Journal of Fluids and Structures 32 (2012) 78–89

Contents lists available at SciVerse ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

How oblique trailing edge of a hydrofoil reduces the vortex-induced vibration

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ARTICLE INFO

Article history:
Received 3 November 2010
Received in revised form
27 November 2011
Accepted 1 December 2011
Available online 17 January 2012

Keywords:
Vortex shedding
Wake
Trailing edge
Flow-induced vibration
Fluid–structure interaction

ABSTRACT

The effect of hydrofoil trailing edge shape on the wake dynamic and flow induced vibration is investigated at high Reynolds number, $Re=0.5\times10^6$–2.9×10^6. Two NACA 0009 hydrofoils with blunt and oblique trailing edges are tested. The velocity field is surveyed with the help of Laser Doppler Velocimetry (LDV), and Particle-Image-Velocimetry, (PIV). Proper-Orthogonal-Decomposition (POD) is used to extract coherent structures from PIV data. Besides, flow induced vibration measurements and high-speed visualization are also performed. A significant reduction of vortex induced vibration is obtained with the oblique trailing edge, in accordance with former reports. High speed videos clearly demonstrate that for both tested hydrofoils, the alternate vortices detach from upper and lower corners of the trailing edge. Due to the oblique truncation, the lower detachment location is shifted upstream with respect to the upper one. Therefore, as the upper vortex rolls up, it coincides with the passage of the lower vortex, leading to their collision. This strong interaction leads to a redistribution of the vorticity, which no more concentrates within the core of Karman vortices. The analysis of the phase locked average of velocity profiles reveals that the oblique truncation leads to a thickening of the core of upper and lower vortices as well as a disorganization of the alternate shedding in the near wake, recovers downstream. We strongly believe that the collision between upper and lower vortices and the resulting vorticity redistribution is the main reason of the vibration reduction obtained with oblique trailing edge. This result paves the way for further optimization of the trailing edge shape.

1. Introduction

Vortex shedding from hydrofoils trailing edge is an important issue from both scientific and engineering viewpoints. The fluctuating forces associated with such alternate shedding may lead to a significant increase of induced vibrations and risk of premature cracks in a variety of industrial applications, such as hydraulic turbines and pumps as well as marine propellers. The formation process of alternate vortices has been investigated by Roshko (1955), Gerrard (1966), Bearman (1984), Griffin (1995) and Williamson and Roshko (1988) among many others. It is well known that the strong interaction between upper and lower separating shear layers at the hydrofoil trailing edge is the origin of the vortex street formation. When a vortex is initiated in one of these shear layers, it grows and becomes strong enough to draw opposing shear layer across the near wake. The vortex is then shed downstream allowing for a second vortex to form in opposing shear layer. The first theory on stability of a vortex street was proposed by von Karman (Milne-Thomson, 1972), who stated that a

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doi:10.1016/j.jfluidstructs.2011.12.003

stable vortex shedding is only possible if the vortices are shed alternately and if the ratio between the lateral and longitudinal spacing is equal to 0.28.

Vortex-induced vibration is noted as important subject in different fields, such as fluid mechanics, structural mechanics, vibrations, computational fluid dynamics and acoustics. Different discussions of these subjects are presented in the reviews of Rockwell (1998), Williamson and Govardhan (2004), Sarpkaya (2004), Bearman (2011) and Assi et al. (2006). Fluid–structure interaction increases vibrations of the structures and may cause structural damage under certain unfavorable conditions. The flow-induced vibration due to vortex shedding is a prevalent fluid–structure interaction problem. For instance, if the shedding frequency coincides with one of the eigenfrequencies of the body, resonance occurs with a significant increase of vibration amplitude. As a result, the structural displacement controls the fluid excitation leading to so-called lock-in phenomenon. It is well known; see for instance Ausoni et al. (2007), that in the case of 2D blunt hydrofoil, the shedding frequency follows a Strouhal law provided that no resonance frequency is excited; i.e., lock-off. Under lock-in condition, the curved vorticity lines turn into straight lines parallel to the trailing edge and the vortex strength is increased (Davies, 1976).

