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VORTEX SHEDDING FROM BLUNT AND OBLIQUE TRAILING EDGE HYDROFOILS

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ABSTRACT

The phenomenon of vortex shedding behind a hydrofoil is an important issue from both scientific and technical point of view. The resulting fluctuating forces may lead to excessive vibrations and premature cracks in the hydraulic machines. According to previous studies, it is well known that an oblique trailing edge, also called "Donaldson cut", reduces the vibration in comparison with a blunt trailing edge; however the physics of the problem is still poorly understood. The purpose of the present work is the experimental investigation of vortex shedding dynamics in the wake of oblique and blunt trailing edge NACA0009 hydrofoils. Experiments are performed at zero incidence angle and high Reynolds numbers, R_{eL} =5 10 ^{5} - 2.9 10 ^{6}. The wake velocity profile is measured by two-component Laser Doppler Velocimetry. Cavitation occurrence in the core of the vortices is used as a mean of wake visualization with the help of a high speed camera. We have found that vortex induced vibration is significantly reduced for oblique trailing edge hydrofoil in comparison with the truncated one, which is in agreement with former reports. A disorganization of the Karman vortex street in the near wake is believed to be the reason of this vibration reduction. The high speed movies clearly show that the alternate shedding of the vortices turns into almost simultaneous shedding at the hydrofoil trailing edge. As a result, the upper and lower vortices pair with a significant thickening of the lower vortex core and a reduction of its strength. Consequently, the fluctuating lift, which is the cause of the structural vibration, is also reduced by the oblique truncation. We believe that this result stands for a basis to better optimize the trailing edge of turbine blades in order to further decrease the flow induced vibration.

KEYWORDS

Vortex Shedding, Wake, Trailing Edge, Flow Induced Vibration

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1. INTRODUCTION

Beyond a certain value of Reynolds number, a periodic and alternate vortex shedding develops in the wake of a bluff body. The fluctuating forces which originate from the vortex shedding, may lead to an increase of mechanical vibration and premature cracks. In hydraulic machines, vortex shedding from stay vanes or runner blades may excite the mechanical structure at one of its eigen frequencies with significant damage, Blevins [1], Lockey et al. [2] and Shi [3]. The formation process of alternate vortices behind a cylinder was investigated by many authors; see review paper by Williamson [4]. It is well known that the interaction between two separating shear layers is the origin of the vortex-street formation. Once generated, a vortex continues to grow, fed by circulation from its connected shear layer, until it is strong enough to draw the opposing shear layer across the near wake. The vorticity of opposing sign cuts off further circulation to the growing vortex, which is then shed downstream. The first theory on the stability of the vortex street was proposed by von Karman [5], who stated that a stable vortex shedding is possible only if the vortices are shed alternately and if the ratio between the stream wise and transverse spacing between vortices is equal to 0.28. It is also well known, see for instance Ausoni [6], that in the case of a 2D blunt hydrofoil, the shedding frequency follows a Strouhal law provided that no resonance frequency is excited; i.e., lock-off. In the case of resonance, lock-in, the vortex-shedding frequency is locked onto the hydrofoil eigen frequency, leading to more organized wake structures and the coherent length is increased. According to Donaldson [7], Heskestad [8], Ippen [9] and Blake [10], the trailing edge geometry plays a major role on the wake dynamic and on the resulting structural vibration. Donaldson [7] performed systematic measurements of flow induced vibration in Francis-turbine runners having different trailing edge shapes. He found a significant reduction of vibration with an oblique cut of the blunt trailing edge with an angle of 30°. Nevertheless, the physical explanation of this reduction is not yet understood.

The objective of the present study is to investigate the effect of the Donaldson cut on the wake dynamics to better describe the physical reasons of the vibration reduction. The case study is made of two similar hydrofoils having blunt and oblique trailing edges, placed in the test section of the EPFL high speed cavitation tunnel. The velocity survey in the hydrofoil wake is performed with the help of a Laser Doppler Velocimeter Besides, flow induced vibration and high speed visualization are also performed.

