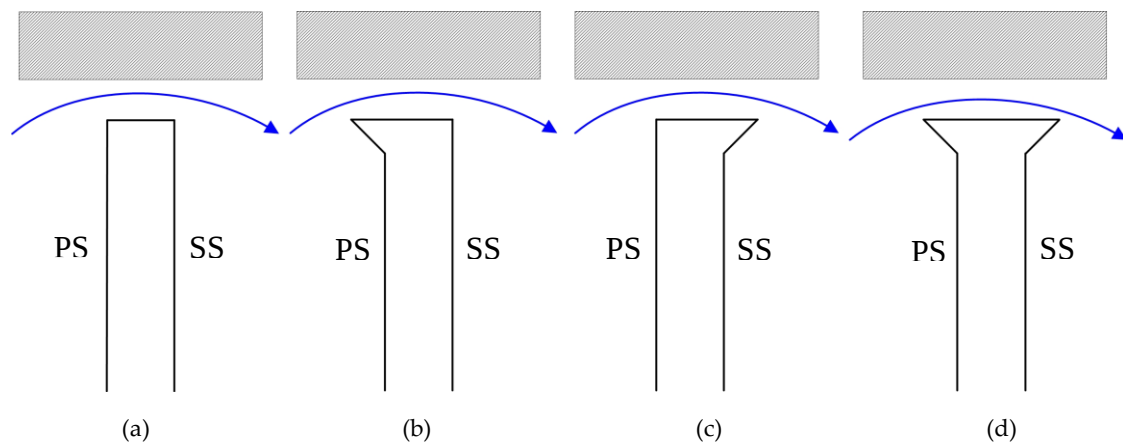


Figure 3. Proposed T-shape tips. (a) M0; (b) MPT; (c) MST; (d) MT.

3. Numerical Setting and Validation

3.1. Numerical Method

In the present paper, a steady-state Reynolds averaged Navier-Stokes (RANS) equation and the SST $k-\omega$ turbulence model [22,29,30] with all y^+ wall treatment were used to calculate the flow field within the gap; then, the acoustics models available in STAR_CCM+ 13.02, including the Curle and Proudman broadband noise models, were adopted to investigate the broadband noise sources. The Segregated flow model was used to compute each of the momentum equations in turn. Moreover, the second-order upwind convection scheme was adopted for the advection scheme. For the boundary conditions, a normal velocity with low turbulence intensity imposed at the inlet and a static pressure was applied at the outlet. The no-slip wall conditions were set at the hydrofoil surface and the tunnel wall.

It should be noted that the SST $k-\omega$ turbulence model has its own limitations, errors and uncertainties [31]. However, the SST $k-\omega$ turbulence model is widely used to investigate the detail flow field in tip clearance for a NACA0009 hydrofoil [22,29]. Consequently, the SST $k-\omega$ turbulence model

with all y^+ wall treatment is employed to evaluate the effect of T-shape tips on energy performance and flow patterns in the gap.

3.2. Mesh Independence

ICEM 17.0 was adopted to obtain the structured hexahedral element for the whole computational region. As indicated in Figure 4, both the O-type topology and local mesh refinement were used.

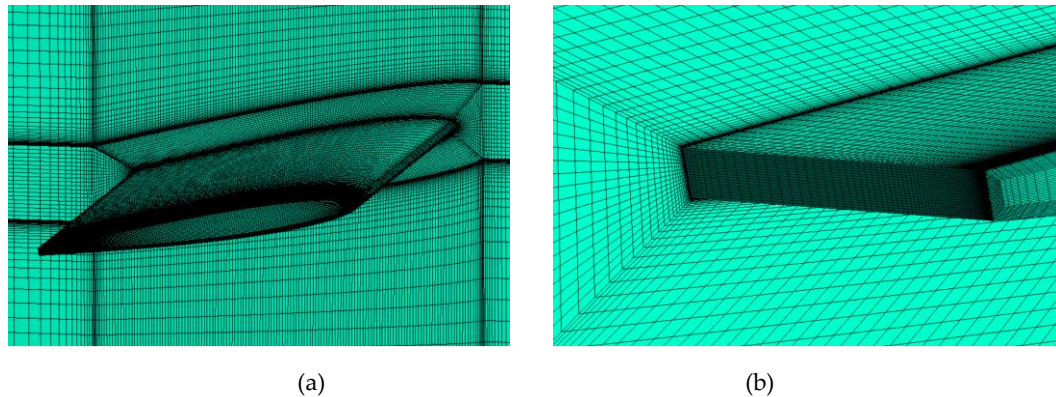


Figure 4. Mesh arrangement. (a) Grids on hydrofoil; (b) Local mesh refinement.

