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Non-linear hydrodynamics of thin laminae undergoing large harmonic oscillations in a viscous fluid

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ABSTRACT

Smoothed Particle Hydrodynamics is implemented to study the motion of a thin rigid lamina undergoing large harmonic oscillations in a viscous fluid. Particularly, the flow physics in the proximity of the lamina is resolved and contours of non-dimensional velocity, vorticity and pressure are presented for selected oscillation regimes. The computation of the hydrodynamic load due to the fluid–structure interaction is carried out using Fourier decomposition to express the total fluid force in terms of a non-dimensional complex-valued hydrodynamic function, whose real and imaginary parts identify added mass and damping coefficients, respectively. For small oscillations, the hydrodynamic force reflects the harmonic nature of the displacement, whereas multiple harmonics are observed as both the amplitude and frequency of oscillation increase. We propose a novel formulation of hydrodynamic function that incorporates added mass and damping coefficients for a thin rigid lamina spanning large amplitudes in viscous fluids in a broad range of the oscillation frequencies. Results of the simulations are validated against numerical and experimental works available in the literature in addition to theoretical predictions for the limit case of zero-amplitude oscillations.

1. Introduction

The dynamic interaction of slender structures with a surrounding viscous fluid represents a challenging fluid–structure interaction (FSI) problem. Increasing attention among researchers is being paid to FSI problems in many fields of engineering, from marine propulsion and vortex-induced vibrations (VIV) (Du et al., 2014; Nguyen et al., 2012), to biomimetic thrusters (Aureli et al., 2010; Triantafyllou et al., 2004), micro-electro-mechanical systems (MEMS) (Kimber et al., 2009) and atomic force microscopy (AFM) (Basak et al., 2006; Sader, 1998). For example, the suppression of VIV on flexible submerged structures has entailed a great deal of research in the field of ocean and offshore engineering in order to ensure acceptable lifespans of marine equipment, including risers, pipelines and offshore platforms (Huang, 2011; Sun et al., 2012; Zhang et al., 2014). At smaller length scales, amplification mechanisms and other engineering systems have been developed to take advantage of VIV hydrodynamics at low Reynolds numbers and harvest power from specific devices (e.g. Chen et al., 2010; Grouthier et al., 2014; Quadrante and Nishi, 2014; Wang et al., 2014). Several approaches have been adopted for studying the vibrations of structures with different geometries coupled with a viscous fluid. Analytical models are appealing due to the availability of closed-form solutions, and a great amount of work has been funneled towards this

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direction (e.g. Lamb, 1920; Amabili and Kwak, 1996; Amabili, 1996a,b). However, the theoretical tractability of these problems is restricted to a few particular cases and the use of numerical and experimental techniques is thus required for solving more general cases, see for example Amabili (2000, 2001) and Amabili et al. (2002).

The vibrations of flexible cantilever beams in a viscous fluid are widely used in engineering applications, such as the above-mentioned. In the case of a slender structure, the cross-section of the cantilever is often modeled as a rectangular plate with negligible thickness. Therefore, the beam is considered infinitely thin in the direction of vibration and it is possible to bypass the complexity of a 3-D vibrational problem by focusing the attention on the two-dimensional flow field generated by transverse oscillations of the beam cross-section, provided that low vibrational modes are considered. Detailed work on the flow variability along the axis of thin cantilevers is reported in Facci and Porfiri (2013), where the acceptability of the two-dimensional approach mentioned above is deemed correct for a wide range of width-to-length ratios. For beam cross-sections undergoing harmonic oscillations, which are of interest in this study, the nature of the displacement and subsequent hydrodynamic response promote the use of a non-dimensional frequency parameter, β, (Sarpkaya, 1986) rather than the classical Reynolds number. Analytical works based on the linearization of the Navier–Stokes equations, (Sader, 1998; Tuck, 1969) have shown the unique dependence of the hydrodynamic load on β for infinitely small oscillations. Results therein are presented in the form of a complex-valued hydrodynamic function, $\Gamma(\beta)$, identifying added mass and hydrodynamic damping originated by the encompassing fluid. A detailed study by Aureli et al. (2012) has taken into account the non-linearities arising from vortex formation, shedding and advection in the case of finite-amplitude vibrations of thin cantilever beams. The hydrodynamic function, $\Theta(\beta, \mathrm{KC})$, computed therein incorporates a correction term, $\Delta(\beta, \mathrm{KC})$, representing the dependence of the resultant fluid force on an amplitude parameter, namely the Keulegan–Carpenter number (KC). Furthermore, several formulations have been proposed to consider the effect of parameters such as the presence of a solid wall or a free surface in the vicinity of the oscillating lamina (Grimaldi et al., 2012; Tafuni and Sahin, 2013), the influence of the beam width-to-thickness ratio (Phan et al., 2013), the coupling of two oscillating bodies in a viscous fluid (De Rosis et al., 2014; Intartaglia et al., 2014), or the effect of a shear-dependent viscosity on the vibrations of a thin lamina (De Rosis, 2014). In each case, a different hydrodynamic response is observed and a variety of hydrodynamic functions have been cast to accurately predict fluid actions in the form of added mass and damping coefficients.

