The Simulation of Tip-Leakage Flow and Its Induced Noise

Shucheng Zhai, Ziying Xion and Hongxing Sun

Abstract In this study, the large eddy simulation (LES) numerical method is applied to simulate the flow filed of a foil with the gap between tip and end plate. The flow field details of three different tip gaps were simulated. The noise source induced by the tip-leakage flow was also predicted by LES method, and then the noise characters of foils with different tip-leakage were calculated by acoustic analogy method using Ffowcs Williams and Hawkings (FW-H) equation. The correlation between noise and vortex was analysed by using the spectral method. This study will give information to rotor tip design.

Keywords Tip-leakage flow · CFD · Noise

1 Introduction

The tip-leakage flow exists extensively in rotary machine such as duct propeller, hydro turbine, jet engine and so on. This kind of high speed separate flow generated by the pressure differentials of rotor surface will induce unwanted vibration and noise which many affect comfort or destroy the structure of ship. So many investigations have be done to bring insight into the mechanism of tip-leakage flow and find method to control it to reduce the negative impact [1]. Many researches focused on the flow characters in tip clearance by numerical or experimental method, and want to explain the correlation between the tip vortex and geometry of the blade tip [2, 3].

The objective of the current work is try to find the correlation between tip-leakage vortex and its induced noise. Firstly to analyse the flow structure of tip vortex generated by NACA 0009 hydrofoil. Secondly to evaluated the noise signal of hydrofoil and investigate the differents between the noise and vorticity spectrum.

S. Zhai (✉) · Z. Xion · H. Sun
National Key Laboratory on Ship Vibration and Noise, China Ship Scientific and Research Center, Wuxi, China
e-mail: zsc_cssrc@163.com

Y. Zhou et al. (eds.), *Fluid-Structure-Sound Interactions and Control*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-10-7542-1_50

2 Model Details and Computational Method

The investigation model is a NACA0009 profile with a chord of c = 100 mm and a span of 150 mm see in Fig. 1a. This hydrofoil is mounted in the channel with the gap *t* between the blade tip and the wall, as shown in Fig. 1b, c. The incidence of the foil is 10°. The flow filed and radiated noise are simulated by commercial code Fluent in the solving condition that the Reynolds number based on the chord is 1.01×10^6. The upstream velocity at inlet is 10.2 m/s. Three kinds of tip-leakage t/c = 0.02, t/c = 0.05 and t/c = 0.1 are compared to find the differences in radiated noise and any correlation between clearance flow. The unstructured hexahedron meshes, about twenty million cells, are used in simulation, and there are at least 20 cells in clearance to capture the details flow. We use LES method with dynamics SGS model to solve the flow field and also the noise source. Then the wall fluctuating pressure generated by hydrofoil and its endplate is used as a input noise source terms of FW-H equation to predict the far field noise.

3 Results and Discussion

3.1 Flow Stucture

The tip-leakage flow structures of different clearance ratios t/c = 0.02 and t/c = 0.1 are analysed.

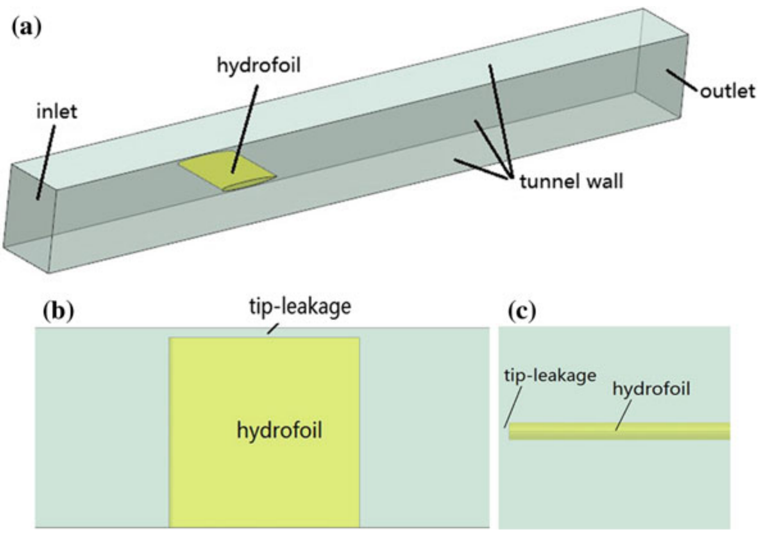


Fig. 1 **a** Computational domains, **b** top view, **c** downstream view of model

