Effect of gap size on tip leakage cavitation inception, associated noise and flow structure.

Shridhar Gopalan and Joseph Katz
The Johns Hopkins University, Baltimore MD

Han L Liu
Formerly, Naval Surface Warfare Center, West Bethesda, MD, USA

Abstract

This paper focuses on the onset of tip-leakage cavitation on a fixed hydrofoil. The objectives are to investigate the effect of gap size on the flow structure, conditions of cavitation inception, the associated bubble dynamics and cavitation noise. The same hydrofoil with three tip gap sizes of 12%, 28% and 52% of the maximum tip thickness are studied. Controlled cavitation tests are performed after de-aerating the water in the tunnel and using electrolysis to generate cavitation nuclei. The experiments consist of simultaneously detecting cavitation inception using a 2000fps digital camera (visual) and two accelerometers (“acoustic”) mounted on the test-section windows. Good agreement between these methods is achieved when the visual observations are performed carefully. To obtain the time dependent noise spectra, portions of the signal containing cavitation noise are analyzed using Hilbert-Huang transforms. Rates of cavitation events as a function of the cavitation index ($\sigma$) for the 3 gap sizes are also measured. The observations demonstrate that high amplitude noise spikes are generated when the bubbles are distorted and “shredded” – broken to several bubbles following their growth in the vortex core. Mere changes to bubble size and shape caused significantly lower noise. High resolution Particle Image Velocimetry with a vector spacing of 180$\mu$m is used to measure the flow, especially to capture the slender tip vortices where cavitation inception is observed. The instantaneous realizations are analyzed to obtain probability density functions of the circulation...
of the leakage vortex. The circulation decreases with increasing gap sizes and minimum pressure coefficients in the cores of these vortices are estimated using a Rankine model. The diameter of the vortex core varied between 540 – 720 \( \mu \)m. These coefficients show a very good agreement with the measured cavitation inception indices.

1. Introduction

Cavitation occurs in liquid flows when a nucleus (bubbles, particles etc.) is captured in a region where the pressure is lower or equal to the vapor pressure (Arndt 1981, Brennen 1995). Such low-pressure regions could be at the cores of vortical structures that frequently occur in shear flows (Arndt 1981, Katz & O’Hern 1986, O’Hern 1991, Ran & Katz 1994, Belahadji et al. 1995, Gopalan et al. 1999). Experimental studies on tip vortex formation and resulting cavitation have been addressed (for e.g.) by Higuchi et al. (1989), Maines and Arndt (1997) and a numerical study of steady-state tip vortex aimed at predicting the core pressure has been reported by Hsiao & Pauley (1998). Several papers in recent years have dealt with cavitation in tip leakage or tip clearance flows, i.e. cases where the wing tip is located near a solid boundary leaving only a narrow gap. A tip leakage vortex develops as a result of the clearance between the tip and the wall, which is prone to cavitation (Farrell & Billet 1994, Boulon et al. 1999). Farrell and Billet (1994) examine the effect of gap size on tip leakage cavitation in a rotating turbomachine and find that for narrower gaps the cavitation inception indices decrease with increasing gap sizes. They also find a minimum in the cavitation inception index near \( \lambda =0.2 \); \( \lambda \) being the ratio of tip gap size to the maximum tip thickness. Conversely, experiments performed by Boulon et al. (1999) in a setup similar to the present study, i.e. no relative motion between the tip and the end wall, do not show a minimum in the cavitation inception index. This
trend is consistent with the present observations and can be explained using a potential flow model, elaborated in Boulon et al. and discussed briefly in section 4 of this paper.

The present paper provides high magnification, high-speed photographs of bubbles during cavitation in the tip leakage vortex along with simultaneous measurements of the resulting noise. The observations demonstrate clearly that high noise spikes occur when the bubbles break-up in the vortex core. Mere oscillations in bubble size and shape cause significantly lower amplitude signals. Detailed measurements of the velocity and thus vorticity and circulation of the tip leakage vortex along with vortex core size are used for estimating the minimum pressure coefficients in the core. These coefficients compare well to the cavitation inception indices. The following are addressed: (i) cavitation inception measurements using visual and acoustic techniques, (ii) a comparison between the acoustic signal and the visual occurrence of cavitation, including a detailed spectral analysis of the signal, (iii) the strength of the tip leakage vortex and the effect of gap size on the leakage flow characteristics. The same hydrofoil with three tip gap sizes of 0.6, 1.4 and 2.6mm are studied, corresponding to $\lambda = 0.12$, 0.28 and 0.52 respectively.