2. CASE STUDY AND EXPERIMENTAL SETUP

Two NACA0009 hydrofoils with truncated and oblique trailing edges are selected for the present investigation. They both have 100 mm chord length, 150 mm span and 10 mm maximum thickness, Fig. 1. Since the boundary layer development over the hydrofoil surface is of prime importance for the wake dynamic, Ausoni [6], a special care is put on the similarity of the surface roughness between the tested hydrofoils to allow for a fair comparison. The measurements are carried out in the EPFL high speed cavitation tunnel, Avellan et al. [11], with a test section of 150 x 150 x 750 mm, maximum inlet velocity, C_{ref}, of 50 m/s and maximum static pressure, P_{inlet}, of 16 bar.

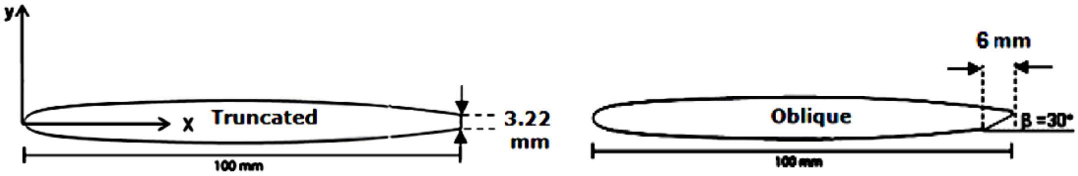

Fig. 1 NACA0009 hydrofoils with truncated (left) and oblique (right) trailing edges

Vortex-induced vibration is monitored on the hydrofoil surface with a Laser vibrometer. The measurement principle of this non-intrusive vibrometer is based on the detection of the frequency shift of the reflected Laser beam, Doppler effect, which is directly related to the displacement velocity of the surface. The measurement point is located at mid span and 10 mm upstream from the trailing edge. To make visible the wake, the ambient pressure is reduced in the test section so that the cavitation may develop within the core of the vortices, which makes them visible. We have already demonstrated, Ausoni [6], that despite the increase of vortex shedding frequency, cavitation has almost no effect on vortex organization. A high speed camera having an image resolution of 512 x 256 pixels at 10'000 Hz frame rate is used to analyze the wake structure. The survey of velocity field in the hydrofoil wake is performed with a single-point two-component Laser Doppler Velocimetry, LDV. The seeding particles are 10 μm diameter hollow glass spheres. The light source is a 10 W Argon-Ion Laser. The optical probe has 38.15 mm beam spacing and 250 mm focal length. The resulting underwater control volume dimensions are 0.075 mm in both x-axis and y-axis, and 1.3 mm in z-axis, see Fig. 1 for the coordinates system definition. The random sampling, which is inherent to LDV, introduces a bias in estimating statistical properties of the velocity. Therefore, this bias is corrected by using the transit-time weighting factor, $\eta_{i,}$ for the estimation of the average according to Saffmann et al. [13]. The mean and fluctuating stream-wise velocities and the transit-time weighting factor are defined below. Similar definitions apply to the transverse component. All the data are acquired for z/b = 0.75.

$$C_{x\ mean} = \sum_{i=0}^{N-1} \eta_i C_{x\ i} \tag{1}$$

$$\eta_i = \frac{t_i}{\sum_{j=0}^{N} t_j} \tag{2}$$

$$C_{x\ stdv} = \sqrt{\sum_{i=0}^{N-1} \eta_i (C_{x\ i} - C_{x\ mean})^2} \tag{3}$$

3. RESULTS

The vortex-induced vibration is measured with the help of the laser vibrometer focused on the hydrofoil surface. For the blunt truncated and the oblique trailing edge hydrofoils, the waterfall spectra of the vibration signals are presented, see Fig. 2, for different free-stream velocities. The comparison of the waterfall spectra for the two trailing edge geometries reveals that the spectral peak heights are significantly higher in the context of the truncated trailing edge. As the vortex shedding frequency approaches one of the natural frequencies of the hydrofoil, the resonance takes place with a significant increase in vibration. A lock-in of the vortex shedding frequency onto the structural eigen frequency, 890 Hz, occurs and a plateau emerges, i.e. a constant shedding frequency for free-stream velocities from 12 to 14 m/s for the truncated trailing edge and from 13 to 15 m/s for the oblique one. The survey of the hydrofoil surface vibration for lock-in condition leads to the identification of the first torsional eigen mode, Ausoni [6].

