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Method of C groove on vortex suppression and energy performance improvement for a NACA0009 hydrofoil with tip clearance in tidal energy

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Tidal energy induced by the gravitation between the earth and moon is the most widespread energy with great development potential by hydraulic machineries. Tip leakage vortex (TLV) has significant influence on the flow pattern and energy performance of hydraulic machineries. In the present work, a C groove method is proposed to suppress the TLV and improve the energy performance of a NACA0009 hydrofoil in tidal energy conversion. The numerical approach with mesh generation and Navior-Stokes equation solution is employed to evaluate the effect of C groove. The geometric and flow parameters including groove width, groove edge rotation, groove position, tip clearance size, and inlet velocity are systematically investigated. The function of the C groove is to suppress the primary TLV by groove jet impingement and weaken the secondary TLV by groove breaking flow, and then improve the flow pattern resulting in a higher energy performance. Results show that the C groove can suppress the vortex area under all conditions, and the maximum decrease of vortex area is 66.55% and 67.94% under tip clearance of 0.2 and 0.4, respectively. The C groove can improve the lift drag ratio of foil under all conditions, and the maximum increase of lift drag ratio is 2.79% and 2.10% under tip clearance of 0.2 and 0.4, respectively. With the C groove, newborn vortexes are induced, which can be classified into three types: newborn groove vortex (NGV) in groove, newborn primary TLV (NPTLV) above suction side downstream groove, and newborn secondary TLV (NSTLV) in tip clearance downstream groove.

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1. Introduction

Ocean hydropower is one of the reliable and sustainable energy sources in our world with great energy density [1,2]. The tidal energy as one kind of ocean hydropower is induced by the force of gravitational attraction from moon and sun, and can be classified into different types according to the use of potential energy and kinetic energy [3]. The flow characteristics are closely related to the energy conversion performance of hydraulic machinery [4–6], so the optimization of flow pattern and suppression of vortex are of great significance to ensure the efficiency and operation stability [7,8]. Tip clearance, despite small in dimension, will generate significant impact on the flow pattern in turbine passage because of the tip leakage vortex and its interaction with the mainstream [9,10], inducing performance drop, cavitation, vibration and so on [11–14]. Therefore, the influence of tip clearance on energy performance and the effective strategy on suppression of TLV evolution should be sufficiently investigated. The review of previous research literature is shown as Fig. 1 to provide the background, motivation, relevancy and novelty of this study.

Previous studies have been conducted to reveal the relationship between tip clearance and energy performance of hydraulic machineries. For ocean energy conversion, the performances of impulse turbine [15] and Wells turbine [16] were significantly deteriorated with the increasing of tip clearance, but a reasonable collocation of non-uniform tip clearance might optimize the overall performance in the Wells turbine. Guénette V et al. [17] found that the impact of tip clearance on bulb turbine efficiency kept strong for all guide vane angles, but the increasing of unit speed weakened this impact. Investigations on mixed-flow pump indicated that the pump efficiency and head were affected by the tip clearance size, and the relationship between them was almost linear near the design condition [9]. For an axial flow waterjet [18], the system efficiency reduced by 25% when the tip clearance increased from

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Nomenclature

TLV	Tip leakage vortex
NGV	Newborn groove vortex
NPTLV	Newborn primary tip leakage vortex
NSTLV	Newborn secondary tip leakage vortex
t_m	Maximum foil thickness
W_∞	Inlet velocity
a_1	Width of tunnel
a_2	L_t Length of tunnel
α	Incidence angle
c	Foil chord
b	Foil span
δ	Tip clearance size

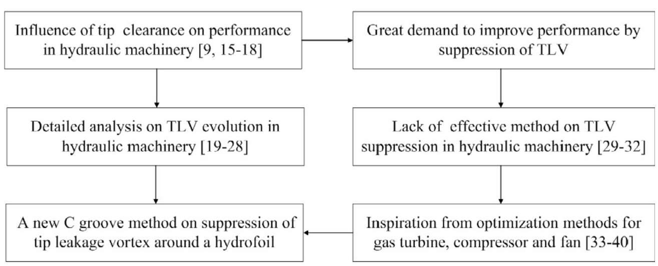

Fig. 1. Outline of previous research literature.

0.7% to 1.5% of impeller diameter. These analyses prove that tip clearance can sharply deteriorate the energy performance in hydraulic machinery, so it is of great demand to suppress the performance drop.