Three sets of meshes were employed to examine the effect of element size in numerical calculation. The drag coefficient C_D and lift coefficient C_L were adopted to check the impact of mesh size and they are expressed as:

$$C_D = \frac{D}{0.5\rho W_\infty^2 S_D}, \quad C_L = \frac{L}{0.5\rho W_\infty^2 S_L} \quad (1)$$

where D and L denote the drag and lift forces parallel and normal to the inflow, which are the forces in Y and Z axial directions in present simulation. S_D and S_L represent the projected area of the foil in Y and Z axial directions, respectively.

Table 1 is the mesh independence results (inlet velocity is 10 m/s). It can be seen that the drag coefficient C_D and lift coefficient C_L keep the same when the number of elements becomes 5500833. Therefore, the configuration of mesh 2 is employed in the following investigation. The grids on the foil surface are arranged with 150 nodes along chord direction, 80 nodes along span direction and 20 nodes along thickness direction. Furthermore, there are 20 nodes along the span direction in the gap to capture flow details. The average value of y^+ on the foil surface is about 10–40.

Table 1. Mesh independence.

Items	Elements	C_D	C_L
Mesh 1	2715286	0.307	1.233
Mesh 2	5500833	0.23	1.246
Mesh 3	6899538	0.23	1.246

3.3. Validation of Numerical Results

As illustrated in Figure 5 (inlet velocity is 10 m/s), there is a good agreement between the experimental TLV trajectory [17] and calculated vortex expressed by Q criterion ($Q = 2 \times 10^7 \text{ s}^{-2}$). Moreover, Figure 6 examines the axial velocity contour on the cut-plane of $y/c = 1$, the numerical simulations agree well with the experiment measurements. The above analysis shows that the mesh and numerical method adopted in the present paper are reasonable.

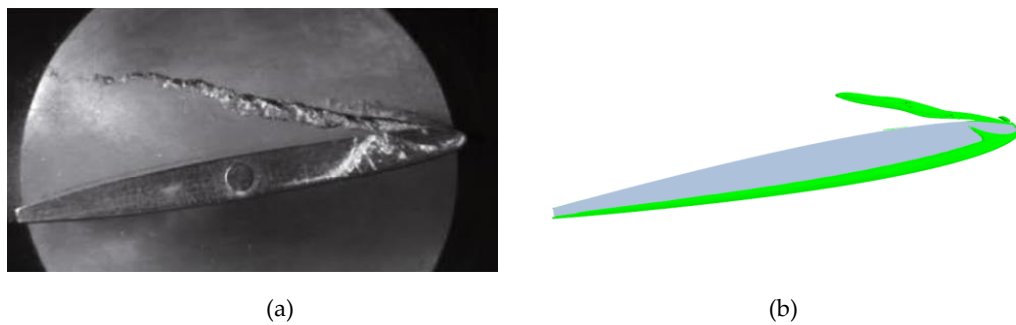


Figure 5. Comparison of experimental TLV trajectory [17] and numerical simulations. (a) Experimental results [17]; (b) Numerical results.

