Experimental verification of the effect of gap geometry on the tip-leakage flow pattern and tip-clearance cavitation

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Abstract. Tip-clearance cavitation is one of the most aggressive and widespread forms of cavitation in hydraulic machinery that occurs due to liquid leaking through narrow gaps between tips or end faces of blades/vanes and a stator wall. The research is aimed at the study of a passive control of tip-leakage flow and tip-clearance cavitation by modifying the gap geometry. The test object was a NACA0022-34 hydrofoil with a 100 mm chord that was equipped with a double-sided axis of rotation. The gap geometry was changed by mounting side plates with different end surfaces (flat and grooved) to the hydrofoil end face. We used high-speed imaging to analyze the temporal and spatial cavity evolution simultaneously on the foil suction side and inside the clearance using three cameras. The implemented control method was shown to allow an effective management of the tip-leakage flow and tip-clearance cavitation, especially at higher angles of attack. The modified end plate makes the tip-leakage flow less prone to cavitation as compared to the original one, i.e. the tip-clearance cavitation inception and development appear to be hampered.

1. Introduction
Tip-clearance cavitation is one of the most aggressive and widespread forms of cavitation in hydraulic machinery that occurs due to a leakage of liquid through narrow gaps between blade tips or end faces of guide vanes and a stator wall. The tip-clearance cavitation includes the following subtypes:
- gap cavitation occurring immediately inside a clearance principally in form of a cavitation sheet due to separation of the leakage flow from an extended end surface of a guide vane;
- vortex cavitation in the cores of tip-leakage vortices (TLV) that are induced by an interaction of the leakage flow coming out to the suction side of a hydrofoil with the primary one;
- tip-separation vortex (TSV) cavitation caused by the leakage flow separation and its further turbulentization and swirling inside a gap.

According to [1], in order to mitigate the tip-clearance cavitation, a gap must be as thin as possible. However, in real hydraulic equipment, the gap size cannot be made infinitesimal. That is why it is necessary to use some means to hinder the tip-clearance cavitation farther. In this context, the passive methods of flow control are more preferable as, due to a small gap thickness, the active approaches appear to be very difficult for implementation. This study aims at an experimental investigation of the tip-clearance cavitation and tip-leakage flow control by modifying the geometry of a thin gap formed by a channel sidewall and 2D hydrofoil end face. For this, vertical grooves similar to those examined...
in [2, 3] were produced on the hydrofoil end surface. The research was carried out for small and high angles of attack and various cavitation regimes.

2. Test object and measurement techniques

The experiments were conducted in the cavitation tunnel in Kutateladze Institute of Thermophysics SB RAS which test section is a 1.3 m long channel of a 80x250 mm rectangular cross-section equipped with transparent windows. The experimental rig, flow conditions, measurement techniques and data-processing procedures are described in detail in [4, 5]. A NACA0022-34 section with the chord length of \( C = 100 \text{ mm} \) was used as a test object. The hydrofoil was equipped with a double-sided axis of rotation with the diameter of \( D = 21.1 \text{ mm} \) that was positioned in its geometric center and, thus, did not exceed its borders (Figure 1-a). In order to guarantee the gap between the foil end face and the test section sidewall, the hydrofoil was made composite: it consisted of the main body of a 65 mm span and a set of replaceable end plates that replicated the foil shape and were attached tightly to the main body (Figure 1-a).