2. Experimental set up and procedure

The tests are performed in a specially designed water tunnel located at The Johns Hopkins University (figure 1a). The 6.35 x 5.08 cm$^2$ test section has a minimum length of 41 cm and maximum entrance velocity of 13 m/s, although the present tests were performed at 5 m/s. The flow is driven by two 11KW centrifugal pumps located 4m below the test section to prevent pump cavitation. The facility has windows (made of optical grade lucite) on four sides to enable easy access for PIV measurements. The constant chord hydrofoil with a chord length of 50mm
and a span of 50 mm is attached to a side window and its tip has a small clearance with the opposite side window (figure 1b). The maximum tip thickness is 5mm (at mid-chord) and the hydrofoil is loaded towards the tip. The estimated spanwise distribution of the lift coefficient at an 0° incidence angle is shown in figure 2. The clearance (or gap) size is varied by varying the thickness of the side window located next to the tip. Boundary layer suction followed by tripping is used on the wall near the tip as shown in figure 1b (side view) to generate a fully developed turbulent boundary layer on the wall.

The free stream velocity in the test-section is fixed at 5 m/s, which corresponds to a Reynolds number $Re_c$, based on chord, $c$ equal to $2.5 \times 10^5$. Plots of cavitation index, $\sigma$ versus the rate of cavitation events, $r_c$, where $\sigma = (P_0 - P_v)/0.5\rho V^2$, $P_0$ is the ambient pressure in the test section, $P_v$ is the vapor pressure and $V$ is the free-stream velocity are obtained in nuclei controlled conditions. The cavitation index is regulated by varying the ambient pressure in the test chamber. The air content is reduced to about 3 ppm by keeping the facility under vacuum for extended periods and the dissolved oxygen content measured using an oxygen meter. The cavitation nuclei are supplied by electrolysis using two vertical wires, located in the settling chamber upstream of the test section next to the honeycombs shown in figure 1a. The bubble generation rate, approximately 2500/s can be controlled by varying the current through the electrodes. The nuclei size distribution generated by this setup is measured using silhouette photographs at high magnification (following the procedure described in Gopalan et al. 1999). As the distribution shown in figure 3 indicates, the bubble diameters vary between 50-250 $\mu$m with a median at approximately 100 $\mu$m.

Two accelerometers (PCB309A, made by PCB Piezotronics) with a resonant frequency of 120kHz were used to detect cavitation events. As shown in figure 4a, one sensor is attached to
the side window and the other to the bottom window, both at the vicinity of the blade trailing edge. A high-speed camera (Kodak Ektapro EM Motion Analyzer, Model 1012) operating at 2000fps is used to record images of the cavitating bubbles in the tip leakage vortex. The timing of the image acquisition is synchronized with the accelerometer signal. Careful comparisons, examples of which are shown in this paper, result in a good correlation between the physical appearance of the bubbles and the accelerometer signal. A Data Translation, 12 bit, A-D board capable of sampling rates up to 1 MHz is used for acquiring the accelerometer signals and the signal from the stroboscope. The data is acquired at 250kHz/channel using LabView based software. Using an in-house code, the accelerometer signals are analyzed for counting the rate of cavitation events and for tagging the high-speed frames (example - figure 5). Each data point in figure 6 is based on a 10 s long signal sampled at 250kHz. The code used to count the cavitation events, first identifies points in the signal with amplitudes greater than 1.2V and then searches for amplitudes ≥ 3.3 V in a time interval of 0.06ms from the original point. If it finds such points it is counted as an event. In order to avoid counting the same event more than once, the program jumps 1.4ms after finding an event and then continues.