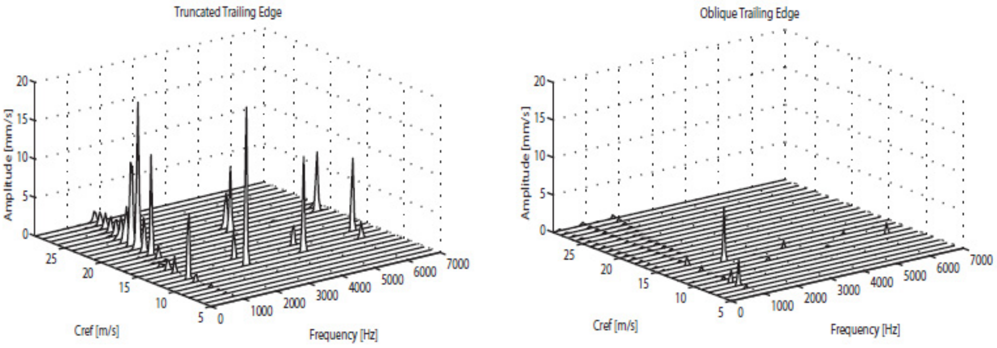

Fig. 2 Waterfall spectra of the Laser vibrometer, Truncated T. E. (left), Oblique T. E. (right)

The vortex shedding frequency, derived from LDV measurements, is plotted for the truncated and oblique trailing edges as a function of upstream velocity, Fig. 3. A linear relationship is observed between the shedding frequency and the upstream velocity in the case of truncated trailing edge except under lock-in condition.

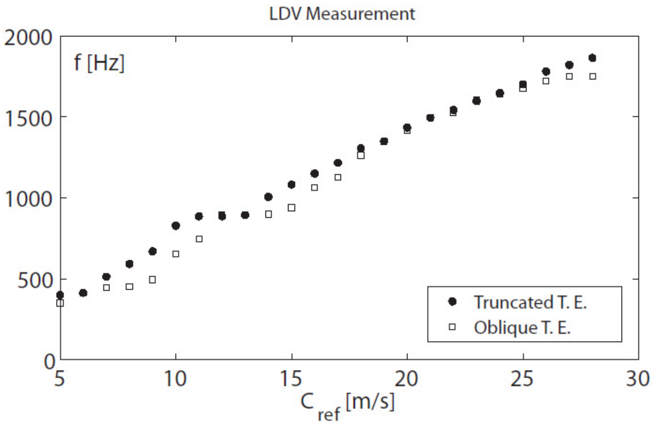

Fig. 3 Shedding Frequency Versus upstream velocity

High speed visualization is performed to observe the cavitation vortices for various upstream velocities. We have deliberately selected the lock-in condition to illustrate the fundamental difference between oblique and truncated trailing edge hydrofoils. In fact, with the hydro elastic coupling, the coherence length of the vortices is significantly increased and their shedding is almost 2D. Under these conditions, the wake dynamics may be easily observed as illustrated in Fig. 4. In the case of truncated trailing edge, the wake exhibits an alternate shedding with the lower and upper vortices being of the same size. On the contrary, for the oblique trailing edge, the sequence clearly shows a disorganization of the Karman vortex street in the near wake. The alternate shedding of the vortices turns into almost simultaneous shedding leading to a spectacular pairing between upper and lower vortices. Immediately after this pairing, cavitation is suppressed in the lower vortex while the upper one remains surprisingly unchanged.

