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Experimental investigation of cavitating flow-induced vibration of hydrofoils

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ABSTRACT

The objective of this paper is to investigate the unsteady cavitation behaviors and corresponding cavity-induced vibrations. Experimental results are presented for NACA66 hydrofoils made of stainless steel and POM Polyacetate for various cavitation regimes. A simultaneous sampling technique is applied to analyse the transient cavitating flow structure and corresponding structural vibration characteristics. The results showed that the maximum vibration amplitude keeps relative small for the inception and sheet cavitation, increases dramatically for the cloud cavitation and declines for the supercavitation. As for the cloud cavitation regime, the trend of the vibration velocity goes up with the growth of the attached cavity, accompanied with small amplitude fluctuations, and decreases with large amplitude fluctuations. At the moment the cloud cavity breaks from the primary attached cavity, the vibration velocity hits the peak. As for the effect of hydroelastic response, the main vibration frequency for POM Polyacetate hydrofoil is larger than that for stainless steel hydrofoil due to the larger angle of attack caused by the twist deformation. The cavitation pattern for POM Polyacetate hydrofoil appears to be fragmentized, corresponding to the chaotic hydroelastic response of the hydrofoil, which is mainly attributed to the disturbance caused by the deformation and cavity-induced vibration.

1. Introduction

Cavitation generally occurs when local fluid pressure reduces to the saturated vapor pressure and consequently bubbles filled with vapor are formed. It is of primary importance for ship propulsion and marine vehicles because it may lead to many problems such as pressure pulsations, vibration, noise and erosion (Joseph, 1995; Aktas et al., 2016; Shi et al., 2016; Chen et al., 2015a, 2015b). The general descriptions of cavitating flow could refer to Brennen (1995), Wang et al. (2001), Franc and Michel (2005) and Foeth (2008). Recently, with the development of the experimental techniques, various test facilities have been used to improve the understanding of the complex structure of cavitating flows (Iyer and Ceccio, 2002; Chen et al., 2017; Li et al., 2008; Luo et al., 2016, Peng et al., 2016). Since the cavitation involves complex interaction between phase-change and vortex structures, it is well known that the unsteady breakdown and shedding of the cavities will induce strong transient loads and lead to further hydrodynamic instabilities, even structure failures. Hence, it is necessary to understand the influence of unsteady cavitation on the flow induced vibrations, which in turn affects the unsteady cavitating flow behaviors.

Flow induced vibration problem has been one of the major issues in a wide range of fields, such as aerospace industry, ocean engineering, marine structure and propulsion for a long time (Donaldson, 1956; Howe, 1988; Williamson and Govardhan, 2004; Müller et al., 2010; Naudascher and Rockwell, 2006; Chen et al., 2015c). So et al. (2000) investigated the structural dynamics and wake flow with the free vibration of an elastic cylinder in a cross flow, using a laser vibrometer to assess the bending displacement and a laser Doppler anemometer to measure the velocity in the wake. They found that the cylinder vibrations enhanced the turbulent mixing and increased the turbulent intensities. Ducoin et al. (2012a, 2012b) experimentally characterized the laminar to turbulent boundary layer transition induced vibrations. It showed that the vibration characteristics depended on the vortex shedding frequency and coupled with natural frequencies of hydrofoils. Based on the general vibration characteristics investigations, many effects, such as material properties and hydrofoil trailing edge shapes, on the flow-induced vibration have also been discussed (Zobeiri et al., 2012; Yao et al., 2014; Astolfi et al., 2015; Yamaguchi et al., 2000a, 2000b). Pärssinen et al. (2007) presented measurements with five plate materials over a range of Reynolds numbers. The results showed that the vibration frequency and amplitude

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are modified due to material properties. As the mass ratio (M^*) is increased the vibration frequency increases and the dimensionless amplitude (A/d) decreases. The number of synchronization regions decreases and the ranges extend wider in terms of Re number with increasing M^*. Al-Jamal and Dalton (2004) presented the computational study on the effect of mass factor to vortex-induced vibration. They discovered that the decreased mass ratio had the effect of increasing the lock-in range. Zhang and Dalton (1996) studies the effect of material damping to the vortex-induced vibrations of a circular cylinder. They found that the material damping not only reduces the amplitude of vibration and the amplification factors on lift and drag coefficients, but also shifts the natural frequencies at which maximum amplitude and amplification occur to larger value.

In addition to the above works that focused on fully wetted flow-induced vibration, flow induced vibration in cavitating flows were experimentally studied (Kawakami et al., 2008; Arndt, 2012; Ducoin et al., 2012a, 2012b; Akcabay et al., 2014; Wu et al., 2015). Amromin and Kovinskaya (2000) analyzed the vibration of an elastic hydrofoil with an attached cavity in periodically perturbed flow, where a beam equation was used to describe the hydrofoil vibration. The results showed that the structural vibration increased significantly due to the cavitation. The high-frequency band was attributed to the hydrofoil resonance with the cavity adding a certain damping and the low-frequency band was corresponding to the cavity volume fluctuations. Ausoni and Escaler (2007) conducted the experimental studies to investigate the effects of cavitation and fluid-structures interaction on vortex generation mechanism. They found that the vortex-induced vibration level significantly increased at cavitation onset and the transverse velocity at the hydrofoil trailing edge increased the vortex strength. Torre et al. (2013) conducted a series of experiments to investigate the influence of the sheet cavitation and supercavitation on the added mass effects experienced by a modified NACA0009 hydrofoil. The results showed that the added mass decreases when cavitation appears because of the increased cavity length.