PIV experiments are performed using a system described in Roth et al. 1995, Roth & Katz 2001. The light source is Nd:YAG laser and images are recorded using a 2Kx2K pixel² digital camera with built in image shifting. Fluorescent particles are used as tracers and a filter in front of the camera lens filters out the incident green light (Sridhar & Katz 1995, Gopalan & Katz 2000). An inclined light sheet (figure 4b) is necessary to measure the circulation of the leakage vortices. When a sheet at an angle \( \alpha \) is used in water bounded by material of different refractive index (lucite), a proper interface at an angle, \( \gamma \), given by \( \tan \gamma / \tan \alpha = n(\text{lucite})/n(\text{water}) \) (where \( n \) is the refractive index) has to be created. As shown in figure4b, we use a triangular
lucite canister attached to the side window and filled with Dow Corning 550 fluid, which has a refractive index of 1.5, i.e. the same as lucite. The images are first analyzed initially with a 64 x 64 pixel$^2$ interrogation window and a 32 pixel spacing. Then using the output of the first run as a “guess input”, the displacements are measured using 32 x 32 pixel$^2$ interrogation windows and 16 pixel vector spacing. This approach is feasible only when there is good particle seeding (4-5 per window) in a 32 x 32-pixel$^2$ window. Under these conditions, the uncertainty in velocity measurements is about 0.4 pixels as discussed in detail in Roth et al (1995). This procedure enables to obtain high-resolution velocity fields with vector spacing of 180µm. Such measurements are imperative since tip vortex core diameters are less than 1mm. Vorticity is calculated from the velocity using a second order finite difference scheme. The error in the vorticity, based on the characteristic vorticity is approximately 25%.

3. Cavitation event rates and cavitation noise

A sample accelerometer signal showing noise spikes caused by cavitation is shown in figure 5. Without nuclei seeding (i.e. bubble generation) the number of cavitation events for a 10s period at this cavitation index decreases from about 50 to 1. The accelerometer signals are analyzed to obtain plots of cavitation index vs. rate of cavitation events, $r_c$, for the three gap sizes. The results (figure 6) show that for all three cases the event rates increase with decreasing $\sigma$ and with decreasing gap sizes. As an example at 10 events/s, $\sigma$ for the 0.6mm gap is 11.5 as compared to 10.1 for the 1.4mm gap and 9.0 for the 2.6mm gap. The slope of the 0.6mm gap is also quite different than those of the 1.4 and 2.6mm gaps. Since all the experiments are performed with similar nuclei distributions, the substantial differences in event rate indicates that the probability of finding low-pressure regions decreases with increasing gap size. For the
2.6mm gap at $r_c > 14$, the curve flattens out. This trend occurs due to the increased concentration of nuclei resulting from prior cavitation events, a self-feeding phenomenon. Figure 6 also contains equations of power fit curves for the three gaps.

Farrell and Billet (1992) for a rotating turbomachine have observed a minimum in the cavitation inception index as a function of the gap size (at $\lambda \sim 0.2$), while Boulon et al. (with a fixed wing) do not, similar to our results. Several features of a tip leakage flow in a rotating turbomachine don’t occur in this study (and that of Boulon et al.)—the motion of the tip relative to the end wall, effect of centrifugal forces and unloading of the tip (ours is intentionally loaded). These differences most likely have a significant impact on the flow structure which may explain why some investigators observe a minimum in cavitation index while some do not. Another related issue is the interpretation of the cavitation inception index and the event rates. Bubbles with diameters of 100$\mu$m require little tension to initiate cavitation, thus the bubble size is intentionally not a critical issue in the present study. Also, generation of 2500 bubbles per second makes cavitation inception less sensitive to bubble populations. However, being a very turbulent flow—a vortex embedded in a boundary layer, infrequent cavitation events (e.g. less than 2 per second) are a result of “extreme” flow conditions and are not typical of the flow. With increasing events rate a trend can be correctly identified. At least for relatively high $\sigma$, the slope of the cavitation event rate curve indicates the distribution of points in the flow with pressure lower than that indicated by the cavitation index. Thus, the slope of the cavitation event rate curve is important in addition to its absolute values.