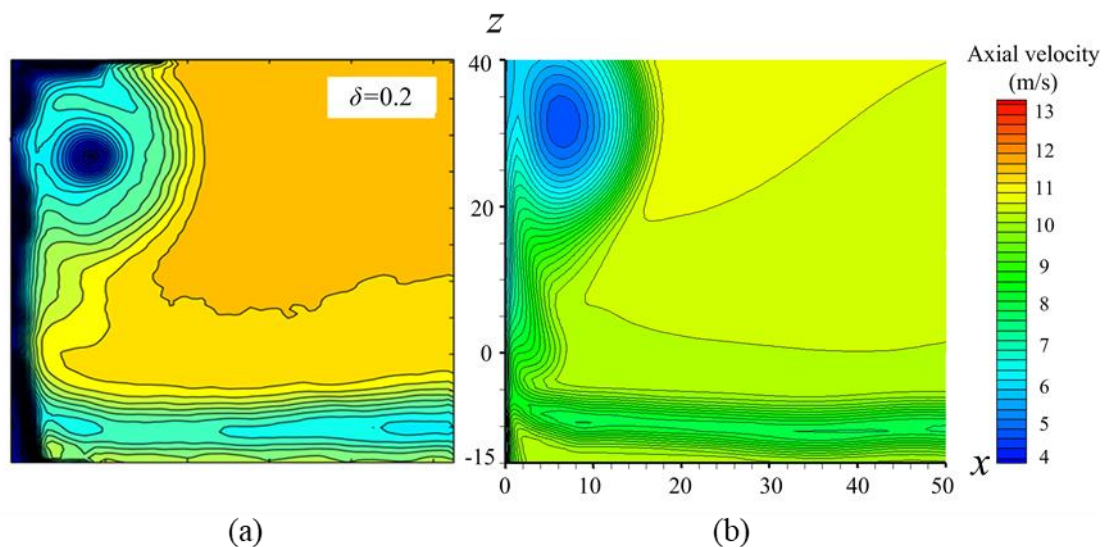


Figure 6. Comparison of the axial velocity contour at cut-plane of $y/c = 1$ between experiment [17] and numerical simulations. (a) Experimental results [17]; (b) Numerical results.

4. Result and Discussion

4.1. Energy Performance

T-shape tip geometry will affect the hydrofoil lift force and drag force, which can be analyzed by the drag coefficient (C_D) and lift coefficient (C_L) defined in Equation (1). Figure 7 shows the lift coefficient, drag coefficient and ratio K of lift coefficient to drag coefficient for different cases. Results show that the lift coefficient gradually increases, the drag coefficient decreases and the lift-drag ratio rises with increase of inlet velocity. Moreover, the impact of the three optimization configurations on the lift coefficient, drag coefficient and K is complex. Firstly, the lift coefficient of the MPT, MST and MT are smaller than that of M0 when the inlet velocity is 5 m/s and 7.5 m/s. As the inlet velocity rises to 10 m/s, the lift coefficient of MST and MT are larger than that of M0. However, for MPT, the lift coefficient is larger than that of M0 only at 10 m/s. Secondly, the drag coefficient of MPT and MST is obviously smaller than that of M0 with the velocity 5 m/s and 7.5 m/s. Finally, the ratio K of MST is larger than that of M0 under all inlet velocities. Moreover, compared with M0, the ratio K of MT is obviously increased when the inlet velocity is 7.5 m/s, 10 m/s, 12.5 m/s and 15 m/s, and the maximum promotion of K is 15.21% at 7.5 m/s. The ratio K of MPT promotes significantly only at 7.5m/s with the maximum promotion of 11.40%.

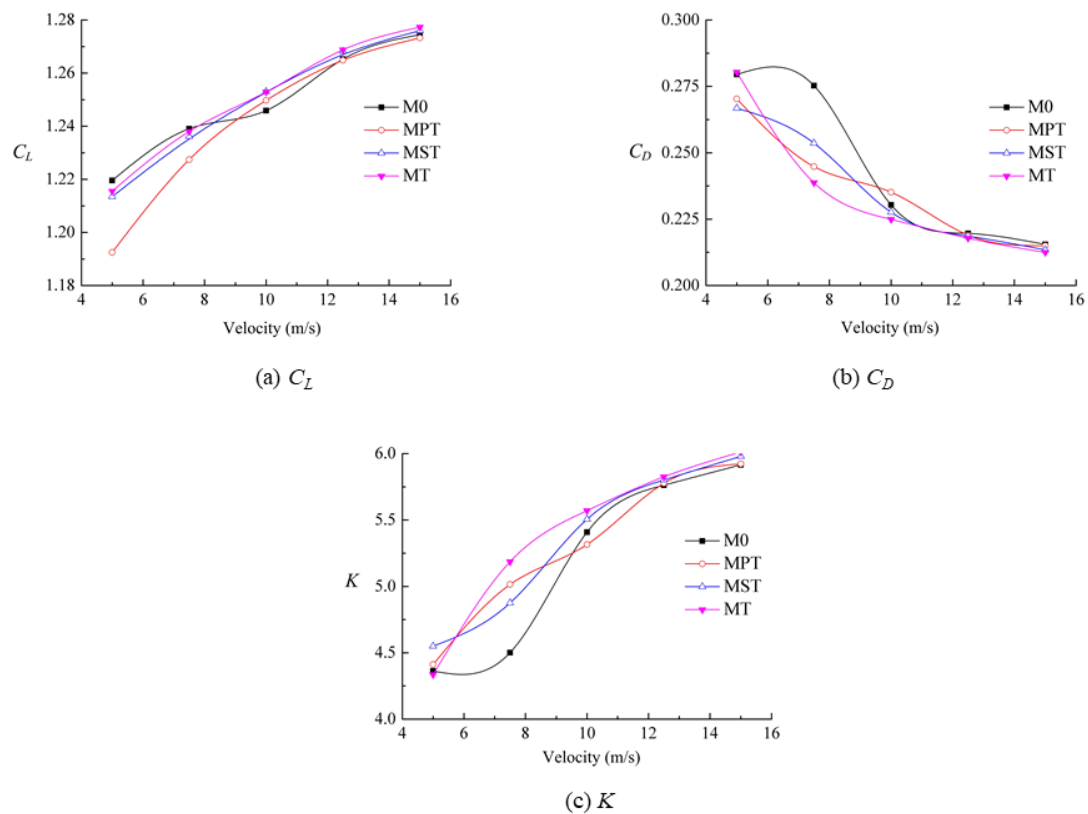


Figure 7. Energy performance of foil for different configurations.

