Mind the gap - tip leakage vortex in axial turbines

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Abstract. The tendency of designing large Kaplan turbines with a continuous increase of output power is bringing to the front the cavitation erosion issue. Due to the flow in the gap between the runner and the discharge ring, axial turbine blades may develop the so called tip leakage vortex (TLV) cavitation with negative consequences. Such vortices may interact strongly with the wake of guide vanes leading to their multiple collapses and rebounds. If the vortex trajectory remains close to the blade tip, these collapses may lead to severe erosion. One is still unable today to predict its occurrence and development in axial turbines with acceptable accuracy. Numerical flow simulations as well as the actual scale-up rules from small to large scales are unreliable. The present work addresses this problematic in a simplified case study representing TLV cavitation to better understand its sensitivity to the gap width. A Naca0009 hydrofoil is used as a generic blade in the test section of EPFL cavitation tunnel. A sliding mounting support allowing an adjustable gap between the blade tip and wall was manufactured. The vortex trajectory is visualized with a high speed camera and appropriate lighting. The three dimensional velocity field induced by the TLV is investigated using stereo particle image velocimetry. We have taken into account the vortex wandering in the image processing to obtain accurate measurements of the vortex properties. The measurements were performed in three planes located downstream of the hydrofoil for different values of the flow velocity, the incidence angle and the gap width. The results clearly reveal a strong influence of the gap width on both trajectory and intensity of the tip leakage vortex.

1. Introduction

Cavitation erosion in large axial turbines, namely Kaplan, bulb and propellers, is still a serious issue for designers and operators as well. The gap, or clearance, between blade tip and casing results in a leakage flow crossing the tip form the pressure side to the suction side of the blade. This flow rolls up into the so called tip leakage vortex (TLV) raising the risk of cavitation occurrence in the vortex core, see figure 1. Depending on the trajectory of the vortex, severe erosion may be observed in the tip of the blades or in the discharge ring. The aggressiveness of the TLV cavitation may be amplified by a strong interaction with the wake of the guide vane. The rotor-stator interaction may actually modulate the vortex cavitation with strong and repetitive collapses and rebounds [1][2]. In this case, periodic inspections and repairs are required leading to an increase of operational cost.

Despite the progress achieved so far in the issue of tip vortex cavitation, mainly for marine propellers, one is still unable today to predict the onset and development of TLV cavitation in axial turbines with acceptable accuracy. Neither numerical simulations, nor model testing are able to provide reliable prediction of this phenomenon. In fact, besides Reynolds number, such cavitation is very sensitive to the gap width and nuclei content in water [3]. Obviously, these

parameters are very hard to control during reduced scale model tests. As a consequence, it is possible to observe severe erosion on a Kaplan prototype while no cavitation was visible at the small scale tests. The numerical computation of tip vortex cavitation is still a challenging task. The limited mesh resolution typically leads to an underestimation of the streamwise vorticity and poor performance in predicting the onset of TLV cavitation [4].

Farell and Billet [5] have investigated the influence of the gap width on the leakage vortex cavitation in an axial pump. They pointed out an optimum dimensionless gap, defined as the ratio of the gap width to the blade thickness, around 0.2 to prevent TLV cavitation. However, real life turbine prototypes tend to run with the smallest possible gap to minimize the leakage flow and efficiency losses. Normal operating gaps are in the order of a few millimeters, resulting in a dimensionless gap typically between 0.01 and 0.1. Moreover, the gap width may change over operating time due to blade tip erosion. Axial turbine designers sometimes use the so called anti-cavitation lip, which is a metallic piece attached to the blades tip. Such a remedy does not suppress erosion but displaces it on the anti-cavitation lip.