Figure 7 shows the trajectory of a tip leakage vortex for a gap of 0.6mm, visualized by cavitating bubbles and superposing 6 consecutive frames recorded at 1000fps. The helical shape of the vortex trajectory is clearly evident. Three samples of high-speed image series at time
intervals of 0.5ms and the associated accelerometer signals are presented in figures 8, 9 and 10 (top views). We have carefully examined numerous such matches between “acoustically” sensed cavitation and visually observed cavitation. Figure 8 is a high-speed image series for the 2.6mm gap. Cavitation noise starts at frame 1303 and continues on till frame 1307 (figure 8b). the highest amplitude noise occurs between frame 1303-1304, where the bubble becomes highly distorted and fragmented. Observe that the bubble migrates towards the tip indicating the existence of secondary flows. As will be discussed shortly multiple flow structures exist only in the case of the wider gap. Table 1 shows the RMS values of the signal between consecutive frames. Clearly, the highest RMS values (an order of magnitude higher) are observed between frames 1303-1304 and then they drops to the background levels (0.3) in frames 1307-1308. The Hilbert-Huang “amplitude” spectrum for this signal (HHS) (procedures described in Huang et al. 1998) is shown in figure 8c and identifies the spectral peaks associated with cavitation as a function of time. A commercially available software (Princeton Satellite Systems) based on N. E. Huang’s code is used for the analysis. The frequencies are included in table 1.

Figure 9a shows another high-speed image series with significant noise emission in frames 2103-2105 (figure 9b). Bubble B is out of focus, is not in the plane of the leakage vortex and simply travels with the free stream. While, bubble A cavitates - undergoes considerable growth, distortion and fragmentation in frames 2103-2105. In frames 2106-2107, the larger part of bubble A begins to shrink and noise is emitted but of considerably lower amplitude. Table 2 summarizes the RMS values and spectral peaks, for this example. High RMS values are observed in frames 2103-2104 and 2104-2105 and the frequencies involved in this cavitation process are extracted from the HHS in figure 9c. In figure 10a, high amplitude cavitation noise is emitted between frames 1495-1496. At this time bubble C is fragmented to three elongated bubbles.
Bubble D undergoes abrupt elongation in frame 1497, emitting further noise. Bubble E emerges around the tip in frame 1496 and is also seen in 1497. The highest noise spike occurs as bubble C is fragmented and a second spike at a slightly lower amplitude appears as bubble D is elongated and deformed. Note that mere deformation of bubbles D & C in frames 1493-1495 results in significantly lower noise levels compared to the ones resulting from fragmentation in the later frames. Table 3 summarizes the RMS values and spectral peaks in this example and figure 10c shows the HHS. Very high RMS values (more than 20 times the level with no cavitation event) are observed in frames 1495-1496 where the highest cavitation activity is observed. One can note from the HHS that the characteristic frequencies involved in these cavitation processes are 20-28 kHz and 5-8 kHz. We have examined numerous such data series. They are all consistent in showing that high amplitude noise is associated with substantial distortion and fragmentation of bubbles. Merely changes in shape or volume of the bubble generate substantially weaker noise signals. The differences in bubble size and noise signals (i.e. the frequency content and amplitude) are not characteristic to their respective gap sizes, i.e. bubbles of various sizes appeared in all gap sizes.

Figure 11 shows extended exposure images of the trajectory of the bubbly tip leakage vortex as seen in a side view for the three gap sizes. The following observations can be made: (a) The vortex trace becomes closer (vertical distance) to the hydrofoil as the gap size is increased; (b) the trajectories in the 0.6 and 1.4mm gaps are continuous and do not show a bump, i.e. a change in slope of the vortex trace that is clearly evident in the case of the 2.6mm gap (figure 11c); (c) It is possible that the cause of this bump is the interaction (merging) of multiple vortices. Note also the outward trajectory of the bubbles in figure 8, this motion is most likely associated with this complex flow structure.
4. Circulation of the tip leakage vortex