4.2. Flow Patterns in the Gap

The flow patterns in the gap are investigated with the inlet velocity of 10 m/s in this section. As shown in Figure 8, the TLV can be divided into the primary tip leakage vortex (PTLV) and the secondary tip leakage vortex (STLV). In STAR_CMM+ software, the iso-surface of the vortex can be frontal projected to the water tunnel wall near the tip, which can be used to examine the effect of the T-shape tips on suppressing the TLV. Compared with the original foil M0, the MPT, MST and MT obviously reduce the TLV area by 4.01%, 5.02% and 4.91%, respectively.

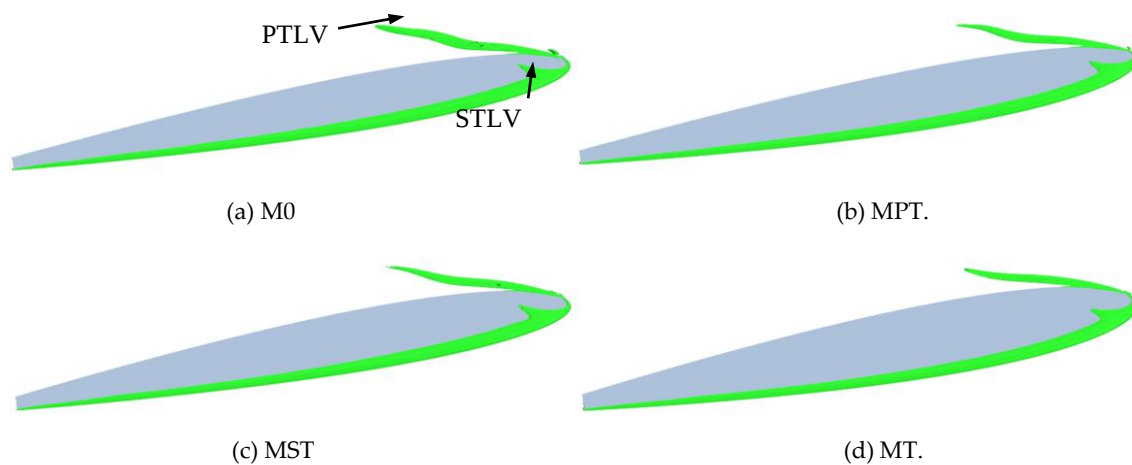


Figure 8. Iso-surface showing TLV at $Q = 3 \times 10^7 \text{ s}^{-2}$.

As indicated in Figure 9, in order to investigate the pressure and vorticity along the PTLV trajectory ($Q = 3 \times 10^6 \text{ s}^{-2}$), 10 monitoring points of P1-P10 were chosen along the PTLV trajectory from 5% c to 50% c with an interval of 5% c .

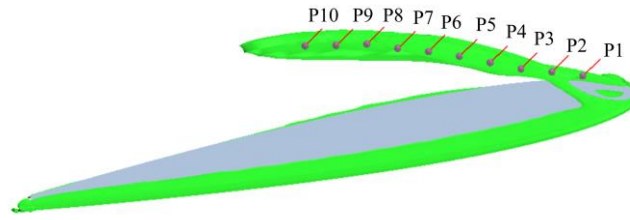


Figure 9. The TLV pattern and trajectory of the case MST ($Q = 3 \times 10^6 \text{ s}^{-2}$).

Figure 10 shows the vorticity and pressure curve along the PTLV trajectory. The vorticity sharply declines and then slowly decreases along the PTLV trajectory. The variation of pressure along the PTLV trajectory is almost opposite to that of vorticity. The pressure curves of four cases vary along the PTLV trajectory, and it is obvious that T-shape tip can increase the pressure along the PTLV trajectory, especially near the leading edge. The MT has the best effect on pressure improvement, which is corresponded to the best energy performance at 10 m/s. The vorticity along the PTLV trajectory is nearly the same for different cases.

