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EXPERIMENTAL INVESTIGATION OF THE VORTEX SHEDDING IN THE WAKE OF OBLIQUE AND BLUNT TRAILING EDGE HYDROFOILS USING PIV-POD

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ABSTRACT

This paper presents an experimental investigation of the vortex shedding in the wake of blunt and oblique trailing edge hydrofoils at high Reynolds number, Re=5 10^{5} - 2.9 10^{6}. The velocity field in the wake is surveyed with the help of Particle-Image-Velocimetry, PIV, using Proper-Orthogonal-Decomposition, POD. Besides, flow induced vibration measurements and high-speed visualization are performed. The high-speed visualization clearly shows that the oblique trailing edge leads to a spatial phase shift of the upper and lower vortices at their generation stage, resulting their partial cancellation. For the oblique trailing edge geometry and in comparison with the blunt one, the vortex-induced vibrations are significantly reduced. Moreover, PIV data reveals a lower vorticity for the oblique trailing edge. The phase shift between upper and lower vortices, introduced by the oblique truncation of the trailing edge, is found to vanish in the far wake, where alternate shedding is recovered as observed with the blunt trailing edge. The phase shift generated by the oblique trailing edge and the resulting partial cancellation of the vortices is believed to be the main reason of the vibration reduction.

NOMENCLATURE

L	Hydrofoil chord length	m
b	Hydrofoil span	m
h	Hydrofoil trailing edge thickness	m
C_{ref}	Velocity at the test section inlet	m/s
σ	Cavitation number	-
f_s	Vortex shedding frequency	Hz
S	Spacing between two consecutive vortices	m
T_s	Vortex shedding period	s

INTRODUCTION

Beyond a certain value of Reynolds number, a periodic and alternate vortex shedding develops in the wake of a bluff body. The formation process of alternate vortices has been deeply studied, e.g., Roshko [1], Gerrard [2], Bearman [3], Griffin [4] and Williamson [5]. The interaction between two separating shear layers is the origin of the vortex-street formation. The generated vortex continues to grow, fed by the circulation induced by 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. Von Karman proposed the first theory on the stability of the vortex street, [6]. He 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.

Vortex-induced vibrations are discussed in the comprehensive reviews of Rockwell [7] and Williamson [8]. The fluctuating forces resulting from the formation of vortices may excite the body into oscillation. The vibrations of the structures are increased due to the fluid-structure interaction and could cause structural damage under certain unfavorable conditions. For instance, resonance occurs when vortex shedding and body have the same frequency value that is close to one of the structure eigen frequencies. Under resonance condition, the response amplitude becomes so high that the structural motion controls the fluid excitation leading to so-called lock-in phenomenon. It is also well known, see for instance Ausoni [9], 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 condition. Under lock-in condition, a more organized wake structures and the coherent length is observed where the vortex span-wise non-uniformities is replaced by parallel vortex shedding mode and the vortex strength is increased, Davies [11] .

As the vortex-induced vibration can be the reason of damage for different engineering structures, a number of studies attempted to control the wake behind structures see Choi [13] for a deep review. Different methods are proposed to control the wake. For instance, thin splitter plate, Hwang [14] and Ozono [15], rotary oscillations of a bluff body, Konstantinidis [16], blowing and suction, Cadot [17], geometry modification in the span-wise direction near the separation point such as a segmented trailing-edge, Rodriguez [18], wavy trailing-edge, Tombazis [19] and Cai [20], small-size tab, mounted on part of the upper and lower trailing edge, Park [21], trailing edge shape modification, Donaldson [22], Heskestad [23] and Blake [24]. The geometry of the trailing edge has a direct influence on the amplitude of the wake flow oscillations and vortex-induced vibration level. However, the method of optimizing the shape of the trailing edge has not been investigated so much contrary to the other methods to control the vortices and wake. Donaldson [22] 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°. However, the physics of this vibration reduction has received little attention.

Therefore, the objective of the present study is to investigate the effect of the oblique trailing edge on the vortex shedding to understand the physical reasons of the vibration reduction. The NACA009 hydrofoil with blunt and oblique trailing edges, placed in the test section of the EPFL high-speed cavitation tunnel, is investigated. The velocity survey in the hydrofoil wake is performed with the help of Particle-Image-Velocimetry, PIV, using Proper-Orthogonal-Decomposition, POD, for post-processing. Besides, flow induced vibration measurements and high-speed visualization are performed.