Reliable design rules for axial turbines are still lacking to avoid premature damage of the blades and the discharge ring. It is still not clear how the clearance flow influences the vortex formation and cavitation occurrence. To gain better insight into the physics of TLV cavitation, the present work addresses this problematic in a simplified case study. The sensitivity of the TLV to the gap width is measured quantitatively via stereo particle image velocimetry and high speed flow visualizations.
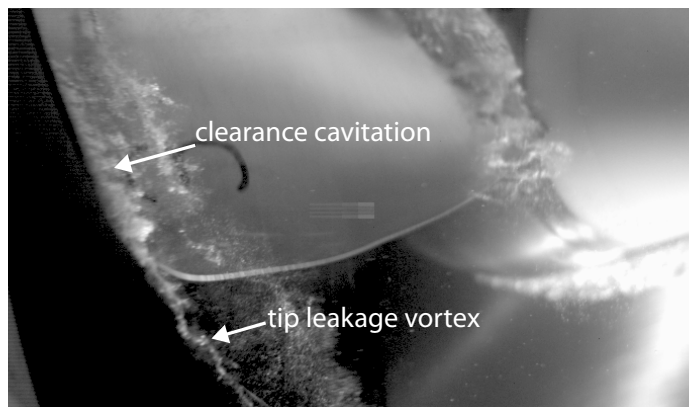

Figure 1. Tip leakage vortex and clearance cavitation in a bulb turbine reduced scale model.

2. Current procedures for reduced scale model testing
The International Electrotechnical Commission (IEC) 60193 standard [6] establishes the rules for reduced scale model testing. The objective of the standard is to guarantee for prototype hydraulic performance, computed from model test results considering scale effects. A basic requirement is to have geometrical similarity between model and prototype. consequently, all the water passages influencing the performance of the prototype should as far as possible be homologous to the prototype.

Concerning the blade tip clearances, the procedure consists in measuring the uniformity of the clearances and checking the accuracy of the similarity between model and prototype. The maximum permissible deviations are given in the table 1. The IEC standard specifically asserts that the relative difference of the tip clearance between the average prototype value and the corresponding scaled model average value must be negative or zero, i.e. *"the prototype clearances shall not exceed the scaled model clearances"*. On the other hand, the uniformity tolerance, i.e. the relative deviation between the individual values of blade tip clearance and the corresponding average value, is set to $\pm 50\%$. This implies that locally, the deviation between the prototype

and the scale model clearance can deviate up to a factor 3. What are the implications regarding hydraulic performances? IEC states that as long as the deviations in geometric similarity are within the limits specified by table 1, the formula for hydraulic efficiency scale-up remains valid. However, no directive is given regarding the influence of the clearance size on the prediction of TLV cavitation from model testing.

From a practical point of view, the dimensions of the tip clearance during model testing are dependent on several factors. Mechanical considerations limit the gap width to a least 0.2 mm to prevent any contact with the casing during the tests. Depending on the scaling factor between prototype and model, it is thus not always possible to respect geometric similarity of the clearances. Moreover, the dimensions of the clearances are checked with the runner at rest and dewatered, i.e. no real time monitoring of the gap width is set up while the turbine is running. During a standard cavitation test, the Thoma number is varied by applying a partial vacuum at the runner exit. The resulting pressure stresses on the runner casing and diffuser, often made of Plexiglas, may therefore affect the gap width. Thermal expansion and contraction due to temperature difference between the assembly hall and the water, especially during winter, can also easily change 0.1-0.2 mm in the clearance size. All these aspects suggest that it is very hard to satisfy the clearance geometrical similarity during model testing. But above all, there is a deep lack of knowledge about the sensitivity of the TLV cavitation to the gap width. Is it possible that slight discrepancies in the clearance similarity between the prototype and the model affect noticeably the tip leakage vortex cavitation?

Table 1. Permissible maximum deviations in geometrical similarity between prototype and model turbine, IEC 60193 standard [6].

	Permissible maximum deviation		
	Uniformity tolerance		Similarity tolerance
	Model	Prototype	Prototype/Model
	Individual value to average value	Individual value to average value	Prototype average value to scaled model average value $(L_P-\lambda_L L_M)/$(reference value) [1]
Clearances Seal and blade tip clearance Seal clearance length Guide vane end clearances	± 50 % - ± 50 %	± 50 % - ± 50 %	≤ 0 ≥0 ≤0
[1] The reference value is taken to be the scaled model average value ($\lambda_L L_M$,) unless otherwise indicated. Angular tolerance is the difference between prototype and model angles.			