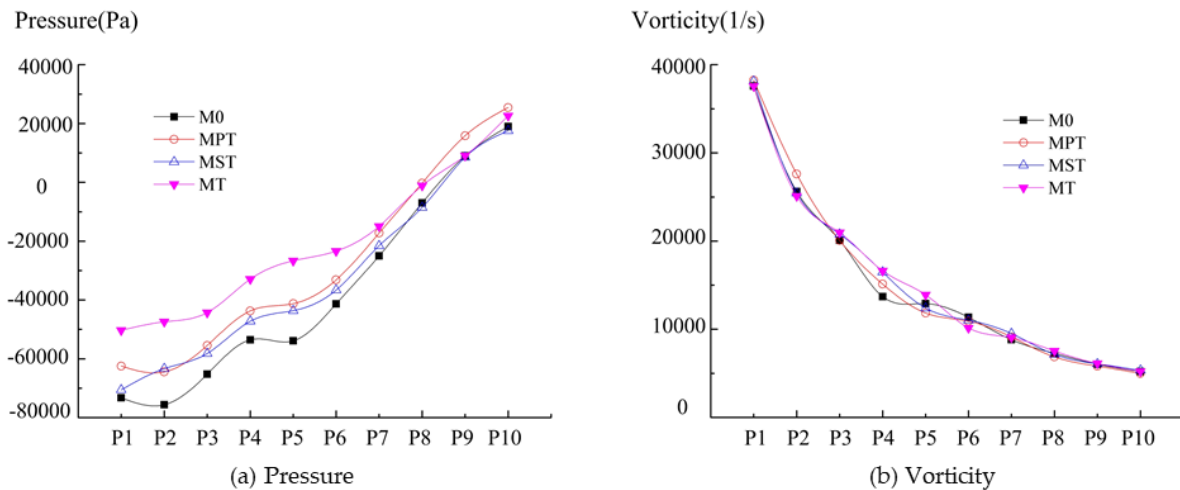


Figure 10. Pressure and vorticity distribution on planes 1–5 with different tip shapes.

4.3. Curle Surface Acoustic Power Characteristic

The Curle noise source model is adopted to compute the dipole noise of the turbulent boundary layer flow on the solid surface. The surface acoustic power (SAP) can be written as:

$$SAP = \iint_S \frac{A_c(\mathbf{y})}{(12\rho_0\pi c_0^3)} \overline{\left(\frac{\partial p}{\partial t}\right)^2} dS(\mathbf{y}) \quad (2)$$

where c_0 is the sound speed in the far field, and $A_c(\mathbf{y})$ denotes the correlation area. The steady-state RANS turbulence models can be employed to obtain the turbulence length scale, turbulence time scale and wall shear stress, and further calculate $\overline{(\partial p / \partial t)^2}$.

The SAP can be expressed in dB:

$$SAP(\text{dB}) = 10 \log \frac{SAP}{P_{ref}} \quad (3)$$

where $P_{ref} = 1 \times 10^{-12} \text{ W/m}^2$ is the reference acoustic power.

For the condition of inlet velocity 10 m/s, the Curle SAP characteristic is studied in this section. Figure 11 shows the Curle SAP on the hydrofoil for different T-shape tips. The areas with higher decibel values of dipole noise are mainly on foil leading edge and foil tip near the leading edge. The main reason is that the vortex is close to the foil surface and has obvious interaction with the foil surface. The decibel values of dipole noise on the foil surface along the downstream direction gradually decrease, and the area of high decibel values (red color) on the tip for MPT and MT is small than that of M0.