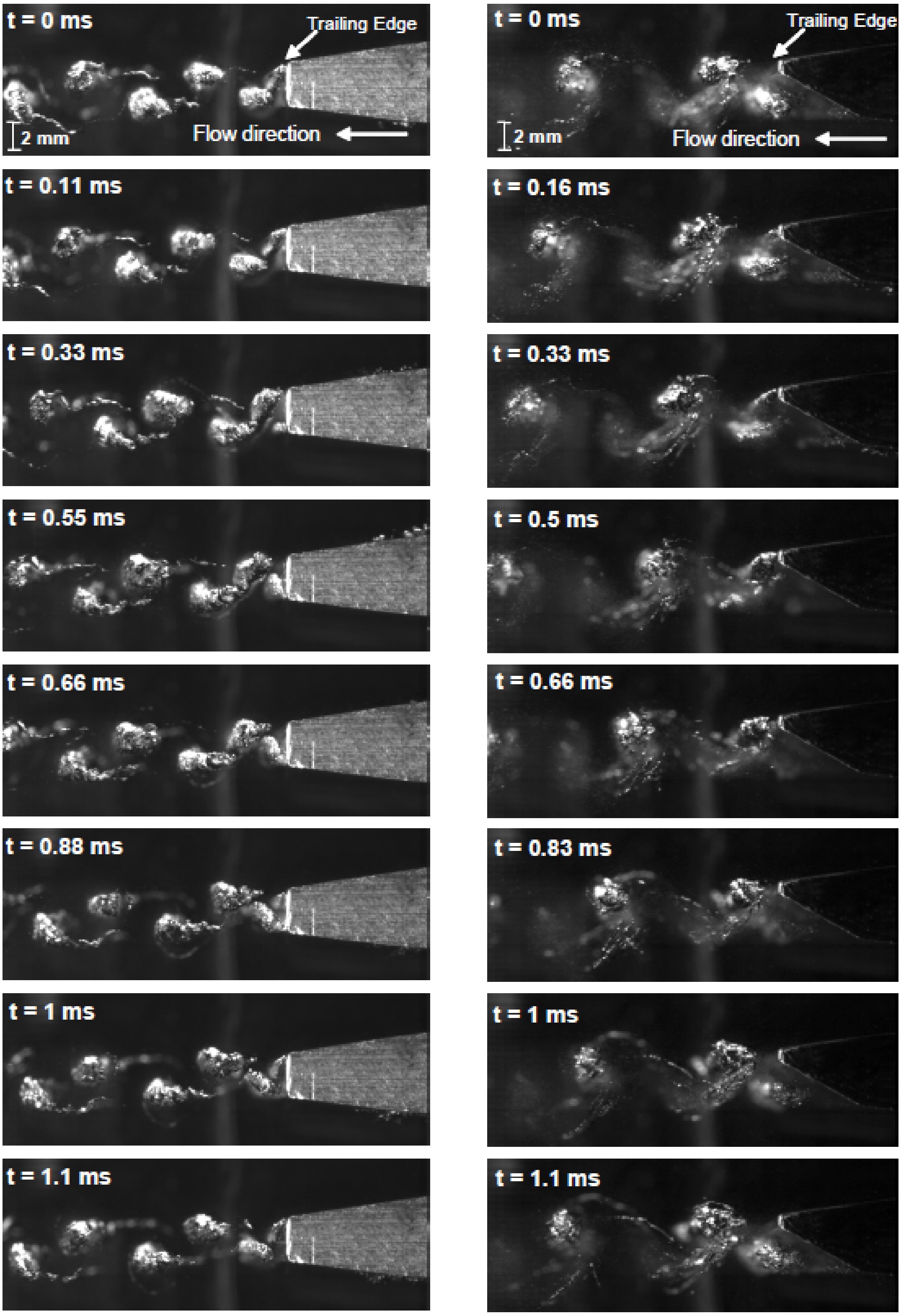

Fig. 4 High speed visualization of wake dynamic:
Left: Truncated T.E., C_{ref}=12 m/s, σ=0.87, Right: Oblique T.E., C_{ref}=13 m/s, σ=0.6

LDV measurements, performed under the same hydrodynamic conditions as in Figure 4, enable to analyze further the wake dynamics. The Figure 5 illustrates, for the truncated and oblique trailing edge hydrofoils, the wake flow measurements at x/L=1.032 under lock-in conditions. Normalized by the free-stream velocity, the mean stream-wise velocity (left) and the stream-wise velocity fluctuations (right) are shown. In the case of oblique trailing edge, the velocity deficit is more pronounced with a slight asymmetric thickening of the wake downward. This is confirmed by the velocity fluctuation profiles, which also reveals more turbulence in the central part of the oblique trailing edge wake. We believe that this is due to the pairing between upper and lower vortices. Moreover, the thickening of the lower part of the wake illustrates the thickening of the core of lower vortices, which is the reason of the cavitation suppression, observed in Figure 4.

