



Nonlinear oscillations of shape-morphing submerged structures: Control of hydrodynamic forces and power dissipation via active flexibility



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HIGHLIGHTS

- We study nonlinear periodic oscillations of a shape-morphing plate in a viscous fluid.
- The plate deforms to an arc of a circle with prescribed curvature during oscillations.
- We study hydrodynamic forces and power dissipation in different regimes.
- Hydrodynamic forces can be controlled and reduced by varying the imposed curvature.
- Hydrodynamic power dissipation exhibits a minimum for optimal plate curvature.

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ABSTRACT

In this paper, we consider nonlinear oscillations of a shape-morphing plate submerged in a quiescent, Newtonian, viscous fluid. We investigate the two-dimensional problem arising from two prescribed concurrent periodic motions of the plate: a rigid oscillation along its transverse direction coupled to a shape-morphing deformation to an arc of a circle with prescribed maximum curvature. As opposed to existing literature concerned with passive flexible structures, this study focuses on actively prescribed deformations of the structure as a means to manipulate the vortex-shedding and convection patterns responsible for hydrodynamic forces and power dissipation during underwater oscillations. We elucidate the potential of the proposed shape-morphing strategy in regulating the added mass and damping effects along with the hydrodynamic power dissipation both in the linear and nonlinear hydrodynamic regime, by utilizing a linear boundary integral formulation as well as computational fluid dynamics simulations. Results show the possibility of minimizing the hydrodynamic power dissipation for optimal values of the imposed curvature, along with significant reduction of the hydrodynamic forces. A simplified semianalytical argument relates these novel effects to specific geometric properties of the plate motion. Findings from this study are directly relevant to cantilever-based sensing and actuation systems operating in fluids, where control and modulation of oscillation quality factors, hydrodynamic forces, and power losses is beneficial.

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1. Introduction

In recent years, a broad class of problems concerned with oscillating slender cantilever-like structures in viscous fluids has attracted a considerable amount of research interest from the fluid–structure interaction (FSI) community. These problems are relevant to many diverse engineering applications, spanning for example atomic force microscopy (Maali et al., 2005; Sader, 1998; Tung et al., 2014), micromechanical sensors and actuators (Eastman et al., 2012; Hosaka et al., 1995; Kimber et al., 2009), piezoelectric fan systems (Bidkar et al., 2009; Ihara and Watanabe, 1994; Kimber and Garimella, 2009), biomimetic robotic propulsion (Aureli et al., 2010a; Behbahani and Tan, 2016; Cen and Erturk, 2013; Cha et al., 2016; Chen et al., 2010; Erturk and Delporte, 2011; Masoud and Alexeev, 2010; Mazaheri and Ebrahimi, 2012; Shyy et al., 2010), and smart material-based energy harvesting devices (Akaydin et al., 2010; Aureli et al., 2010b; Cha et al., 2016; Dias et al., 2013; Erturk and Delporte, 2011; Singh et al., 2012; Shahab and Erturk, 2015). In these applications, the operation of such devices is often primarily controlled by the complex nonlinear coupling in the FSI problem, resulting in hydrodynamic forces experienced by the submerged structure and power dissipation during underwater oscillation.

In an effort to tackle the solution of this class of problems, neglecting hydrodynamic effects along the axis of the submerged structure is a common modeling assumption that simplifies the treatment by considering only the local cross sectional oscillation and provides accurate results almost everywhere in the fluid field (Facci and Porfiri, 2013). The reduction of the fully coupled three-dimensional (3D) FSI problem to a two-dimensional (2D) one has been first proposed for the case of an oscillating submerged microcantilever in Sader (1998), by adapting the hydrodynamic function concept developed in Tuck (1969) for a linear unsteady Stokes flow. Within this approach, a one-way coupled fluid problem is solved, typically via a boundary element method, for a set of governing nondimensional parameters to determine the hydrodynamic forces exerted on the structure during the oscillation. These forces are then used to construct a mathematically manageable representation, in terms of the governing parameters, to be incorporated in a reduced-order dynamic model of the submerged structure. This technique has been extensively used in several works concerned with small amplitude oscillations of flexible submerged structures in unsteady Stokes flows (Brumley et al., 2010; Intartaglia et al., 2014; Green and Sader, 2002, 2005; Van Eysden and Sader, 2007).

