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Parametric excitations and lock-in of flexible hydrofoils in two-phase flows

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ABSTRACT

This work introduces a reduced-order method to study the parametric excitations and lock-in of flexible hydrofoils caused by unsteady two-phase (cavitating) flow. The reduced-order method is based on a 1-DOF structural model coupled with a van der Pol wake oscillator with empirically derived relations for the variation in lift, cavity-length, and cavity-shedding frequency as a function of a non-dimensional cavitation parameter. The results are compared with several available data from both numerical simulations and experimental measurements. The frequency content of both the predicted and measured vibrations suggested that, in addition to the primary cavity-shedding frequency and the hydrofoil natural frequencies, unsteady two-phase flows may excite additional modulated frequencies due to time-varying fluid-added mass effects. The results show that these frequency modulations might cause the flexible hydrofoil to undergo higher-order resonances, as well as parametric resonances. While the maximum deformations for the primary and higher-order resonances were observed to damp out, parametric resonances might persist even with realistic fluid damping coefficients (4–12%). It was observed that with higher effective foil flexibility, the cavity-shedding frequencies may be significantly modified from the rigid foil trends, and may instead lock-in with the system natural frequencies.

1. Introduction

Lift-generating-structures (LGS), such as propulsors, turbines, rudders, hydrofoils, and control surfaces operating in water and in high-speed conditions near the free surface, may be vulnerable to hydrodynamic cavitation. Hydrodynamic cavitation develops when the liquid changes to vapor if the local pressure drops to the saturated vapor pressure. The cyclic formation and breakdown of cavities induces large load fluctuations, and may result in undesirable effects such as vibration, noise, loss of performance, material fatigue, erosion, etc. (Franc, 2006). These effects are particularly critical for flexible LGSs, which have a promise to deliver superior performances during off-design conditions or when operating in spatially/temporally varying flows (Liu and Young, 2009; Motley et al., 2009; Young, 2008); note that flexible LGSs can also be used as renewable energy harvesting devices (Erturk et al., 2010; Peng and Zhu, 2009).

In a recent study, Akcabay et al. (2014a) showed that for flexible hydrofoils in cavitating flows, the cavity-shedding frequencies may lock-in (collapse on) to one of the wetted natural frequencies of the hydrofoil ("primary lock-in")

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and/or their subharmonics ("secondary lock-in"). Lock-in, in general, is a resonant-type phenomenon that occurs if primary frequencies of different system physics (e.g. fluid, elastic, acoustic) coalesce due to particular operating or design conditions. In the scope of fluid and elastic lock-in, much work has been given to the aeroelastic and hydroelastic stabilities in single-phased flows; classic examples include flow-induced vibrations of flexible cylinders (e.g. Facchinetti et al., 2004; de Langre, 2006; Khalak and Williamson, 1999; Williamson and Govardhan, 2004). At lock-in, vortex-shedding frequencies, if near one of the structural natural frequencies, will deviate from the Strouhal law and will rather match with the particular structural natural frequency. Interested readers may refer to Rockwell and Naudascher (1978) for a review of fluid and acoustic lock-in examples.

Besides lock-in, it has also been shown in Akcabay et al. (2014a) and Rajaomazava et al. (2013) that unsteady hydrodynamic cavitation may also produce additional modulated frequencies in the vibration response; this is because the effective fluid-added mass fluctuates with changes in the fluid-mixture density. A major implication of the presence of modulated frequencies for cavitating systems is the added risk for primary parametric resonance: a case if the parametric excitations occur at twice of one of the system natural frequencies, for which vibrations may get much higher than for the case with classical resonance. It is important to note that the topic of parametric excitations due to density variations is also relevant for a wide range of multiphase flow problems; examples include boiling or cavitating flows inside or outside pipes (Klein, 1981), surface piercing foils/propellers (Motley et al., 2013; Kramer et al. 2013; Young and Savander, 2011; Young and Kinnas, 2004; Young and Kinnas, 2002), and parametric roll excitations of marine vessels (Umeda et al., 2004; France et al., 2003). Parametric excitations may also be induced by gravity waves (Joubaud et al., 2012) and by periodic large-scale vortex shedding of lightweight natural and artificial swimmers (e.g. Ruiz et al., 2010; Dabiri, 2006). Parametric excitations have been extensively studied in the context of mechanical systems, sensor technologies, and electronics. In the scope of mechanics, asymmetric rotary machineries; wind-turbines with base excitations; and marine structures that are exposed to cavitation, free-surface waves, or multiphase flows may all be susceptible to parametric excitations.