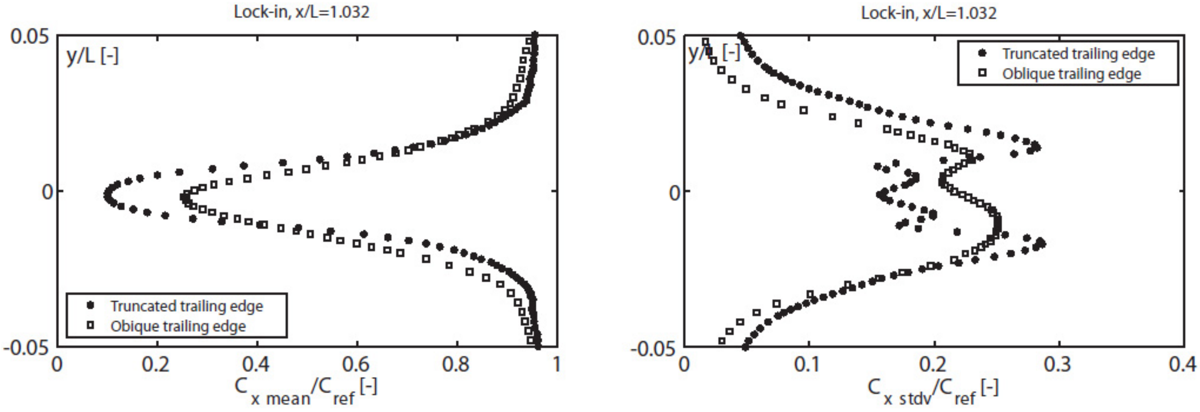

Fig. 5 Mean (left) and standard deviation (right) of velocity profiles in the wake of oblique and truncated T.E. hydrofoils (Lock-in, x/L=1.032)

4. CONCLUSIONS

The vortex shedding phenomenon generated in the wake of a hydrofoil with an oblique trailing edge, which mitigates the flow induced vibrations in comparison with a truncated trailing edge, is investigated. Two hydrofoils featuring truncated and oblique NACA 0009 geometry are tested in the EPFL high speed cavitation tunnel. Experiments are performed for a flow incidence angle of $\alpha = 0°$ and high Reynolds numbers, $R_{eL} = 5\ 10^5 - 2.9\ 10^6$, based on the hydrofoil chord length. LDV measurements of the flow velocity field in the wake under lock-in condition are performed, as well as high speed visualization and flow induced vibration measurements. In the context of the oblique trailing edge and in comparison with the truncated one, the vortex-induced vibration is shown to be significantly reduced. The processing of high speed visualization is evidencing a spatial phase shift of the upper and lower vortices at their generation stage, leading to their pairing and partial destruction of the lower vortex intensity. According to these experimental results, we believe that the phase shift between two vortices is the main reason of the vibration reduction. The fluctuating lift force is therefore significantly reduced in comparison with the case of the blunt truncated trailing edge. As a result, the hydrofoil experiences a significantly lower vortex-induced vibration. Moreover, the wake flow measurements reveal decreases of the velocity fluctuations and confirm the above statements.

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NOMENCLATURE

L	(m)	Hydrofoil chord	$C_{x\ stdv.}$	($m.s^{-1}$)	Standard deviation streamwise velocity
b	(m)	Hydrofoil span	C_{ref}	($m.s^{-1}$)	Reference velocity
f_s	(Hz)	Vortex shedding frequency	η_i	-	Weighting factor
$C_{x\ mean}$	($m.s^{-1}$)	Mean stream wise velocity	σ	-	Cavitaion number