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Numerical investigation of the interaction of a vortex dipole with a deformable plate

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ABSTRACT

Energy harvesting from coherent fluid structures is a current research topic due to its application in the design of small self-powered sensors for underwater applications. The impact of a vortex dipole with a deformable cantilevered plate at the plate tip is herein studied numerically using a strongly coupled staggered fluid–structure interaction algorithm. Three dipole Reynolds numbers, Re=500, 1500, and 3000, are investigated for constant plate properties. As the dipole approaches the plate, positive vorticity is produced on the impact face, while negative vorticity is generated at the tip of the plate. Upon impact, the dipole splits into two, and two secondary dipoles are formed. The circulation and, therefore, the trajectories of these dipoles depend on both the Reynolds number and the elasticity of the plate, and these secondary dipoles may return for subsequent impacts. While the maximum deflection of the plate does not depend significantly on Reynolds number, the plate response due to subsequent impacts of secondary dipoles does vary with Reynolds number. These results elucidate the strong interdependency between plate deformation and vortex dynamics, as well as the effect of Reynolds number on both.

1. Introduction

The desire for sensor systems and networks with long operational lives for use in remote locations has driven research into small-scale energy harvesting from the surrounding fluid. Examples include energy harvesting from flapping flags (Giacomello and Porfiri, 2011; Michelin and Doare, 2013), miniature water turbines (Myers et al., 2007; Priya et al., 2005; Cellini et al., 2014), unsteady aerodynamic loads on airfoils (de Marqui and Erturk, 2012) and the wake of bluff bodies (Allen and Smits, 2001; Akaydin et al., 2012). One particular energy harvesting modality receiving attention recently is associated with the energy exchange between coherent fluid structures and deformable plates (Akaydin et al., 2010a,b; Weinstein et al., 2012; Peterson and Porfiri, 2012b; Goushcha et al., 2014). Employing an electro-active polymer as the deformable plate facilitates conversion of mechanical energy imparted from the fluid to the plate into usable electrical energy (Nemat-Nasser and Li, 2000; Shahinpoor and Kim, 2001).

Due to their prevalence in nature and simplicity of generation in a laboratory environment, vortex rings are often employed as a canonical coherent fluid structure in energy harvesting studies involving compliant smart materials. For example, Peterson and Porfiri (2012b) presented a series of experiments in which a vortex ring impacts the tip of a cantilevered electro-active polymer and

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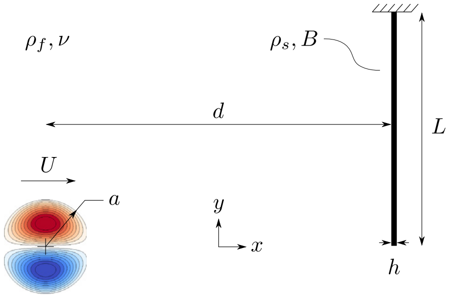

Fig. 1. Schematic of the problem setup, including pertinent physical parameters and variable definitions.

assessed the resulting energy harvesting capacity. Goushcha et al. (2014) reported an alternate configuration in which a vortex ring advects past a cantilevered electro-active polymer plate oriented in the same direction as the ring propagation. As the ring passes by, the induced pressure distribution along the plate changes and the plate starts vibrating. Subsequent rings can either enhance or mitigate the vibration amplitude and, consequently, the energy harvesting capacity.

A first order model approximating a vortex ring approaching a wall can be constructed using potential flow by replacing the vortex ring with a pair of free vortices. The kinematics of the impact of the vortex pair with an infinite rigid wall in an ideal fluid is well known (Milne-Thomson, 1996). Saffman (1979) extended the canonical solution for point vortices to account for finite core size and demonstrated that the core deforms when the pair is in the vicinity of the wall. van Heijst and Flor (1989) presented experimental results of a dipole impacting a rigid wall. They observed a rebound effect, in which secondary dipoles form after the initial impact. Peace and Riley (1983), as well as Lim et al. (1991), have shown that the rebounding is in essence a viscous effect, where the pressure field of the impacting dipole results in vorticity production on the surface of the no-slip wall, which ejects and combines with the primary dipole to generate a pair of secondary dipoles that can propagate away from the wall in some cases.

Orlandi (1990) presented high Reynolds numbers numerical simulations that demonstrate increasingly complex vortex dynamics produced with increasing Reynolds number, including collisions of secondary dipoles with the wall and the formation of finer tertiary structures. The dynamics of oblique dipole/wall collisions were studied by Clercx and Bruneau (2006). Peterson and Porfiri (2013) considered the impact of a vortex dipole with the tip of a semi-infinite rigid plate. Their results show that secondary (and tertiary) dipoles form along the plate in a manner similar to the findings of Orlandi (1990), while vorticity shed from the tip combines with half of the initial dipole to generate a secondary tip dipole. The hydrodynamic loading in the vicinity of the tip of the plate during primary impact is a relatively weak function of the incoming dipole Reynolds number in the range of 500–3000.

Compared to the previous research involving rigid boundaries, the interaction of a vortex dipole (or pair) with a compliant surface has not been investigated in detail. Peterson and Porfiri (2012a) presented a fully-coupled analytical fluid–structure interaction (FSI) model of the impact of a point–vortex pair with a deformable cantilevered plate in an ideal fluid. Their model represents the plate and vortex motion well only when the vortex pair is sufficiently far from the plate; however, the absence of viscosity precludes vorticity production along the plate. As shown in the study of the impact with a semi-infinite rigid plate (Peterson and Porfiri, 2013), the production of vorticity on the plate surface can dramatically influence the overall dynamics during impact. The present investigation considers the impact of a vortex dipole with the tip of a deformable cantilevered plate. Based on the findings from the analytical potential flow fluid–structure interaction model of Peterson and Porfiri (2012a) and their follow-up work of a dipole in a real fluid impacting a semi-infinite rigid plate (Peterson and Porfiri, 2013), the model proposed herein incorporates viscous effects to adequately resolve fluid–structure interactions and the attendant vortex dynamics. Specifically, a strongly coupled staggered FSI simulation is used to investigate the interaction of a Lamb dipole (Lamb, 1932) with a finite length cantilevered plate. The results of the simulation are analyzed in terms of vortex dynamics and plate loading, as well as energy transfer from the dipole into potential and kinetic energy of the plate.

2. Problem setup

A schematic of the two-dimensional (2D) problem under consideration is shown in Fig. 1. A Lamb dipole is initialized at a distance d from a cantilevered plate of length L and thickness h. The fluid is modeled as incompressible and Newtonian, with density ρ_f and kinematic viscosity ν. A Cartesian coordinate system is defined at the mid-point between the initial position of the dipole and the plate tip, with the x coordinate aligned with the direction of dipole propagation and the y coordinate oriented parallel to the plate in its undeformed state. The plate is thin, that is, $h \ll L$; the deflection is confined to the x direction only and considered small compared to the length of the plate. Consequently, the plate is modeled as a Kirchhoff–Love plate, with density ρ_s and bending stiffness per unit width B, undergoing pure cylindrical bending.[1] The dipole is completely characterized by its

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[1] We note that the use of linear plate theory results in an extensible plate. In the current study, which employs a cantilevered plate configuration, the plate tip deflections are less than $0.3L$. For tip deflections of $0.3L$, the discrepancy in the tip displacements predicted by linear versus nonlinear theories is