3. Case study and methodology

The influence of the gap width on the TLV strength and cavitation is investigated on a simplified case study. A Naca0009 hydrofoil with a 100 mm chord is used as a generic blade in the test section of EPFL cavitation tunnel. The foil maximum thickness is 10 mm. The test section dimensions are $150\times150\times750$ mm and the walls are made of 80 mm Plexiglas for a good optical access to the flow. The operating flow parameters are the inlet velocity V_∞, the pressure in the test section and the foil incidence angle. The hydrofoil is mounted on a sliding mounting support allowing an adjustable gap width between the blade tip and wall. The gap can be varied smoothly between 0 to 20 mm. A strip of distributed roughness (4 mm wide, 25 μm diameter sand) is applied to the foil leading edge in order to trip the turbulent boundary layer.

The three dimensional velocity field induced by the TLV is investigated using stereo particle image velocimetry in cavitation free regime. A double pulsed YAG laser provides a 2 mm wide laser sheet, perpendicularly to the vortex axis as it is shown in figure 2. Pairs of images were acquired using two cameras viewing the scene with a 30° angular shift. The test section

window is equipped with a water box to mitigate the optical distortion. To avoid parasitic light scattering, the seeding is ensured by 20 μm fluorescent particles, produced in-house [7], and the cameras are equipped with long pass optical filters. Velocity fields are computed via an adaptive multi-pass correlation algorithm, which adjusts the size and shape of the individual interrogation areas (IA) with the local seeding densities and flow gradients. The criterium for the IA size is the presence of at least 8 particles and a minimum of 16×16 pixels. A total of 182×120 velocity vectors with a spatial resolution of about 0.6 mm is finally obtained. The distance from the wall of the first measured velocity vector is approximately 0.2 mm.

Velocity measurements are performed in three planes, located 1, 1.2 and 1.5 chords downstream of the hydrofoil, for different values of the flow velocity and foil incidence angle (3°, 5°,7°,10°,12°). For each operating condition, the clearance between the blade tip of the hydrofoil and the test section wall is varied in a range of 0 to 20 mm, corresponding to a dimensionless gap between 0 and 2. The mean three dimensional velocity fields are determined after processing 100 individual vector fields. It was verified that increasing this number did not affect the mean vortex characteristics. The vortex wandering is a typical feature of tip vortices and it consists in random fluctuations of the vortex core. If not filter out in the averaging process, vortices appear to be more diffuse than in reality [8]. To avoid this effect, each individual velocity field is shifted in order to align all the vortex centers before averaging. The vortex viscous core radius is then estimated by a best fit of the Lamb-Oseen model over the experimentally measured velocity profiles. Typical values of approximately 3.5 mm are obtained.

The vorticity is computed by the numerical differentiation of the velocity field. The derivatives are estimated with a fourth-order Richardson extrapolation scheme. To minimize bias errors and avoid any undesirable effect of the differentiation of noisy field, the spatial sampling resolution of the velocity field is increased via a cubic spline interpolation.