Although the phenomenon of cavitation and cavitating flow-induced vibration has been studied, a brief review of these recent works indicates that we still have inadequate understanding on the correlation between the structural vibration and the transient cavitating flow patterns, since it's difficult to measure the unsteady vibration velocity/amplitude and moreover synchronize the cavitation behaviors. The objective of this work is to shed light on the unsteady cavitating flow and corresponding vibration characteristics via a simultaneous sampling technique. Further investigation of the flow induced vibration with different structural material properties is presented. The effect of hydroelastic response on the flow-induced vibrations and the cavitation development is also discussed.

2. Experimental set-up

Experimental studies are conducted in a closed-loop cavitation tunnel at Beijing Institute of Technology (Li et al., 2008; Wu et al., 2015), which is shown in Fig. 1. The test section is 0.7 m long and has a rectangular section with width of 0.07 m and height of 0.19 m. A tank with volume of 5 m^3 is located upstream of the test section, and a vacuum pump is connected to the top of the tank. Two main control parameters, the upstream pressure and the flow velocity, are measured by the vacuometer (with the uncertainty 0.25% of the maximum range) and the electromagnetic flowmeter (with the uncertainty 0.5% of the maximum range) respectively.

The cavitation patterns are documented by a high-speed digital camera (HG-LE, by Redlake), with two light sources illuminating the flow field from different directions, as shown in Fig. 2. The measurement system has a sampling frequency of up to 10^5 frames per second, and in order to maintain desirable spatial resolutions, 2500 fps is used in this study.

The vibration velocities are measured on the pressure side of hydrofoil with a single point Laser Doppler Vibrometer (LDV) Polytec PSV-100

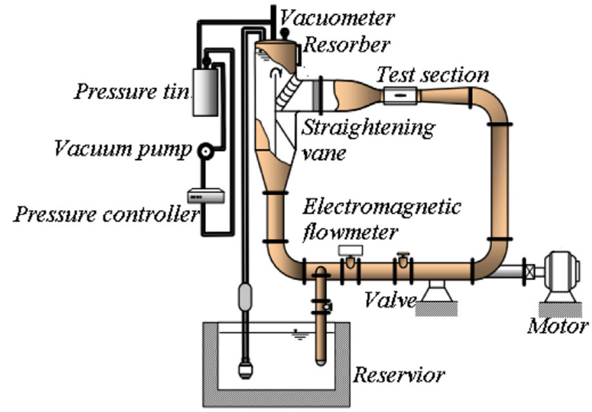

Fig. 1. Schematic of the cavitation tunnel.

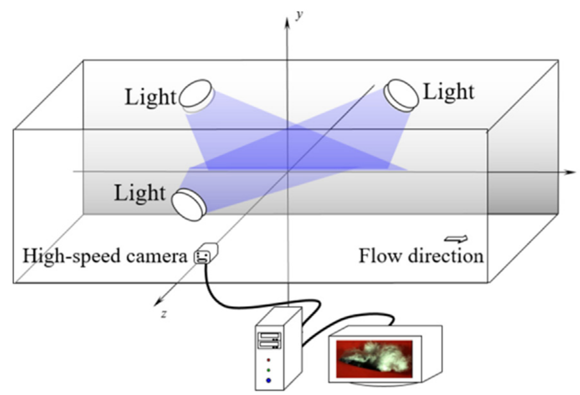

Fig. 2. Schematic of high-speed camera.

(Wu et al., 2015) through the transparent bottom wall of the test section, as shown in Fig. 3. The analog output with voltage signal is directly proportional to the target velocity component along the direction of the laser beam, with the calibration accuracy within 1%. The smallest possible measurement range (20 mm/s as its peak), with the velocity resolution less than 0.02 μm/s, is used to optimize the signal-to-noise ratio. The sample frequency of 22 kHz has been chosen to recover an accurate description of the main frequencies and suppress noise at higher frequencies. Then the voltage signal can be fed into digital inputs of a data acquisition system (NI X Series Multifunction Data Acquisition), whose largest sampling rate is 1.25 M Sample per channel, and 20.48 kHz is used in the present study, followed by a three-level 1-D wavelet analysis using the Haar wavelet (Strang and Nguyen, 1996) to de-noise the signal.

To better investigate the correlation between the unsteady cavitation behaviors and the flow induced vibration, a simultaneous sampling system, which combines the high-speed visualization and unsteady vibration measurement setups with a controller, is applied in the experiments, as shown in Fig. 3. As a single-shot waveform generator, when the controller is triggered, the voltage signal will jump to a higher value above the threshold value (1000 mV is used in the present work) and an electrical waveform will be generated to trigger the high-speed camera and the Laser Doppler Vibrometer, so that the cavitation images and unsteady vibration velocities will be captured simultaneously and then the signal data will be transferred to different data acquisition system respectively. Even though the sampling rate of high-speed camera is far less than that of LDV system, each cavity image will be synchronized with the vibration velocity signal according to the physical instantaneous time.

The modified-NACA66 (Wu et al., 2015), which has a uniform cross-section of shape with chord length $c = 0.075$ m, span $b = 0.069$ m