![Figure 1. 3D models of a NACA0022-34 hydrofoil with a double-sided axis of rotation with (a) flat and (b) grooved end faces and schematics of the gap geometry for (c) the flat and (d) grooved end surfaces: \( d \) and \( l \) are the groove diameter and depth, \( e \) is the distance between neighboring grooves and \( w_1 \) and \( w_2 \) are the minimum gap widths for the two cases considered. The joint line denotes a line along which the foil main body and the end plates are connected together.](image)

In the present research, two end plates with different end face geometries were used. The surface of the first one was flat (Figure 1-a, c) while, on the other, vertical grooves were milled (Figure 1-b, d). The groove parameters were selected to be optimal according to [2, 3]: \( d = 2 \text{ mm}, \ l = 1 \text{ mm}, \ e = 1 \text{ mm} \) (Figure 1-d). The first and last grooves in the nose and aft parts of the profile were located at the distance of 1 mm from the leading and trailing edges, respectively. In order to compare the results for both cases accurately, the gap cross-section area was made identical for the flat and grooved end faces:

\[
(C-D)\cdot w_1 = N\cdot \pi d^2/8 + (C-D)\cdot w_2,
\]

where \( N = 26 \) is the overall number of the grooves, \( w_1 = 0.8 \text{ mm} \) (Figure 1-c) and \( w_2 = 0.3 \text{ mm} \) (Figure 1-d) are the minimum thicknesses of both clearances. There were no grooves above and below the
rotation axis (Figure 1-b). The clearance was produced only from the side of transparent sidewall whereas, on the opposite side, it was absent (Figure 2).

Figure 2. Schematic of the hydrofoil disposition in the test section (top view). The joint line denotes a line along which the foil main body and the end plates are connected together. \( w_2 \) is the minimum width of the grooved gap.

The investigation was performed for the attack angle \( \alpha = 3^\circ \) and \( 9^\circ \). Different flow conditions were achieved by varying the cavitation number \( \sigma = (p_{in} - p_V)/(\rho U_0^2/2) \) in the range from 1.74 to 0.79 for \( \alpha = 3^\circ \) and from 3.97 to 1.31 for \( \alpha = 9^\circ \) by changing the mean flow velocity \( U_0 \) from 7.75 to 12.99 m/s. Here, \( p_V \) is the saturation vapor pressure of the operating liquid (distilled water), \( \rho \) is the liquid density and \( p_{in} \) is the static pressure that was gauged at a sidewall close to the inlet of the test section by a pressure transducer. \( U_0 \) was measured by PIV in the central longitudinal plane of the test section far upstream of the hydrofoil position. The Reynolds number \( Re = CU_0/v \), where \( v \) is the kinematic viscosity of the operating liquid, equaled to \( 1.3 \cdot 10^6 - 1.6 \cdot 10^6 \) for \( \alpha = 3^\circ \) and \( 0.97 \cdot 10^6 - 1.44 \cdot 10^6 \) for \( \alpha = 9^\circ \). The Strouhal number was defined as \( St = fL_{C_{max}}/U_0 \), where \( f \) is the frequency of oscillations of a cavitation sheet length or cloud cavity shedding and \( L_{C_{max}} \) is the maximum length of an attached cavity on the foil suction side.

In order to study the spatial patterns and dynamics of gas-vapor cavities and evaluate their integral parameters such as the maximum (for unsteady regimes) and average (for steady flow conditions) length of a cavitation area (streamwise dimension of the region on the foil suction side where the cavitation occurs), periods of cavity oscillations, characteristic frequencies of cloud shedding process and the maximum size of travelling bubbles, we employed a high-speed imaging. The visualization was performed at the sampling rate of 20 kHz with an optical magnification of 0.11 using three Photron FASTCAM SA5 CMOS-cameras (digit capacity 12 bits, resolution 1024x1024 pix., acquisition rate 7 kHz) equipped with Nikon AF Nikkor 50 mm f/1.4D and Nikon AF Micro-Nikkor 60 mm f/2.8D lenses. The cameras were mounted in different positions: from top, from side and at the angle of 25° with respect to the hydrofoil.