CASE STUDY AND EXPERIMENTAL SETUP

The case study is made of two NACA009 hydrofoils with truncated and oblique trailing edges. Experimental investigations are carried out in the EPFL high-speed cavitation tunnel, Avellan et al. [12], where a maximum velocity of 50 m/s may be reached at the inlet of the 150 x 150 x 750 mm test section with an upstream turbulence intensity of 1 percent. Both hydrofoils have 100 mm chord length, L, 150 mm span, b, and 10 mm maximum thickness, Fig. 1. The hydrofoils mounting in the test section are fixed on one side and free on the other side. Since the boundary layer development over the hydrofoil surface is of prime importance for the wake dynamics, Ausoni [10], a special care is put on the similarity of the surface roughness between the two hydrofoils to enable a fair comparison. Vortex-induced vibration is monitored on the hydrofoil surface with a Laser vibrometer with the frequency range of up to 22 kHz. The data acquisition system has a maximum sampling frequency of 51.2 kHz. The vibration measurement point is located at mid span and 10 percent of chord length upstream from the trailing edge. The ambient pressure is reduced in the test section to allow for cavitation development within the vortices, which makes them visible. A high-speed camera having an image resolution of 512 x 256 pixels at 10'000 Hz frame rate is used to visualize the wake structure.

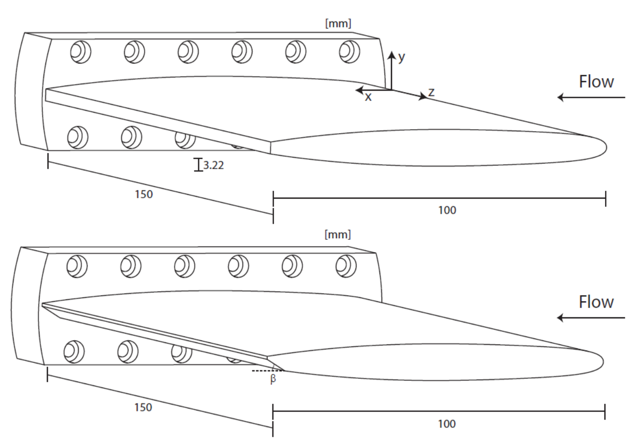

Fig. 1. NACA009 hydrofoils with truncated (up) and oblique (bottom) trailing edges

Particle-Image-Velocimetry is performed using hollow glass spheres of 10 µm diameter as seeding particles. The Laser sheet, of 1 mm thickness, is provided by two ND:YAG pulsed Laser sources of 532 nm wavelength. The double pulses may be repeated at a maximum rate of 10 Hz. The pairs of images, captured with an intensified double frame camera, are cross-correlated to derive instantaneous velocity fields. The interrogation area size is 32x32 pixels with an overlap of 50%. The picture size is 1'280 x 1'024 pixels. A Gaussian window function is used to reduce the cyclic noise from the correlation map.

The Proper-Orthogonal-Decomposition, POD, is used as a post processing technique to make apparent the large coherent structures in the hydrofoil wake. POD is particularly powerful in extracting the phase of the vortex shedding in an individual velocity field and filtering the low energetic part of the flow. It is based on a linear decomposition of velocity field with respect to orthogonal modes, Eq. 1

$$u^n = \sum_{i=1}^{N} a_i^n \phi^i \qquad (1)$$

where u^n is a vector representing the velocity components in the entire measurement area and n is the sample index. Given a set of N velocity fields (snapshots), u^n, a correlation matrix C is defined as

$$C = U^T \cdot U \qquad (2)$$

where U is a matrix made of velocity components of N snapshots. N real positive eigen values, λ^i, each associated with an eigenvector, q^i, are obtained from the eigenvalue problem defined by Eq. 3.

$$C \cdot q^i = \lambda^i \cdot q^i \qquad (3)$$

The normalized POD modes, ϕ^i, are obtained from Eq. 4.

$$\phi^i = \frac{\sum_{n=1}^{N} q_n^i . u^n}{\left\| \sum_{n=1}^{N} q_n^i . u^n \right\|} \qquad (4)$$

The POD coefficient, a^n, in Eq. 1 presents the projection of the velocity field onto the POD eigenmode.

$$a_i^n = (u^n, \phi^i) \qquad (5)$$

Exact reconstruction of the velocity field, Eq.1, may be obtained through a linear combination of N modes. The first mode represents the mean flow. The phase of vortex shedding may be derived from the two following modes.

In our specific case study, POD method offers an interesting way to perform phase averaging of the velocity fluctuation even if the sampling frequency is far below the vortex shedding frequency. It saves the use of an external trigger, which is usually adopted in similar case studies.