Since vortex-induced vibration can be the reason for damage to different engineering structures, a number of studies attempted to control the wake behind structures, refer to Choi et al. (2008) for an in-depth review. Different methods are proposed to control the wake. For instance, thin splitter plate (Hwang et al., 2003; Ozono, 1999); rotary oscillations of a bluff body (Konstantinidis et al., 2005); acoustic waves (Roussopoulos, 1993); blowing and suction (Park et al., 1994; Cadot and Lebey, 1999); geometry modification in the span-wise direction near the separation point, such as a segmented trailing-edge (Rodriguez, 1991); wavy trailing-edge (Tombazis and Bearman, 1997; Cai et al., 2008); small-size tab, mounted on upper and lower trailing edge (Park et al., 2006); trailing edge shape modification (Donaldson, 1956; Heskestad and Olberts, 1960; Blake, 1986). It is well established that the geometry of the trailing edge has a direct influence on wake structure and vortex-induced vibration level. The vortex shedding from a cambered hydrofoil with beveled trailing edge with different angle at high Reynolds number was studied by Dwayne (2005). He noted that the thicker or blunter trailing edge is producing stronger vortex shedding. Moreover, the boundary layer is separated at the beveled trailing edge and an asymmetric vortex shedding is found. Mosallem (2008) investigated the characteristics of flow past a beveled trailing edges attached to the flat plates with two different angles, 27° and 60°. The results show an asymmetric wake behind the smaller beveled trailing edge contrary to the greater one that a symmetric wake is observed. The flow past a hydrofoil with blunt and various base cavity shapes at high Reynolds numbers was studied numerically (Do et al., 2010). The base cavity at the trailing edge has effect on the wake structure, decreasing the intensity of the trailing edge pressure fluctuations. As a result, the lift fluctuations reduce. In addition, the study of Lockey et al. (2006) shows that the V-shaped trailing edge reduces the vortex-induced vibration. Donaldson (1956) performed systematic measurements of flow-induced vibration in Francis turbine runners with 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, a clear explanation of the physics behind the vibration reduction is still lacking.

The objective of the present study is to investigate the effect of an oblique trailing edge on the wake dynamics to better describe the physical reasons for vibration reduction and allow for further optimization. The case study consists of two similar hydrofoils having blunt and oblique trailing edges and placed in the test section of the EPFL high-speed cavitation tunnel. The survey of the velocity field in the hydrofoil's wake is performed via Laser Doppler Velocimetery (LDV), and Particle-Image-Velocimetry (PIV). The Proper-Orthogonal-Decomposition (POD), is used for PIV data post processing to identify large coherent structures in the wake. In addition, flow-induced vibration and high-speed visualization are also carried out.

2. Case study and experimental set-up

Two NACA 0009 hydrofoils with truncated and oblique, $\beta = 30^\circ$, trailing edges are selected for the present investigation. The hydrofoils are made of stainless steel and they are fixed on one side and free the other side. Both have 100 mm chord length, L, 150 mm span length, b, and 10 mm maximum thickness, h, Fig. 1. Since the state of the boundary layer on the hydrofoil surface is an important parameter for correct comparison between the wakes dynamics of two selected hydrofoils (Ausoni et al., 2007), a special care is taken to ensure a similarity of their surface roughness. The measurements are carried out in the EPFL high-speed cavitation tunnel (Avellan et al., 1987), with a test section of $150 \times 150 \times 750\ \mathrm{mm}^3$, maximum inlet velocity, C_{ref}, of 50 m/s, and maximum static pressure, P_{inlet}, of 16 bars. The free stream turbulence intensity, derived from LDV measurement of the velocity field at test section inlet, was found to be around 1%.

Vortex-induced vibration is monitored on the hydrofoil surface with a Laser vibrometer. The measurement principle of this non-intrusive device is based on the detection of frequency shift between incident and reflected laser beam, Doppler Effect, which is directly related to displacement velocity of the surface. The measurement point is located at mid-span and 10% of chord length, upstream from the trailing edge. To allow for flow visualization, the wake is made visible by reducing the ambient pressure in the test section so that cavitation can develop within the core of the vortices. According to Ausoni et al. (2007), despite the increase of the vortex shedding frequency, cavitation has almost no effect on the wake structure. A high-speed camera, having an image resolution of 512×256 pixels at 10 000 frames/second frame rate is used to analyze the wake structure.

A survey of the velocity field in the hydrofoil wake is performed with a single-point, two components Laser Doppler velocimeter, LDV, and a 2–D Particle-Image-Velocimeter (PIV). For both methods, hollow glass spheres of 10 μm diameter,