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Effect of trailing edge shape on hydrodynamic damping for a hydrofoil

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ABSTRACT

Flow induced vibration on a hydrofoil may be significantly reduced with a slight modification of the trailing edge without alteration of the hydrodynamic performance. Particularly, the so called Donaldson trailing edge shape gave remarkable results and is being used in a variety of industrial applications. Nevertheless, the physics behind vibration reduction is still not understood. In the present study, we have investigated the hydrodynamic damping of a 2D hydrofoil with Donaldson trailing edge shape. The results are compared with the same hydrofoil with blunt trailing edge. The tests are carried out in EPFL high speed cavitation tunnel and two piezoelectric patches are used for the hydrofoil excitation in non-intrusive way. It was found that the hydrodynamic damping is significantly increased with the Donaldson cut. Besides, as the flow velocity is increased, the hydrodynamic damping is found to remain almost constant up to the hydrofoil resonance and then increases linearly, for both tested trailing edge shapes and for both first bending and torsion modes.

1. Introduction

Flow induced vibration is a major issue in a variety of industrial applications. In the particular case of hydropower generation, the strong increase in global energy demand and the liberalization of electricity market is putting more pressure on designers of turbines and pumps. Hydropower sector is struggling to supply more energy with enhanced efficiency and security while playing a growing role in stabilizing the electricity grid. In this context, hydraulic machines are operated more often at off-design conditions and subjected to frequent starts and stops, which may lead to excessive vibration with increased risks of mechanical failures.

Among the various hydrodynamic excitation sources of vibration, the vortex shedding from hydrofoils trailing edge is particularly dangerous because of the strong coherence of alternate shedding, which generates lift fluctuation and may lead to mechanical resonances. Although the phenomenon of vortex shedding has been widely investigated, most of the studies were limited to the case of the flow around a cylinder at relatively low Reynolds number (Williamson and Govardhan, 2004). Bourgoyne et al. (2003) carried out time-averaged flow-field measurements for a modified NACA 16 with two trailing-edge bevel angles at high Reynolds number (between 1×10^6 and 50×10^6). A strong dependence on Reynolds number was revealed, which the authors explained by a change in flow's dynamic components. Shannon (2007) investigated the mechanism of trailing edge noise by measuring flow field and acoustic variables for incompressible and high Reynolds

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Nomenclature

β	ratio of the excitation frequency to the undamped natural frequency [dimensionless]
ς	total damping factor [dimensionless]
ς_s	structure damping factor [dimensionless]
ς_h	hydrodynamic damping factor [dimensionless]
μ	dynamic amplification factor [dimensionless]
ν	Poisson's ratio [dimensionless]
ρ_s	density [kg/m^3]
υ	kinematic viscosity [m^2/s]
C^*	reduced flow velocity $C^* = C/fL$ [dimensionless]
C	flow velocity [m/s]
E	material Young modulus [GPa]
f	hydrofoil vibration frequency [Hz]
f_e	excitation frequency [Hz]
f_1	undamped natural frequency for 1st bending mode [Hz]
f_2	undamped natural frequency for 1st torsional mode [Hz]
H	hydrofoil trailing edge thickness [m]
L	the profile chord length [m]
x	deflection of the patch [m]
x_0	static deflection [m]
$\dot{x}$	velocity [m/s]
$\ddot{x}$	acceleration [m/s^2]
w_n	natural frequency of the hydrofoil [rad/s]
S_t	Strouhal number $S_t = fh/C$ [dimensionless]
R_e	Reynolds number $R_e = Ch/\upsilon$ [dimensionless]

number flows. Ausoni et al. (2007) have shown how a blunt trailing edge hydrofoil may undergo large vibration when the shedding frequency locks onto the resonance frequency of its 1st torsion mode. They have also highlighted the significant role of the boundary layer and cavitation occurrence on the roll-up mechanism of trailing edge vortices.

In an attempt to mitigate the flow induced vibration due to wake instability, a large number of remedies were proposed, with a common idea of disturbing the process of vortex roll-up in the formation zone. Theoretical analysis of trailing edge noise produced by turbulent flow over an airfoil was presented by Howe (1988). He concluded that surface beveling had a significant effect on the radiation only at sufficiently high frequencies that the trailing edge may be regarded as a straight-sided wedge over distances of the order of the turbulence length scale. Krentel and Nitsche (2013) performed experimental investigations on four different trailing edge shapes of a bluff airfoil, in order to mitigate the process of periodic and alternate vortex shedding. They have shown that a significant reduction of noise may be obtained with optimized trailing edge geometry. In hydraulic machines, it is well known that vortex shedding from the blades trailing edge may excite the mechanical structure. By sharpening the trailing edge, the frequency of the noise may be shifted with reduced amplitude (Ruprecht et al., 2003). Mosallem (2008) performed numerical simulation of the flow field past beveled trailing edges. The results displayed an asymmetric wake beyond 27° beveled trailing edge and Von Kàrman street vortices beyond 60° beveled trailing edge. In a well detailed experiment, Zobeiri et al. (2012) has shown how a simple 30° oblique truncation of a hydrofoil trailing edge may significantly reduce the vibration without alteration of hydrodynamic performances. They clearly observed that the oblique truncation generates a phase shift between upper and lower vortices and leads to their "collision" and partial cancellation. As a result, a significant thickening of their viscous cores and a reduction of their intensity were obtained. Donaldson (1956) performed systematic measurements of flow-induced vibration in Francis turbine runners with a large variety of trailing edge shapes. He found a substantial reduction of vibration with a combination of a straight line at 45° angle and a 3rd polynomial curve (see Fig. 1). Although this so-called Donaldson trailing edge shape performs well in a variety of industrial applications, the physics behind the vibration reduction is still lacking.

One way to evaluate the effect of trailing edge shape on the flow induced vibration is the measurement of resulting change in the hydrodynamic damping. In fact, any alteration of the wake dynamic directly impacts the fluid structure interaction and the way the flow reacts to damp out the structural vibration. Hydrodynamic damping has long been of special interest in many flow configurations such as cables, pipes (Blevins, 1990; Naudascher and Rockwell, 2006) and cylinders (Chaplin and Subbiah, 1998). Kaminer and Nastenko (1976) first measured the hydrodynamic damping related to bending oscillations of blade profiles in water flow. He pointed out that hydrodynamic damping varies in a linear way with reduced flow velocity and may be influenced by the profile solidity. Recently, Seeley et al. (2012) investigated experimentally the hydrodynamic damping of three hydrofoils. The results indicated that although the natural frequency was not altered by the flow, the damping ratio increased in a linear manner with respect to flow velocity.

The identification of a blade hydrodynamic damping is a difficult task as previously reported by many authors (Seeley et al., 2012; Roth et al., 2009). The vibration due to flowing water makes traditional testing methods of dynamic system identification impractical. In order to overcome these difficulties, Roth et al. (2009) used underwater spark generated bubbles to create shock waves that excite the hydrofoil in a wide frequency band in non-intrusive way. The mechanical response was monitored on the hydrofoil surface with a laser vibrometer. The damping factor was estimated by fitting an exponential function on the envelope of the hydrofoil impulse response. Nevertheless, it was found that beyond a threshold value of 15 m/s flow velocity, such a method is no more appropriate since the flow induced vibration becomes significantly larger than the impulse response. An alternate technique for the mechanical excitation of a hydrofoil is the use of embedded piezoelectric actuators (Seeley et al., 2012; De La Torre, 2013; De La Torre et al., 2013), which provides an interesting and non-intrusive way to excite a specific eigen mode of immersed hydrofoils.