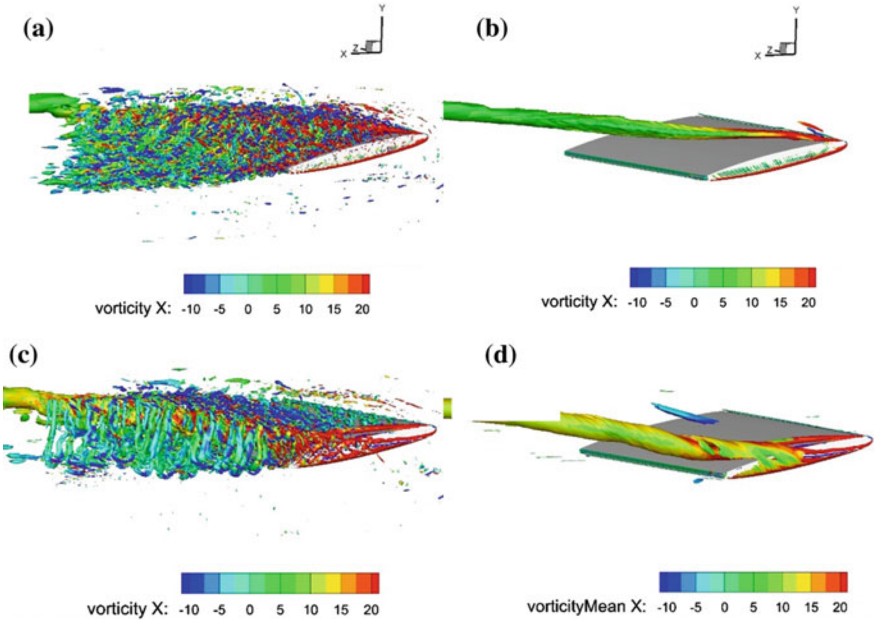


Fig. 2 Instantaneous flow field and averaged flow field: **a** instantaneous flow field of t/c = 0.02 Q = 1 isosurface, **b** averaged flow field of t/c = 0.02 Q = 1 isosurface, **c** instantaneous flow field of t/c = 0.1 Q = 1 isosurface, **d** averaged flow field of t/c = 0.1 Q = 1 isosurface

Figure 2a–d show the instantaneous and averaged flow field which is process using time average on the instantaneous results simulated by LES method. The vortex isosurface is identified by Q criterion and rendered by axial vorticity value. The boundary layer flow structures on hydrofoil, such as hairpin vortex structure as well as in tip clearance, could be seen in instantaneous results. The tip vortex, induced vortex and tip separated vortex are shown clearly in the averaged results. There are some different between t/c = 0.02 and t/c = 0.1 results. The hairpin vortex in tip clearance is richer when t/c = 0.02 and disperse when t/c = 0.1. Comparing with averaged results, when increase the scale of clearance ratio, the flow separated vortex generated on pressure surface of hydrofoil will meet the tip vortex and mixed, then the influence range of tip vortex is increased and shown broken state. This enhanced effect of tip vortex is the mechanism of the hairpin difference shown in different tip-leakage ratios. The flow field validation is in Fig. 3. The calculations are shown good agree with the experimental results [1].