RESULTS

The standard deviation of the vibration signals measured with a Laser vibrometer, is presented for different upstream velocities in the case of truncated and oblique trailing edges, Fig. 2. A dramatic increase of vibration is observed under resonance condition, where the vortex shedding frequency approaches one of the natural frequencies of the hydrofoil. A Lock-in of the vortex shedding frequency onto the structural eigen frequency occurs at 890 Hz and for upstream velocities ranging from 12 to 14 m/s for the truncated trailing edge and 13 to 15 m/s for the oblique trailing edge. The survey of the hydrofoil surface vibration for lock-in condition leads to the identification of the first torsion eigen mode, Ausoni [9].

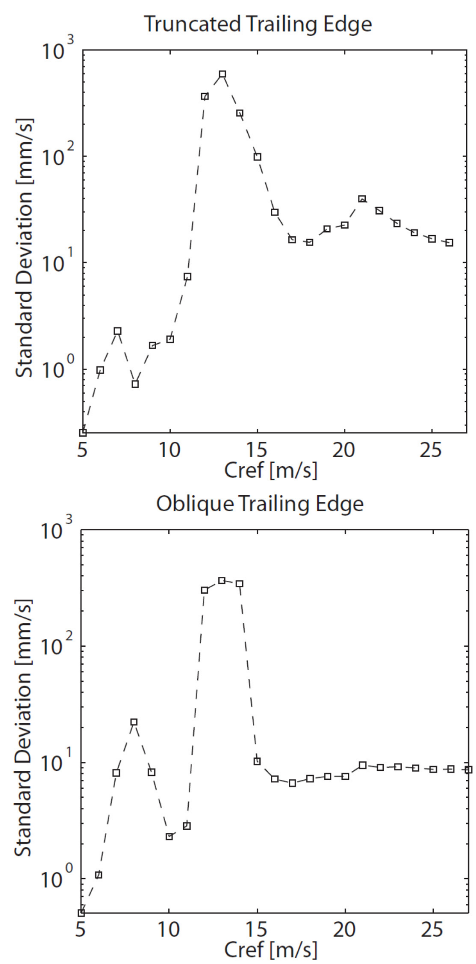

Fig. 2. Standard deviation of the vibration signal versus upstream velocity, Truncated T. E. (up), Oblique T. E. (bottom)

The vortex shedding frequency versus upstream velocity is plotted in the case of truncated and oblique trailing edges, Fig. 3. A quasi-linear relationship is observed between the shedding frequency and the upstream velocity except for lock-in condition, where a constant frequency is observed.

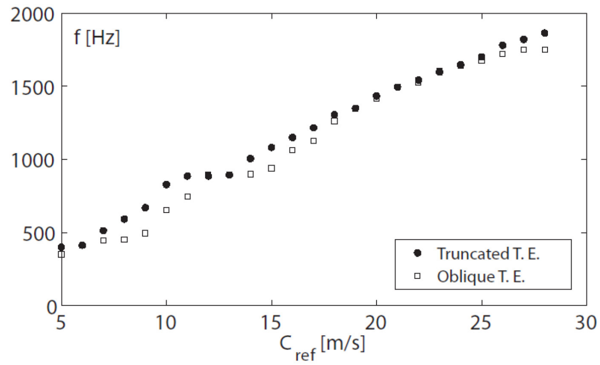

Fig. 3. Shedding Frequency versus upstream velocity

We have deliberately focused on 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 may be easily observed as illustrated in Fig. 4. The truncated trailing edge induced an alternate shedding in the wake with the lower and upper vortices of the same size. On the contrary, for the oblique trailing edge, a disorganization of the vortex street in the near wake is observed. The alternate shedding of the vortices turns into almost simultaneous formation leading to a collision and partial cancellation of the vortices. It is well known that for two vortices of equal strength, an inverse relationship is found between cavitation inception and vortex core size, Ausoni[9]. As a result, since cavitation is almost suppressed in the lower vortex immediately after the collision, we may already conclude that the lower vortex experiences a thickening of its viscous core.

The generation mechanism of vortices from the truncated and oblique trailing edges under cavitation free condition is analyzed with the help of PIV-POD phase averaging technique by considering 1'000 snapshots and the first ten most energetic modes, Fig. 5. The partial cancellation of upper and lower vortices in the case of oblique trailing edge is clearly observed.

A snapshot of the magnitude of the instantaneous velocity, normalized with the reference velocity, along the wake of truncated and oblique trailing edges is made visible in Fig. 6. The magnitude of the velocity decreases along the wake in both cases. However, lower velocity magnitude is observed in the far wake of truncated trailing edge.