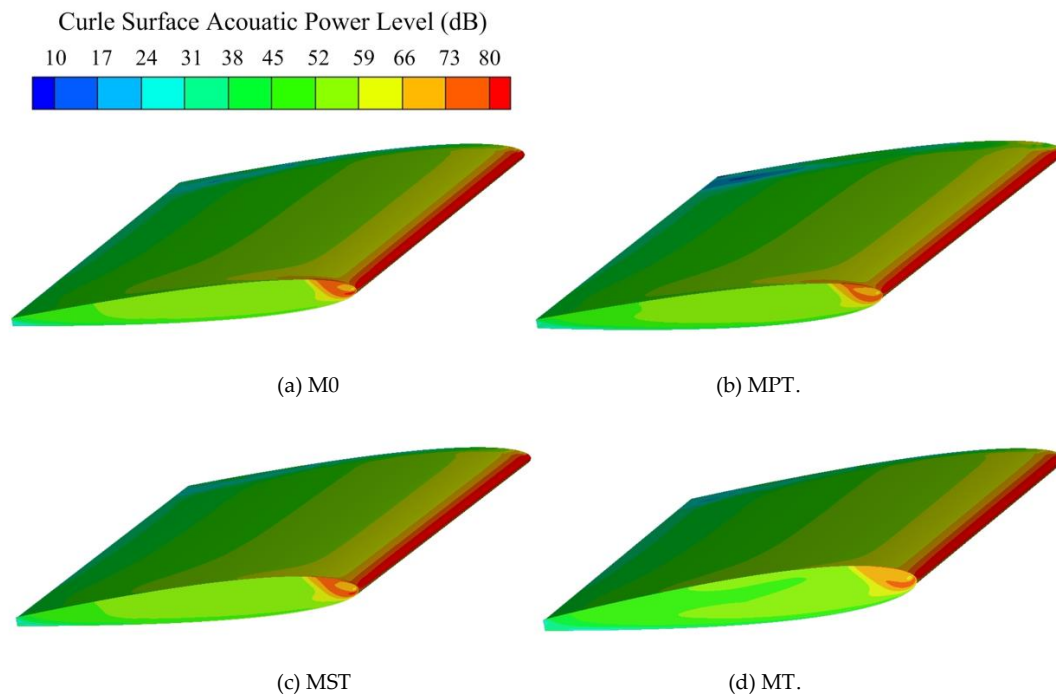


Figure 11. Curle surface acoustic power (SAP) of the hydrofoil for different T-shape tips.

The effect of T-shape tips on Curle SAP of hydrofoil with tip clearance is demonstrated in Table 2. The relative change is defined as $\Delta\text{SAP} = (\text{SAP} - \text{SAP}_0)/\text{SAP}_0$, where SAP_0 is the value of M0, and the average SAP denotes the surface average value of the Curle SAP. It can be concluded that the maximum SAP for MPT and MT decreases by 2.64% and 3.03%, respectively, and the average SAP for MPT, MST and MT decreases by 0.50%, 0.04% and 0.97%, respectively. For the foil end surface, the MT model can effectively suppress the dipole noise, the maximum SAP and the average SAP decrease 4.75% and 1.74%, respectively. In order to evaluate the impact of the TLV on the dipole noise of the side wall near tip surface, the data of the side wall is listed in Table 2. The average SAP of the side wall for MPT, MST and MT decreases by 0.12%, 0.01% and 0.12%, respectively. In addition, the maximum SAP for MT decreases by 0.43%.

Table 2. Curle SAP for different schemes.

Scheme Item		MPT	MST	MT
$\Delta\text{SAP}\%$ (Hydrofoil)	Maximum SAP	−2.64	0.03	−3.03
	Average SAP	−0.50	−0.04	−0.97
$\Delta\text{SAP}\%$ (Tip)	Maximum SAP	−2.11	−0.81	−4.75
	Average SAP	−1.92	0.33	−1.74
$\Delta\text{SAP}\%$ (Side wall)	Maximum SAP	0.20	−0.39	−0.43
	Average SAP	−0.12	−0.01	−0.12

4.4. Proudman Acoustic Power Characteristic

The Proudman noise source model can be employed for steady-state RANS turbulence models, and visualizes the acoustic power per unit volume which is generated by the quadrupole sound sources of the flow. The total acoustic power can be described as:

$$AP = \alpha_c \rho \frac{U^3}{L_t} \frac{U^5}{c_0^5} \quad (4)$$

$$U = \frac{L_t}{T} \quad (5)$$

$$AP(\text{dB}) = 10 \log \frac{AP}{P_{ref}} \quad (6)$$

where $\alpha_c = 0.629$ denotes a constant value, U represents the turbulence velocity, L_t is the turbulence length scale and T denotes the turbulence time scale.

The Proudman acoustic power characteristic was studied under the inlet velocity of 10 m/s. To reveal the quadrupole noise around the foil, five cut-planes 1–5 were chosen at 10% c , 15% c , 20% c , 30% c and 50% c , respectively. Figure 12 shows the Proudman AP on these five cut-planes. The quadrupole noise mainly concentrated near the PTLV and STLV in the tip clearance, and the larger decibel value of the quadrupole noise mainly appeared near the STLV and the area where the STLV flow interacts with the PTLV. In addition, the MT model had a slight suppression effect on the quadrupole noise in planes 1–3.