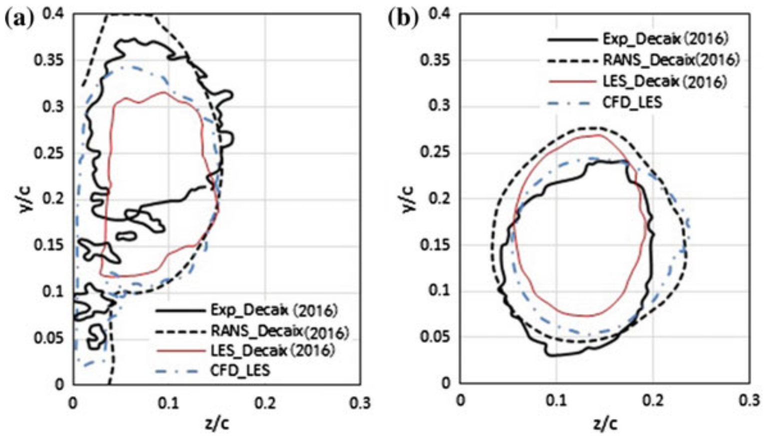


Fig. 3 Tip vortex flow validation: **a** $\omega_x^* = 2$, x/c = 1, t/c = 0.02, vortex isosurface, **b** $\omega_x^* = 4$, t/c = 0.1, x/c = 1, vortex isosurface

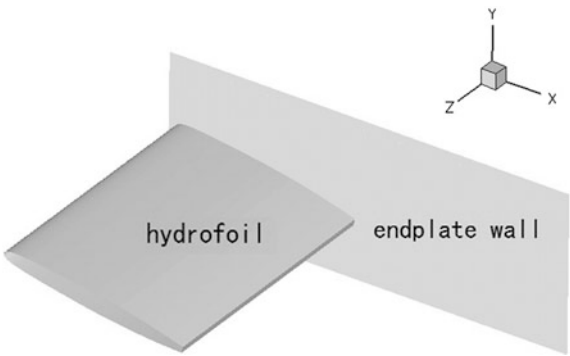
3.2 Noise

The noise results generated by different tip-leakage ratios t/c = 0.02, t/c = 0.05 and t/c = 0.1 are analysed. The acoustic receiver is at 1 m above the trailing edge on the middle chord. To collect the hydrofoil noise signal within 0.5 s, the sampling frequency is 20 kHz. The crude signal is processed by discrete Fourier analysis with hamming window and filtered by 1/3 octave filter processer.

The hydrofoil tip clearance flow is complex, the pressure gradient and the pressure fluctuation is seriously, so the noise source region contains not only the hydrofoil surface, but also the end plate close to the wing tip. As shown in Fig. 4.

Figure 5a is the 1/3OCT spectrum of foil with three different tip-leakages and the perpendicular distance from the noise calculate point to foil training edge is 1 m. In Fig. 5a, three spectrums show almost the same characters except at 1250 Hz frequency band. There is a strong peak in spectrum of foil with $t/c = 0.05$ and $t/c = 0.1$,

Fig. 4 Schematic diagram of the noise source surface



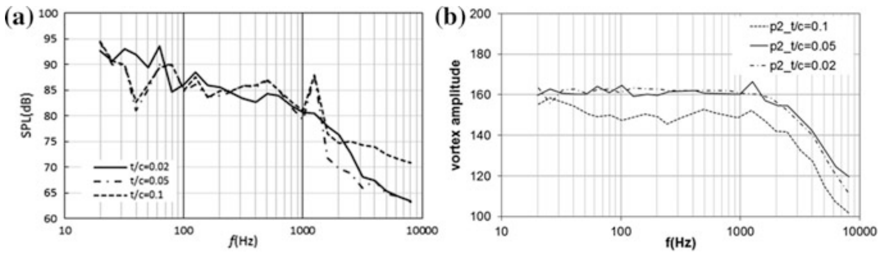


Fig. 5 **a** Acoustic spectrum level of foil with different tip-leakage, $P_{ref} = 1 \times 10^{-6}$ Pa. **b** Votrex spectrum of clearance separated flow