Experimental and numerical studies have shown that, when the oscillation amplitude is moderately large, the predicted hydrodynamic forces based on the linear theory may significantly underestimate the actual forces experienced by the submerged structure (Aureli and Porfiri, 2010; Aureli et al., 2012a; Bidkar et al., 2009). Major discrepancies are especially observed in the behavior of the hydrodynamic damping, which displays an important dependence on the oscillation amplitude in this nonlinear regime and has been associated to increased vortex shedding and convection for large amplitude oscillation (Bearman et al., 1985; Graham, 1980; Keulegan and Carpenter, 1956; Sarpkaya, 1986; Smith and Stansby, 1991; Troesch and Kim, 1991).

In previous works by our group, we have demonstrated that hydrodynamic forces and power dissipation due to large amplitude oscillations in the nonlinear regime can be modulated via structural modification, for example by modifying the aspect ratio of the oscillating cross section (Phan et al., 2013). In Ahsan and Aureli (2015), we introduced a set of flanges on the oscillating structure as a means to effectively control the mechanisms of vortex shedding and convection. Results therein demonstrate that the flanges promote a specific vortex-structure interaction pattern that results into reduction of hydrodynamic damping and power losses for an optimum flange size. It should be noted that the optimum flange size is dependent on the specific dynamic characteristics of the oscillation, including frequency and amplitude. Therefore, while the use of flanges is effective for modulating hydrodynamic effects at a fixed operating point, this solution may be suboptimal if the cantilever is designed to oscillate over a broad range of frequencies and amplitudes.

To overcome this limitation, in this study we investigate the effect of an actively imposed shape-morphing deformation as a novel strategy to control hydrodynamic forces and power dissipation. To this aim, we consider a submerged thin plate, representative of the cross section of an oscillating cantilever system, that undergoes two concurrent periodic motions: a rigid oscillation along its transverse direction coupled to a shape-morphing deformation to an arc of a circle with prescribed maximum curvature. In a practical implementation of this system, the prescribed “chord-wise” curvature could be impressed via smart materials, such as piezoelectric patches (Jalili, 2010), electroactive polymers (Bar-Cohen, 2004), or shape memory alloys (Lagoudas, 2008), embedded in the flexible structure. When considering a 2D cross section of the system, the situation is reminiscent of the span-wise flexibility studied in the literature on the propulsion performance in flapping wing and fin systems, see for example Cleaver et al. (2014), Lauder and Madden (2007), Masoud and Alexeev (2010), Triantafyllou et al. (2000) and Wang et al. (2015). In these studies, it has been observed that span-wise flexibility significantly improves the propulsion performance and considerably reduces drag forces. It should be noted that, in these studies, the structure’s flexibility is “passively imposed” by typically prescribing the material stiffness. In this case, the resulting structural displacements are thus evaluated via dynamic equilibrium with the hydrodynamic actions (Katz and Weihs, 1978; Lauder et al., 2006; Lucas et al., 2014; Masoud and Alexeev, 2010). Conversely, in this work, we assign the actual displacement for the deforming structure by completely prescribing its motion, independently of the hydrodynamic response to the deformation. Correspondingly, the fluid problem is solved by considering the actively deforming structure as an infinitely stiff moving boundary in the fluid domain.

Towards this goal, we identify the nondimensional parameters that govern the fluid problem and study the hydrodynamic forces and power dissipation over a wide range of these parameters, describing frequency, amplitude of oscillation, and imposed curvature. In this study, we first focus on the asymptotic case of infinitely small amplitudes of oscillation, where

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