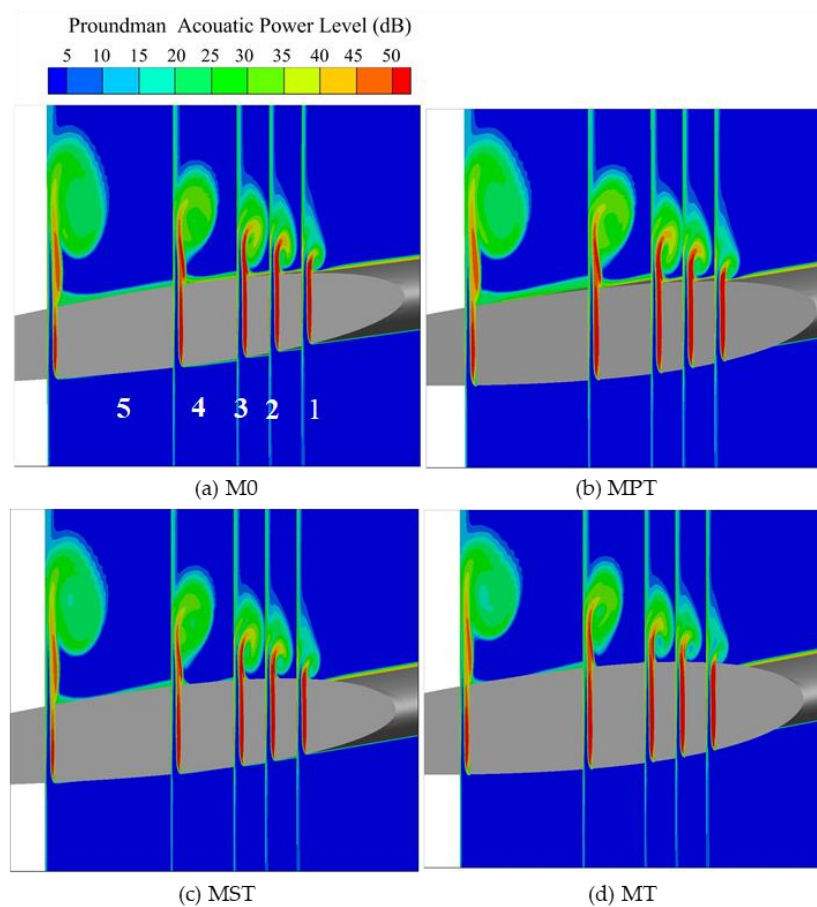


Figure 12. Proudman AP on five cut-planes.

Some comparisons were made at the power levels of 50 dB and 55 dB. As shown in Figure 13, the isosurfaces represent the value of noise at 50 dB. The main noise was located at the tip clearance leakage vortex and the leading edge. In comparison with M0, the area of noise for the three T-shape cases was not significantly reduced. As shown in Figure 14, the noise at the PTLV of the MST and MT was smaller than that of the original model M0. In STAR_CMM+ software, the iso-surface of the Proudman AP can be frontal projected to the water tunnel wall near the tip, which can be adopted to evaluate the impact of the T-shape tips on suppressing the Proudman AP. In comparison with original foil M0, the MST model obviously reduced the area of Proudman AP by 6.55% for 55 dB. However, the other two optimization configurations of MPT and MT could not effectively reduce the total area of the Proudman AP.

Note that although T-shaped tips can reduce the area of TLV, this does not mean that the intensity of quadrupole noise sources can be effectively suppressed. For example, compared with original foil M0, the TLV area of the MPT was reduced by 4.01%, but the area of Proudman AP was not significantly reduced. This is because in the sound source region, quadrupole noise mainly depends on Reynolds stress [32], not the size of vortex.