Finally, cavitation in the TLV core is also used as a tracer to follow the vortex trajectory. A high speed camera with a powerful 11 ms lighting is used to visualize the gap width effect on the TLV dynamic at 20,000 FPS.
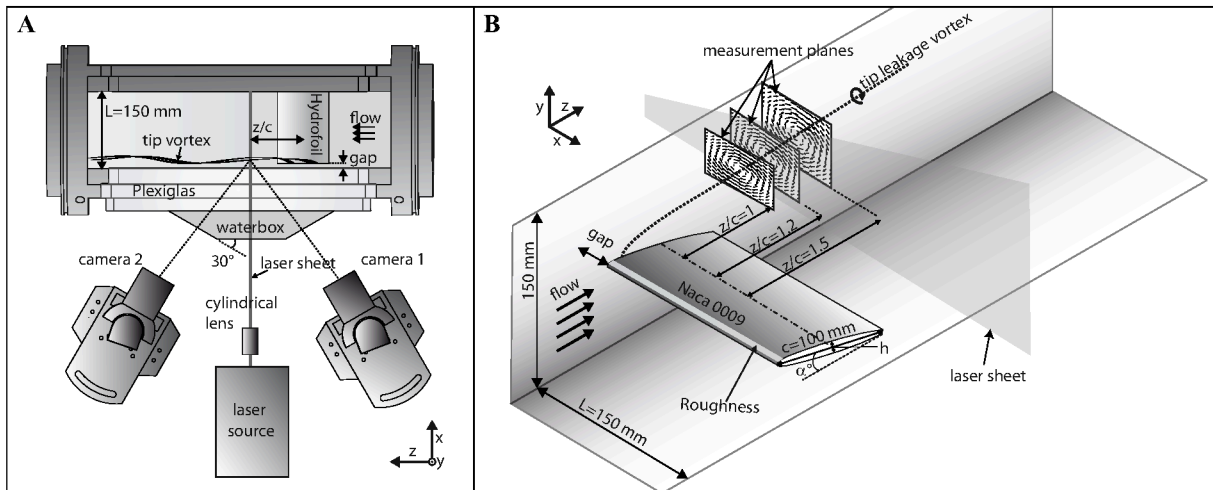

Figure 2. Stereo PIV configuration for the velocity field measurements. **A**: top view of the tunnel test section and optical instruments. **B**: isometric view of the inlet test section with the three measurement planes.

4. Result and discussion

4.1. Gap width and TLV intensity

Figure 3 depicts the influence of the dimensionless gap on the TLV intensity for an incidence angle of 5°. The symbols represent the evolution for four inlet velocities and the solid line is the mean value. At a fixed incidence angle, the vortex strength is proportional to the inlet velocity according to the Kutta-Joukowski theorem. The vorticity in the vortex center is thus normalized by the inlet velocity and foil maximum thickness to merge the data on a single curve.

The existence of a specific dimensionless gap, around 0.3, for which the vortex strength is maximum and is the most prone to generate cavitation is clearly revealed. If the dimensionless gap is reduced below 0.3, the vortex intensity drops very sharply toward zero, corresponding to the TLV disappearance in the absence of gap. In fact the vortex become so weak below the dimensionless gap 0.06 that it is no longer clearly identifiable. For dimensionless gap higher than 0.3, the vortex intensity decreases gradually toward an asymptotic value for which the wall influence is negligible. For sake of readability, the figure depicts only the measurements acquired one chord behind the hydrofoil at a fixed incidence angle. The value of the specific dimensionless gap depends on the foil incidence angle but similar trends are observed for all operating conditions.

To minimize energy losses, axial turbines are generally operated with a dimensionless gap between 0.01 and 0.1, where the sensitivity of the TLV intensity to change of gap width is very high. The theoretical maximum TLV intensity is thus avoided. The IEC standard allows a gap that may deviate locally up to a factor 3 between the prototype and the scaled model, cf. table 1. The normalized TLV intensity varies thus potentially by the same factor. The pressure drop causing the onset of cavitation in the vortex center is proportional to the ratio of the vortex strength to core size, squared [3]. Since no significant evolution of the vortex core size was observed, the pressure within the vortex is believed to decrease as the dimensionless gap is increased (up to 0.3).