Figures 12 (a-f) show sample instantaneous vorticity and velocity, in the inclined plane (x’y, figure 4b) with a vector spacing of 180µm. Figures 12b, d and f are the “zoomed in” counterparts of figures 12a, c and e that correspond to gap sizes of 0.6, 1.4 and 2.6mm respectively. A section of the tip leakage vortex can be seen within the dashed boxes for each of the gap size. The object on the left in these maps is the hydrofoil with portions of the trailing edge and tip visible. Since the local flow is generated by an interaction of a wing tip with a turbulent boundary layer, it is not surprising that instantaneous realizations contain multiple vorticity peaks. However, unlike the tip leakage vortex all the others are intermittent and appear in different locations at different images. The tip vortex peak appears consistently although its exact location varies slightly, which is vortex meandering (figure 14). Furthermore, clearly the tip vortex cores have substantially higher overall circulation. Also, just below the hydrofoil (figures 12a and c only), we can see a trail of vortical structures that are weaker than the primary leakage vortex. These secondary vortices are similar to those seen by Farrell & Billet (1994). Figure 12c for the 2.6mm gap shows a vortex core much closer to the hydrofoil as expected from figure 11c.

We have analyzed 70 instantaneous realizations for the 0.6mm clearance and 65 for the 1.4mm and 2.6mm clearances. The regions with peak vorticity where the tip leakage vortices dissect the sheet were selected and regions with vorticity higher than 500 1/s considered to be part of the vortex core. The circulation was computed from $\Gamma = \sum \omega \, dA$, where $\omega$ is the vorticity in an elemental area $dA$ ($=180 \times 180 \, \mu m^2$). The regions with peak vorticity where the tip leakage vortices dissect the sheet are selected and regions with vorticity higher than 500 1/s are
considered to be part of the vortex core. The error in the circulation of the vortex based on a mean value is approximately 20%. Probability density histograms of the measured circulation normalized by the free-stream velocity and chord length are presented in figure 13. It is evident that the characteristic vortex strength decreases as the gap size increases. Table 4 shows the mean and standard deviation of the tip vortex strength.

Figure 13 also shows the estimated pressure coefficients (C_{pmin}) at the center of a Rankine vortex, \( C_{pmin} = -\frac{2}{\pi^2} \left( \frac{\Gamma}{Vd} \right)^2 \) where \( d \) is the diameter of the vortex core. The vorticity distributions show that \( d \) mostly varies between 3-4 vector spacings (i.e. 540-720\( \mu \)m). No significant differences in the core sizes have been seen in the three gap sizes, although this statement is greatly affected by the “coarse” resolution. Consequently, we show the magnitudes of \( C_{pmin} \) for \( d = 540 \mu m \) and 720 \( \mu m \) as a function of \( \Gamma \). Values of \( C_{pmin} \), for a core diameter of 540\( \mu m \), corresponding to the mean and up to an additional three standard deviation levels are presented in table 4. As is evident these \( C_{pmin} \) estimates are consistent with the corresponding values of \( \sigma \) in figure 6. For the 2.6mm gap, 3 standard deviation levels are required to match the inception level cavitation index that explains the steep slope of the curve in figure 6, compared to the trends in the smaller gaps.

The locations of the vortex cores in all the instantaneous realizations (points of maximum vorticity in the cross-section of the vortex) are shown in figures 14 (a-c) for the three clearances. All show substantial meandering over ranges that are much larger than the core size. The meandering increases with gap size. Even in the 0.6mm case where it is confined to a region with diameter of 3.7mm (in the x’y plane), the meandering range is 7.4% of the chordlength. The vertical distance of the cores from the trailing edge decreases as the gap size increases. On an average, this distance is 9.3, 8.75 and 5 mm, i.e. 18.6%, 17.5% and 10% of the chord length for
the 0.6, 1.4 and 2.6mm gap sizes respectively. These results agree with the vortex traces in figure 11. Similar trends have been observed by Boulon et al. (1999) who explain this trend using a potential flow model. A vortex near a wall has an “image” that causes an induced velocity with direction from the pressure side to the suction side (downward in this case). With decreasing gaps the induced velocity increases, increasing as a result the y-distance of the vortex from the hydrofoil. The higher induced velocity also increases the effective incidence angle, which would in turn increase the lift.