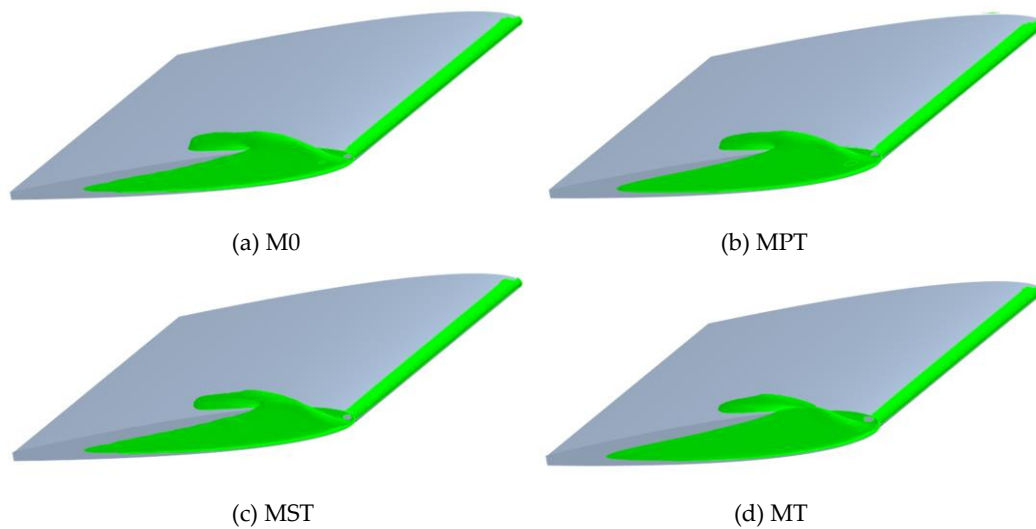


Figure 13. Isosurfaces showing Proudman AP sound sources at 50 dB.

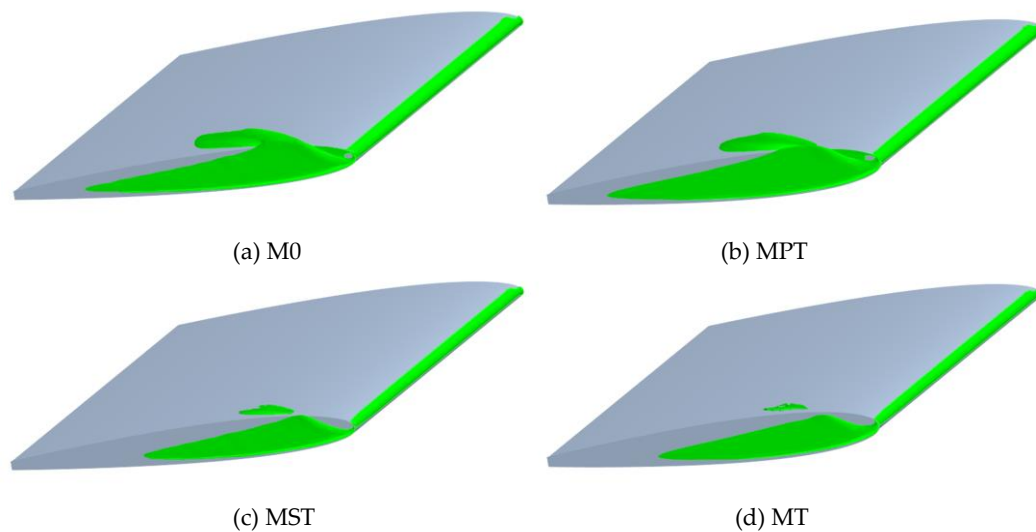


Figure 14. Isosurfaces showing Proudman AP sound sources at 55 dB.

5. Conclusions

The effect of T-shaped tip on the energy performance, flow patterns and broadband noise sources for a NACA0009 hydrofoil with tip clearance was carried out in the present paper. The numerical calculation was verified by comparing the flow experimental measurements with the numerical simulation results. The conclusions are summarized as follows:

- (1) The impact of the T-shape tip on lift coefficient, drag coefficient and ratio of lift coefficient to drag coefficient is complex. Under all inlet velocities, the MST model effectively improves ratio of lift coefficient to drag coefficient with maximum promotion of 4.26%. In addition, the ratio of lift coefficient to drag coefficient for the MT model obviously increases when the inlet velocity is 7.5 m/s, 10 m/s, 12.5 m/s and 15 m/s, and the maximum promotion is 15.21% at 7.5 m/s.
- (2) The T-shape tip can suppress the TLV, which makes the vortex area decrease with a maximum drop of 5.02%. The three optimization configurations improve the pressure along the PTLV trajectory near the leading edge.
- (3) The MPT and MT have good suppression effect on the hydrofoil dipole noise, and reduce the maximum Curle AP of the foil with 2.64% and 3.03%, respectively.
- (4) Compared with the original foil M0, the MST model obviously reduces the area of the Proudman AP by 6.55% for 55 dB. However, the optimization models of the MPT and MT cannot effectively reduce the total area of the Proudman AP.

Author Contributions: Z.H., L.T. and C.H. proposed the T-shape method, Z.H. and Y.H. completed the numerical simulations, Z.H. and Y.H. analyzed the data, Z.H., Y.H., L.T. and C.H. wrote the paper.

Funding: This research was funded by the National Natural Science Foundation of China [grant number 51809148], the Beijing Natural Science Foundation [grant number 3192015], the Open Research Fund Program of State Key Laboratory of Hydrosience and Engineering [grant number sklhse-2018-E-01], the State Key Laboratory of Hydrosience and Engineering [grant number 2018-KY-02].

Conflicts of Interest: The authors declare no conflicts of interest.

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