The vorticity evolution along the wake, normalized with chord length and reference velocity, is presented in the case of truncated and oblique trailing edges, Fig. 7. It is well known that an inverse relationship is found between vorticity and the core size of two vortices with equal strengths. As a result, since higher vorticity is found for the truncated trailing edge, about two times higher than the oblique trailing edge, indicating that the oblique truncation produces a thickening of vortex cores. Furthermore, in the case of oblique trailing edge, the lower vortices experiences less vorticity than the upper ones, which is in accordance with cavitation suppression reported above, see Fig. 4.

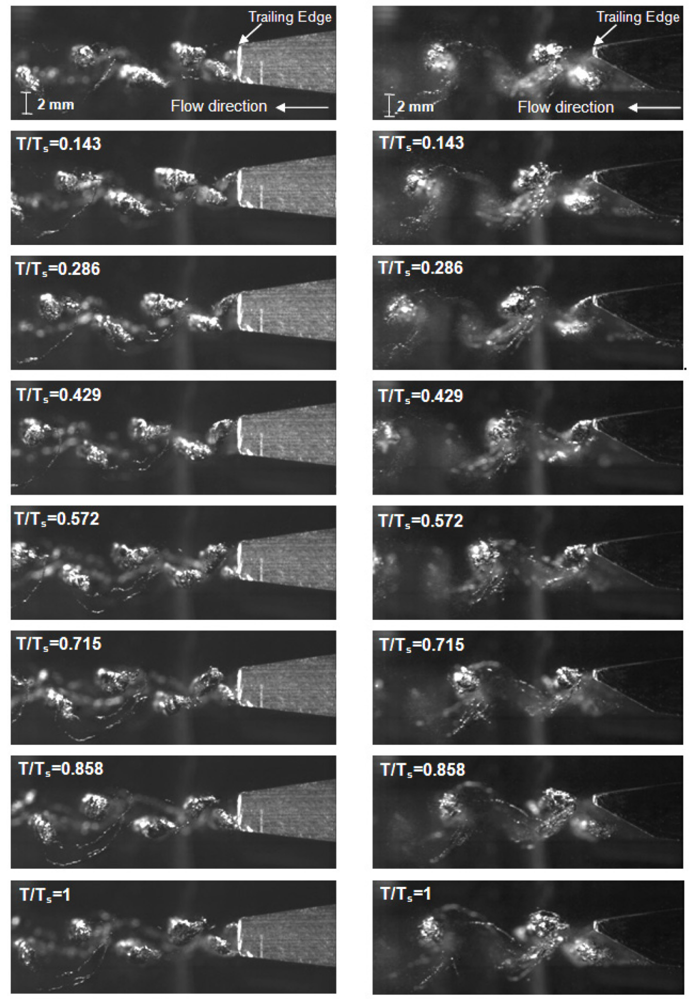

Fig. 4. High speed wake visualization:
Left: Truncated T.E., C_{ref}=12 m/s, σ=0.87,
Right: Oblique T.E., C_{ref}=13 m/s, σ=0.6

The vortex street arrangement along the wake is presented in Fig. 7. According to the work of von Karman [6], the stable vortex street is found only when a symmetrical double row is observed. As a result, a stable vortex street is not observed in the near wake of oblique trailing edge due to the unequal spacing, $S_l \neq S_r$, between the lower vortex and two upper vortices. However, an equal spacing, $S_l = S_r$, is observed in the far wake similar to the truncated trailing edge case , which is in accordance with the von Karman stability criteria. An almost simultaneous formation of vortices at the oblique trailing edge and their partial cancellation can be noted as the main reason of the vibration reduction.