Note that in addition to hydrodynamic cavitation, various other sources may excite flexible LGSs. For example, the incoming flow may not necessarily be uniform (Xiu and Karniadakis, 2003), the base structure onto which the LGS was attached to might undergo mechanical vibrations (Larsen and Nielsen, 2007), or there may be unsteady flow separation and vortex shedding (Chae et al., 2015; Poirel and Yuan, 2010), or the LGS may undergo controlled oscillations (Huang et al., 2013; Anderson et al., 1998; Fish and Lauder, 2006). It should be noted that much work has been published on flow-induced vibration in single-phase media, and it is not the focus of the current paper. Instead, the focus of this work is to study the effects of cavity-induced vibrations on flexible foils in absence of external excitations, as it is a special case of flow induced vibrations that can lead to parametric excitations due to large density fluctuations caused by periodic cavity shedding, a phenomena that does not exist in single phase flows, in addition to lock-in. However, for final practical engineering designs, one should combine the results of this study with other checks (e.g. flutter and divergence instability conditions (see Chae et al. (2013) for more details), (single-phase) vortex-induced vibration and lock-in of flexible foils (see Chae et al. (2015) for more details), and other resonant conditions (e.g. Young, 2008; Motley et al., 2013; Kramer et al., 2013).

This paper studies the critical conditions for frequency lock-in and parametric excitations of flexible hydrofoils in unsteady cavitating flows through the development of a simple reduced-order method (ROM). This ROM was validated with experimental studies for two different flexible, rectangular foils across a wide range of flow conditions, to demonstrate that the ROM is not limited to a specific case. The ROM is designed to capture the critical physics governing the dynamic response and stability of flexible hydrofoils in unsteady cavitating flows, and is useful to quickly explore a large operating space to identify critical conditions before designing and calling for further experiments or higher fidelity numerical studies. The ROM can also be used to assist the design of control strategies to mitigate cavity-induced vibrations.

2. Physical model

Akcabay et al. (2014a), Akcabay and Young (2014), Chae et al. (2015), and Chae et al. (2013) modeled the spanwise bending and twisting deformations of a flexible, cantilevered, rectangular hydrofoil through Eq. (1), which was coupled to a viscous, incompressible, and multiphase flow solver (see Akcabay et al. (2014a) for a detailed sketch of the geometry).

$$\mathbf{M_s}\ddot{\mathbf{X}}+\mathbf{C_s}\dot{\mathbf{X}}+\mathbf{K_s}\mathbf{X}=\mathbf{F_{fluid}}. \tag{1}$$

In Eq. (1), $\mathbf{M_s}$, $\mathbf{C_s}$, and $\mathbf{K_s}$, are, respectively, the foil mass, material damping, and stiffness matrices; $\mathbf{X}$ is the vector of structural displacements (spanwise bending and twisting deformations), where the overhead dots denote the Lagrangian time derivatives. Following Theodorsen (1935), Munch et al. (2010), Young et al. (2012), and Chae et al. (2013), the fluid forces induced on the hydrofoil ($\mathbf{F_{fluid}}$) were decomposed into fluid added mass, fluid damping, and fluid stiffness force components as

$$\mathbf{F_{fluid}}=-\mathbf{M_f}\ddot{\mathbf{X}}-\mathbf{C_f}\dot{\mathbf{X}}-\mathbf{K_f}(\mathbf{X}+\boldsymbol{\lambda}_0), \tag{2}$$

where $\mathbf{M_f}$, $\mathbf{C_f}$, and $\mathbf{K_f}$ are, respectively, the fluid-added mass, damping, and stiffness matrices; while $-\mathbf{K_f}\boldsymbol{\lambda}_0$ is the fluid force component due to the initial alignment of the foil relative to the inflow (e.g. initial angle of attack and foil camber). As shown in Theodorsen (1935), Munch et al. (2010), and Akcabay et al. (2014a), all components of $\mathbf{F_{fluid}}$ are proportional to the fluid density ρ_f, $\mathbf{C_f}$ and $\mathbf{K_f}$ depend on the flow velocity and the square of the flow velocity, respectively, and both terms have an additional dependency to the flow frequency due to fluid memory/radiation effect associated with the foil interactions