The discrepancies in TLV cavitation occurrence between reduced scale models and prototypes are often explained by the non similarity of nuclei content and Reynolds number. In fact, the cavitation inception index scales with the squared root of Reynolds number [9]. Nevertheless, the present study suggests that besides these effects, the influence of the gap width is another important parameter that has to be taken into account.
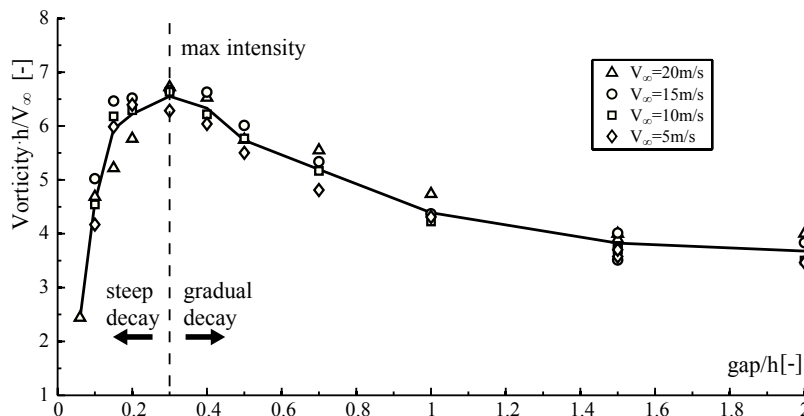

Figure 3. Evolution of the normalized vorticity in the center of the TLV as a function of the dimensionless gap. The foil incidence angle is 5°. The solid line is the mean value.

4.2. Influence on the TLV cavitation

The stereo PIV measurements have highlighted the existence of a specific gap width for which the vortex strength is at maximum. However, the velocity measurements were performed downstream to the hydrofoil in cavitation free regime. High speed visualizations of the cavitating

TLV were performed to evaluate the effect of the gap width on the vortex trajectory and cavitation. The figure 4 (Left) illustrates arbitrary instantaneous captures of the cavitating TLV with different gap widths, side view. The flow is coming from the right at 15 m/s, the incidence angle is set to 5° and the pressure, hence the cavitation number is kept constant for all cases. To assess the mean TLV trajectory, we have summed the images captured during 11 ms at 20,000 FPS. The result is given in figure 4 (Right) for the same conditions. The scatter of cavitation bubbles in the vortex core unveils the wandering amplitude of the TLV.

The amount of cavitation in the TLV is related to the intensity of the vortex. It clearly appears that the vortex reaches a maximum intensity at the dimensionless gap 0.3. On the other hand, the amount of cavitation in the TLV downstream to the hydrofoil is similar for the dimensionless gap 1 and 0.1. These observations are in good agreement with the vorticity measurements in cavitation free regime, cf. figure 3.

The trajectory of the TLV is highly dependent of the wall proximity. The smaller the gap, the more the vortex is pulled away from the hydrofoil. This effect can be explained by considering the image vortex, symmetrical to the actual tip vortex with respect to the confinement wall. This latter induces an upward velocity on the actual TLV, displacing the vortex axis away from the hydrofoil. The change in slope of the TLV trajectory downstream to the the foil trailing edge is another feature of the vortex image system. At this location, the downward velocity induced by the image vortex due to the foil suddenly disappears, resulting in an abrupt change of the vortex trajectory [10]. This is particulary visible if the TLV remains relatively close to the foil along the chord, as it is the case for gap/h=1 and gap/h=0.7. Despite the limited duration of the flow visualizations of 11 ms, multiple independent recordings showed that the vortex trajectory is very stable spatially. Moreover, comparisons with PIV measurements revealed that the vortex center location is virtually unaffected by the cavitation in its core.

Cavitation in the clearance region also appears when the gap is reduced, see for example gap/h=0.3 and gap/h=0.1. This results from boundary layer separation in the gap and can be reduced if the pressure side of the hydrofoil edge is rounded [11]. Clearance cavitation should be avoided as it sheds a large amount of nuclei downstream. These nuclei may gather in the low pressure region in the vortex center, raising the risk of cavitation occurrence. As the gap is reduced, the vapor strips well visible in the clearance indicate that the flow turns from streamwise to upward jet.

5. Conclusion

The influence of the gap width on the tip leakage vortex has been studied in a simplified case study: a NACA0009 was used as a generic blade in a water tunnel and the gap was varied by means of a sliding mounting support. Quantitative measurements of the TLV were performed using stereo particle image velocimetry downstream to the hydrofoil while high speed flow visualizations revealed the cavitating vortex trajectory.