3. Results

3.1. Small angle of attack

At the low attack angle \( \alpha = 3^\circ \), tip-clearance cavitation is first initiated at the cavitation number of \( \sigma = 1.54 \) and 1.84 for the flat and grooved end faces, respectively. For the flat face, the tip-clearance cavitation occurs in form of a cavitation sheet close to the foil leading edge. In case of the grooved end, cavitation arises inside the hollows as a street of traveling bubbles that presumably appear in the cores of vortices oriented along the valleys. These vortices resemble streaks by nature in a bypass transition to turbulence. Thus, the grooves are favorable for the tip-clearance cavitation inception. However, transition to unsteady regimes in case of the grooved end face occurs on the contrary at a lower cavitation number (\( \sigma = 0.77 \)) than that for the flat end (\( \sigma = 0.89 \)) (Figure 3). As expected, this may be linked with the fact that local cavitation in the grooves makes the shape of the end surface fuller or, in other words, it becomes closer to the flat one. That is why the gap area at least in the foil
nose part is decreased and the tip-leakage flow rate is limited. Thus, the grooves allow a slight mitigation of the tip-cavitation development.

![Figure 3](image)

**Figure 3.** Instantaneous images of the main cavity on the foil suction side (top view) and tip-clearance cavitation (side view) for the (a) flat ($\sigma = 0.83$, St = 0.11) and (b) grooved ($\sigma = 0.78$, St = 0.11) geometry of the gap between the foil end face and the test section sidewall for unsteady flow conditions when the cavity length is $L_{c}^{\text{max}}/C = 0.63$. The attack angle is $\alpha = 3^\circ$. The flow direction is from the left.

### 3.2. Large incidence angle

At the higher foil inclination $\alpha = 9^\circ$, the grooves turn out to be in general more effective as compared to the smaller angle of attack. For the flat face, cavitation in the clearance starts to develop at $\sigma = 3.81$ but, in the grooves, it becomes visible only when $\sigma = 1.92$. Examples of steady cavitating flows for both cases are shown in Figure 4. Transition to unsteady flow conditions occurs at $\sigma = 1.47$ and 1.19 for the flat and grooved surfaces, respectively (Figure 5). The lengths of cavitating vortex cores in the grooves (and, thus, the strength of the vortices) are changed depending on the phase of evolution of the main cavity on the foil suction side as for the case without hollows. When the primary cavity reaches its maximum length, the pressure on the suction side drops, the pressure gradient along the clearance increases and the tip-clearance cavitation becomes more pronounced and vice versa. Thus, it can be concluded that at higher incidence angles the grooves appear to be more effective.
Figure 4. Instantaneous images of cavitation on the foil suction side (top view) and tip-clearance cavitation (side view) for the (a) flat ($\sigma = 1.55$) and (b) grooved ($\sigma = 1.42$) geometry of the gap between the foil end face and the test section sidewall for steady flow conditions when the cavity length is $L_c/C = 0.4$. The attack angle is $\alpha = 9^\circ$. The flow direction is from the left.

Figure 5. Instantaneous images of the main cavity on the foil suction side (top view) and tip-clearance cavitation (side view) for the (a) flat ($\sigma = 1.34$, $St = 0.1$) and (b) grooved ($\sigma = 1.12$, $St = 0.11$) geometry of the gap between the foil end face and the test section sidewall for unsteady flow conditions when the cavity length is $L_c^{\text{max}}/C = 0.64$. The attack angle is $\alpha = 9^\circ$. The flow direction is from the left.
4. Conclusions
Using a high-speed imaging and local pressure measurements, the inception and evolution of tip-clearance cavitation along with the primary cavity on the suction side of a NACA0022-34 hydrofoil was investigated for the attack angle of 3° and 9° and the two gap geometries – flat and grooved – of the same cross-section area. It was shown that, at the small incidence angle, the grooves induce vortices and, thereby, provoke the inception of tip-clearance cavitation, i.e. the tip-leakage flow becomes more prone to cavitation. However, they allow a slight mitigation of tip-clearance cavitation development by hindering the transition to unsteady flow conditions. At the higher foil inclination, the passive control turns out to be very effective as it allows a substantial hampering of tip-clearance cavitation for both cavitation inception conditions and transition to unsteady regimes.

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