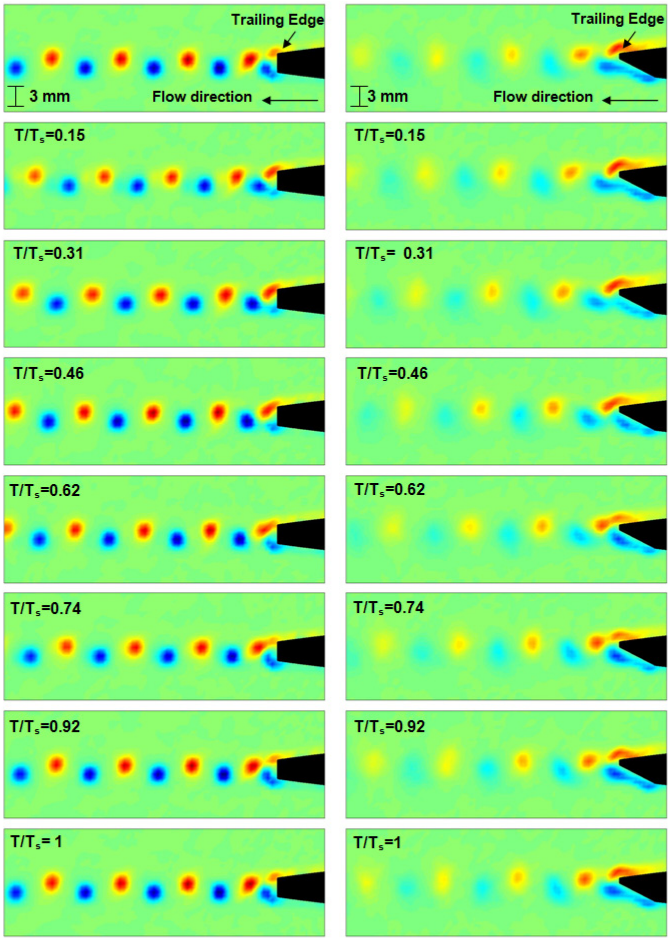

Fig. 5 Wake visualization (one shedding period), Normalized vorticity, Left: Truncated T.E., Cref=12 m/s, Right: Oblique T.E., Cref=13 m/s

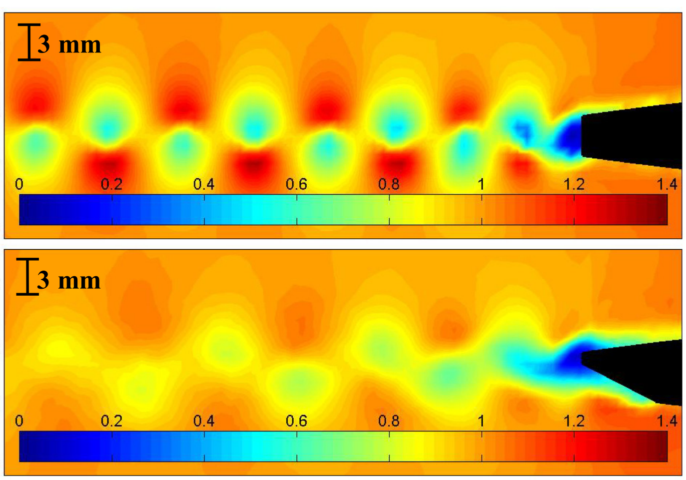

Fig. 6. A snapshot of normalized magnitude of the instantaneous velocity field along the wake, lock-in

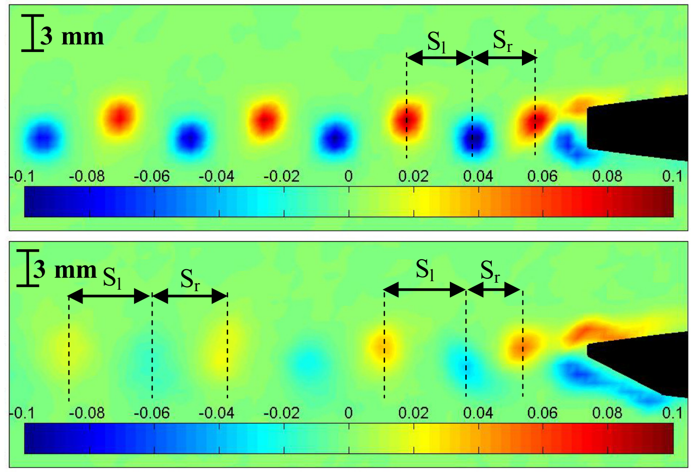

Fig. 7 Normalized vorticity evolution along the wake, lock-in and Vortex arrangement in the wake of truncated (up) and oblique (bottom)

CONCLUSIONS

The vortex shedding generated in the wake of a hydrofoils with oblique and truncated trailing edge is investigated with PIV using POD post processing technique in the wake under lock-in condition. Moreover high-speed visualization and flow induced vibration measurements are performed, as well. In the case of the oblique trailing edge and in comparison with the case of the truncated trailing edge, the vortex-induced vibration is reduced significantly. High-speed visualization made apparent a spatial phase shift between the upper and lower vortices leading to their partial cancellation. As a result, the hydrofoil experiences a significantly lower vortex-induced vibration. Moreover, the POD analysis applied to the PIV results reveals smaller vortex core diameter, higher vorticity for the truncated trailing edge in comparison with the oblique trailing edge. The phase shift between upper and lower vortices, introduced by the oblique truncation of the trailing edge, is found to vanish in the far wake, where more organized and alternate shedding is recovered, as observed with the blunt trailing edge. According to these experimental results, the phase shift generated by the oblique trailing edge and the resulting partial cancellation of the vortices is believed to be the main reason of the vibration reduction physical process.

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