Results clearly show a strong influence of the gap width on both trajectory and intensity of the TLV. As the gap scaled by the blade thickness is reduced from 2 to 0, the vortex intensity increases to a maximum, at the dimensionless gap 0.3, before falling down abruptly. The region of large vortex strength variation with the gap width corresponds precisely to the operating clearances for axial turbines. Since clearance similarity is hard to satisfy in model testing, the TLV sensitivity to the gap width may explain the occurrence of severe erosion on a Kaplan prototype while no cavitation was visible at the small scale tests.
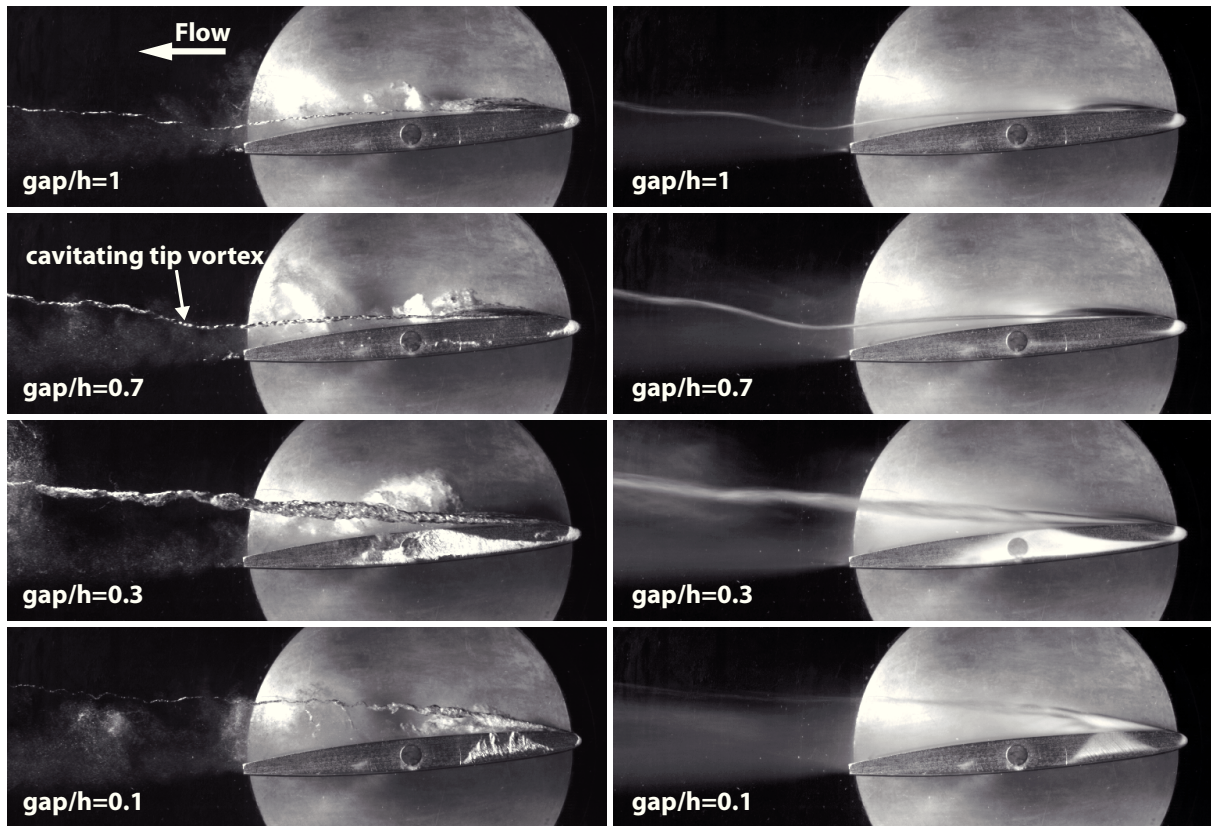
Figure 4. Left: Sapshots of the cavitating TLV generated by a NACA0009 with different gap widths. Right: superposition of the cavitating TLV visualizations during 11 ms. Flow conditions: velocity=15 m/s, cavitation number=1, incidence=5°.

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