The performance drop, as mentioned above, is closely related to the tip leakage vortex and its induced deterioration of flow pattern. For hydraulic turbomachinery, the measurement results of Miorini and Wu [19–21] showed that the tip leakage vortex incepted near the blade tip around 20–30% chord, and grew in size when it developed into the flow passage, and finally broke down when it approached the adjacent blade. You et al. [22–24] also found that the tip leakage vortex started around 30% blade chord close to the suction side of blade tip, and proposed that the flow pattern optimization near blade tip about 30% chord might be effective to avoid cavitation and vibration. The flow pattern around NACA0009 hydrofoil for tidal energy conversion was also researched [25,26] by the Stereo-PIV and high-speed flow visualization. It was found that there was a strong relationship between the clearance size and TLV trajectory around the hydrofoil. With the increasing of tip clearance size, the TLV became closer to suction side of a hydrofoil, and the TLV trajectory downstream the trailing edge obviously shifted. However, the start location of primary TLV was about 15% chord for all the tip clearances. On basis of the experimental and simulation results of the same hydrofoil [27,28], an empirical formula law of TLV core trajectory was proposed from leading edge to about 50% chord. These findings revealed that the inception regions of TLV in different hydraulic machineries were all near the suction side of blade tip, and corresponded to a chord location under specify condition. Consequently, a local optimization method can be effective to suppress the evolution of TLV and further improve the performance of hydraulic machinery with tip clearance.

On review of the previous work, it is found that some optimization strategies have been proposed to improve the flow pattern near the tip clearance. The effect of convergent gap configuration on the cavitation performance in a shrouded underwater propulsor was evaluated experimentally [29] and the results indicated that the rounding blade corner on pressure side could restrain the gap cavitation. The improved effect [30] of twice blade tip rounding on energy performance was also found on an axial flow pump, but the TLV vorticity increased and the cavitation region enlarged. Guo et al. [31] studied the flow pattern of NACA0009 hydrofoil with a round tip and a sharp tip, and the results showed that despite the sharp tip decreased energy loss caused by the primary tip leakage vortex, the tip separation vortex near the foil tip would increase remarkably. In terms of cavitation, the sharp tip condition restrained cavitation on the foil surface, but the cavitation on foil tip in tip clearance region might be intensified. A T-shape blade tip was proposed to improve the performance of a mixed-flow pump [32], and the results indicated that this tip shape can improve the pump efficiency by 1.86% and reduce leakage flow rate by 15.95%. But this method had to modify the whole blade tip and would induce the asymmetrical radial force on the principal axis. As can be seen, above researches make positive effect on the suppression of TLV and performance drop, but they also have some negative effects and restrictions under different applications. The related research on TLV suppression in hydraulic machinery is still rare, and the effective methods to suppress TLV evolution and evaluate its influence parameters need to be further investigated.

Though the researches in hydraulic machinery are rare, there are similar and related works on TLV suppression for gas turbine, compressor and fan. The influence of flat, squealer, dimpled, chamfered, and grooved blade tip patterns on performance of a gas turbine was systematically studied [33], and the results showed that the grooved blade tip had the best overall performance. Other researches on tip patterns including flat tip, squealer tip, carved tip [34,35] were also conducted for gas turbine, and the effect of tip pattern on performance varied for different turbine types and operation conditions. For compressors, the recessed tip pattern was proposed [36,37], and the results showed that this tip pattern could successfully suppress the leakage vortex. The numerical results of a compressor [38] showed that the dovetailed-crown tip could reduce the tip leakage vortex and increases energy performance, and an optimized parameter of this tip pattern was recommended. The effect of single or double recessed tip, pressure or suction side recessed tip, and various groove tips on energy performance and noise level in an axial fan were studied [39,40]. It was indicated that recessed tip and side recessed tip could reduce the tip leakage vortex, but their effect on performance improvement was limited under the relative low pressure rise condition [39]. For different tip patterns, the direct groove tip parallel to the main flow direction presented the best effect on performance improvement, but the complex vortex pattern induced by groove resulted in the increasing of noise near the blade tip [40]. In general, it is indicated that there are already successful means, like groove method and recessed method, on suppressing tip leakage flow under wide conditions for gas turbine, compressor and fan.

From above analysis, some effective methods to suppress evolution of TLV and improve the energy performance have been proposed. However, those schemes still have some drawbacks. The recessed method induces extra vortexes in tip clearance and then results in stronger flow instability, and the groove method fails to effectively weaken the primary TLV. Meanwhile, the existing researches on schemes including tip rounding, tip thickening and convergent gap only simply evaluate their effect, and the in-depth understanding of TLV evolution and generated impact on flow pattern are still not revealed. Therefore, a new method on TLV suppression and energy performance improvement needs to be proposed, and the mechanism of this new method needs to be

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