5. Conclusion

Tip leakage cavitation is studied in detail on a fixed hydrofoil with three tip gap sizes of $\lambda = 0.12, 0.28$ and 0.52. The cavitation event rates decrease with increasing gap size. One of the main findings of this paper is the relationship between visual appearance of cavitation and the amplitude of the noise signals, i.e. what really causes high cavitation noise? High amplitude cavitation noise is observed only when bubbles get highly distorted and fragmented. Much weaker signals (by an order of magnitude) are observed when the bubbles merely change shape or size. Cavitation noise is consistently observed in the 20-28 kHz and 5-8 kHz range. High resolution PIV data is used for measuring the circulation, estimate the size and location of the tip leakage vortex. One needs even better resolution to identify the correct size of such vortex cores, but the results show a core size ranging from $540\mu$m-720\mu$m. The vortex strength decrease with increasing gap sizes. Minimum pressure coefficients calculated using a Rankine vortex model and the measured strengths and core diameters, lead to results that are consistent with the measured cavitation indices. The tip leakage vortex trajectory moves closer to the hydrofoil as
the clearance is increased. Meandering of the vortex core is substantial in all cases and increases with increasing clearances.

**Acknowledgments**

This project has been graciously supported by the Naval Surface Warfare Center – Carderock Division. The authors would like to thank Y Ronzhes, Y C Chow, B McFadden, Dr. E Malkiel and Dr. J Karni for their contributions.

**References**


Figure 1. (a) Experimental facility (b) Close-up of test-section.
Figure 2: Estimated spanwise lift distribution on the hydrofoil at 0° incidence.
Figure 3. Size distribution of cavitation nuclei measured upstream of the leading edge of the hydrofoil.
Figure 4. (a) Set up for cavitation inception measurements (b) Set up for PIV measurements.
Figure 5: A sample accelerometer signal showing several spikes caused as a result of cavitation.
Figure 6. Cavitation event rates as a function of the dimensionless pressure, $\sigma$, for three gap sizes.

Figure 7. Six consecutive frames, 1 ms apart, are superimposed to show the trajectory of the bubbly tip leakage vortex. The gap size in this example is 0.6mm.
Table 1

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Figure 8: (a) A high-speed series (frames 1299-1304) at 2000fps (gap size, 2.6mm). Flow is from left to right with suction surface, tip and trailing edge (TE) visible ($\sigma=10$); (b) corresponding accelerometer and strobe signals (indicated by vertical bars); (c) Hilbert-Huang spectrum of the accelerometer signal. Frame timings are indicated by dashed lines.
Table 2

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Figure 9: (a) A high-speed series (frames 2103-2107) at 2000fps (gap size, 2.6mm). Flow is from left to right with suction surface, tip and trailing edge visible (σ=10); (b) corresponding accelerometer and strobe signals (indicated by vertical bars at the bottom). (c) Hilbert-Huang spectrum of the accelerometer signal. Frame timings are indicated by dashed lines.
Table 3

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Figure 10: (a) A high-speed series (frames 1493-1498) at 2000fps (gap size, 0.6mm). Flow is from left to right with suction surface and tip visible (σ=10); (b) corresponding accelerometer and strobe signals (indicated by vertical bars). (c) Hilbert-Huang spectrum of the accelerometer signal. Frame timings are indicated by dashed lines.
Figure 11. A 0.25s long exposure showing the trajectory of the bubbly tip leakage vortex as seen in a side view (figure 1b), for gaps of (a) 0.6mm; (b) 1.4mm; (c) 2.6mm. Flow is from left to right. The hydrofoil with its trailing edge and tip is visible on the left edge of the images.
Figure 12a, b
Figure 12c, d
Figure 12. Sample instantaneous vorticity (a, c and e) and their “zoomed in” counterparts (b, d and f) also show the instantaneous velocity in the plane x’y for gap sizes of 0.6, 1.4 and 2.6mm respectively. The dashed boxes in the two views represent the same area.
Figure 13: Probability density histograms of circulation in the tip leakage vortex for the three gap sizes and corresponding minimum pressure coefficients.

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<th>1.4 (0.28)</th>
<th>2.6 (0.52)</th>
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Figure 14a
Figure 14b
Figure 14. Locations of the tip leakage vortex cores in the plane x’y for gap sizes of (a) 0.6mm (b) 1.4mm and (c) 2.6mm.