but without this phenomenon shows in t/c = 0.1. It is thought that the tip-leakage vortex occurs in the gap between the blade tip and the endplate because of the pressure gradient between the pressure side and suction side of hydrofoil. Some regular vortexes generated in the gap drop from the tip, when increasing the gap scale, which may excite the hydrofoil radiate noise. In order to confirm this speculation, some monitoring points were put close to the gap and to record the vorticity value with time. The spectrum analysis of vorticity time history is shown in Fig. 5b, which indicates that there is a clearly peak in t/c = 0.05 and t/c = 0.1 line. The frequency band is the same as shown in acoustic spectrum. Figure 6 is the tip vortex isosurface of the Q-criterion coloured by axial vorticity. The tip-separation vortex is well present for large gap t/c = 0.1 and vortex shedding could be seen clearly in cross section map. At small gap t/c = 0.02, the vortex is much more smaller and keeps away from the hydrofoil surface. When the tip gap is small, the tip endplate will be covered by boundary layer generated by tunnel wall. Then the pressure side vortex is hard to flow over the endplate and there is no influence to suction side vortex. The Strouhal number of the tip-leakage vortex shedding is St = $ft/u_{\text{inlet}} \approx 1.25$.

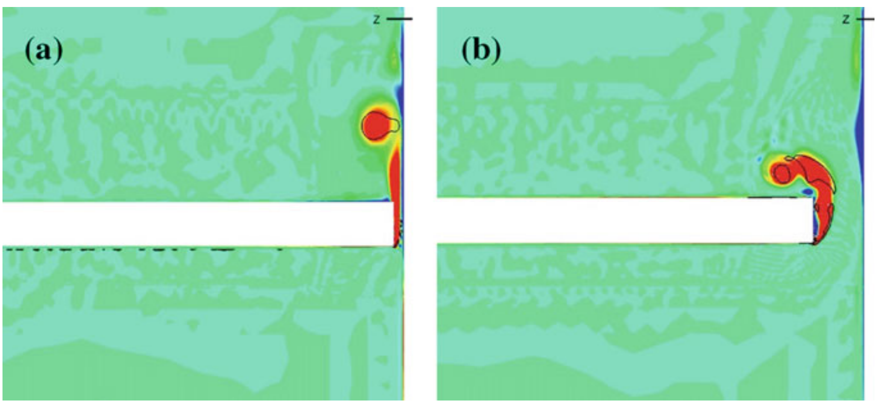


Fig. 6 The axial vorticity contoure of different tip-leakage ratio at the same x position x/c = 0.2, **a** t/c = 0.02, **b** t/c = 0.1

These characters mean that special tip-leakage could excite the acoustic peak because of the tip-separate vortex. Therefore, the results of this paper will give the designer a reference to choose gap scale of the rotary machine.

4 Conclusions

The tip-leakage flow and induced noise are analysed in this study. The LES and FW-H analogy method are used to predict the acoustic of hydrofoil with different tip-leakage ratios (t/c = 0.02 to t/c = 0.1) and incidence (10°). First, the LES computations are analysed to capture the main character of tip vortex and find their variety law with different tip-leakage ratios.

The noise results are analysed to describe the acoustic peak generated by the tip vortex. It is put in evidence that the vorticity spectrum of tip vortex also show the same peak frequency. For the small gap (t/c = 0.02), there is no tip-separation vortices are obervered. For the large gap (t/c = 0.1), the tip-separation vortices are distinct. The Strouhal number of tip vortex shedding is about 1.25.

For future works, the investigation of tip induced noise will be tested by hydrophone in laboratory and to verify the relationship between tip-separation and its shedding frequency.

References

1. Decaix J, Balarac M, Dreyer M, Farhat M (2016) RANS and LES computations of the tip-leakage vortex for different gap widths. J Turbul 16(4):309–341
2. Kato H, Taniguchi H, Matsuda K, Funazaki KI, Kato D, Pallot G (2011) Experimental and numerical investigation on compressor cascade flows with tip clearance at a low Reynolds number condition. J Therm Sci 20:481–485
3. You D, Wang M, Moin P, Mittal R (2006) Effects of tip-gap size on the tip-leakage flow in a turbomachinery cascade. Phys Fluids 18(10):683