In this work, a Smoothed Particle Hydrodynamics (SPH) numerical investigation is proposed for the formulation of a novel hydrodynamic function characterizing thin rigid laminae oscillating in an unbounded viscous fluid at moderate-to-high frequencies and large amplitudes. We build on the work of Aureli et al. (2012), where the derived hydrodynamic function, $\Theta(\beta, \mathrm{KC})$, is limited to specific ranges of frequency and Keulegan–Carpenter number. We consider similar frequencies and extend the amplitude range up to oscillation strokes comparable with the plate width. At small amplitudes, the fluid force is observed to reflect the harmonic nature of the displacement, while multiple harmonics appear at larger amplitudes, and a loss of the force harmonicity is noted. We proceed by extracting added mass and damping coefficients for each pair, (β, KC), via Fourier analysis, and extrapolate a new hydrodynamic function that is considered a good approximation in the chosen range of non-dimensional parameters.

The application of Smoothed Particle Hydrodynamics to FSI problems has become widely popular in the last two decades (Bouscasse et al., 2013; Caleyron et al., 2013). SPH is a numerical technique based on the discretization of continuum fields of hydrodynamics through the use of mesh-less nodes, generally identified as particles. Thus the methodology represents a numerical equivalent of using the Lagrangian approach for solving the equations of hydrodynamics. Although SPH has originally been derived in the study of astrophysics (Gingold and Monaghan, 1977; Lucy, 1977), its Lagrangian nature is also appealing to problems of fluid mechanics, particularly in cases that are not easily solvable using other computational techniques, such as Finite Difference Methods (FDM) or Finite Volume Methods (FVM). SPH algorithms are robust and perform well especially in the presence of flow fields with rapidly changing properties, moving boundaries and free surfaces (Liu et al., 2014; Marrone et al., 2011; Monaghan, 1994). For example, the discretization process through mesh-based methods often requires the implementation of burdensome re-meshing techniques to accurately model a moving boundary in a viscous fluid. This is not necessary in SPH, where both fluid and solid quantities are not retrieved on a grid, but intrinsically retained by the particles, and spatial interactions are computed through weighted interpolations about neighboring particles. This feature of SPH algorithms makes them also easy to implement, suitable to parallelization, and very attractive for large simulations (Dominguez et al., 2013b; Ferrari et al., 2009). However, the use of SPH for the analysis of the vibrations of slender structures in a viscous fluid has not yet been investigated, and this work is intended to show how this methodology can be successful in solving the hydrodynamic coupling between an oscillatory viscous flow and a thin rigid lamina.

2. Mathematical formulation and numerical model

2.1. Governing equations and non-dimensionalization

In this work, we consider harmonic large-amplitude oscillations of a rigid lamina in a quiescent viscous fluid. The nomenclature adopted to describe the FSI problem is summarized in Fig. 1. Particularly, we focus our analysis on a thin rectangular plate, Ψ, with B and H representing the width and thickness, respectively, and $H \ll B$. The problem is formulated by attaching a Cartesian reference frame, $O(x, y, z)$, to Ψ, such that the y-axis is aligned with B, the z-axis is through H, the x-axis closes the right-hand system and the origin is coincident with the centroid of Ψ. The lamina oscillates in the vertical