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Stabilizing effect of porosity on a flapping filament

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ABSTRACT

A new way of handling, simultaneously, porosity and bending resistance of a massive filament is proposed. Our strategy extends the previous methods where porosity was taken into account in the absence of bending resistance of the structure and overcomes related numerical issues. The new strategy has been exploited to investigate how porosity affects the stability of slender elastic objects exposed to a uniform stream. To understand under which conditions porosity becomes important, we propose a simple resonance mechanism between a properly defined characteristic porous time-scale and the standard characteristic hydrodynamic time-scale. The resonance condition results in a critical value for the porosity above which porosity is important for the resulting filament flapping regime, otherwise its role can be considered of little importance. Our estimation for the critical value of the porosity is in fairly good agreement with our DNS results. The computations also allow us to quantitatively establish the stabilizing role of porosity in the flapping regimes.

1. Introduction

Motion of deformable, slender structures immersed in an incompressible viscous fluid is common in natural phenomena, and can be found in many applications such as paper processing (Lundell et al., 2011), energy harvesting (McKinney and DeLaurier, 1981; Boragno et al., 2012; Orchini et al., 2013) and passive control (Favier et al., 2009; Lācis et al., 2014; Orchini et al., 2015). In the present paper, we study numerically how porosity – a key factor in a number of both biological and technological tissues – plays a role in the dynamics of a flapping hinged filament, commonly referred to as the flag-in-the-wind problem. Similar to previous works (Peskin, 2002; Zhu and Peskin, 2002; Kim and Peskin, 2007), an immersed boundary (IB) approach has been used in order to efficiently handle elastic interfaces interacting with a viscous incompressible fluid. The IB method is used for a wide range of applications, from blood flow around cardiac valves (Kovacs et al., 2001) and animal locomotion (Fauci and Peskin, 1988) to flow in deformable tubes (Beyer, 1992).

The flag-in-the-wind – i.e. an elastic one-dimensional boundary tethered at one end in a two-dimensional laminar flow – has been studied theoretically, numerically and experimentally as the archetype for the instability of an elastic structure subject to a fluid flow. Under certain conditions a phenomenon, known as flutter, is caused by a positive feedback between the body's deflection and the forcing exerted by the fluid flow. Often, a number of frequencies are triggered by the uniform flow affecting the body, which begins to resonate when its own natural frequency has been excited. This paper aims at

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investigating how porosity affects the stability of slender elastic objects exposed to a uniform stream. The long-term motion of the filament can result in a fixed-point solution, a limit-cycle flapping or a chaotic motion, depending on the governing parameters of the system (Shelley and Zhang, 2011).

Starting from Rayleigh's first theoretical approach in Rayleigh (1879) involving the evolution of a two-dimensional vortex sheet, the stability analyses of the flag have been enriched by inertial and structural mechanical properties (Connell and Yue, 2007; Lighthill, 2007; Coene, 1992; Argentina and Mahadevan, 2005; Skotheim and Mahadevan, 2004). More recently, increasingly accurate numerical studies (most of them using an immersed boundary approach) have come into support of analytical results (Peskin, 2002; Uhlmann, 2005; Pinelli et al., 2010; Favier et al., 2014). In particular, Zhu and Peskin (2002) first pointed out the important role of length and mass on the onset of flapping, and described the bistable behavior of the flapping. Both Kim and Peskin (2007) and Huang et al. (2007) developed methods to handle massive filaments more efficiently. The first numerical study taking into account porosity was by Kim and Peskin (2006), in which the dynamics of a porous massless 2D parachute not resisting bending was investigated. An overview of the dynamics of slender interacting body with fluid flows is found in Shelley and Zhang (2011).

In the present work, we propose a way of modeling porosity and bending resistance of a massive filament which overcomes some of the major drawbacks of the method proposed in Kim and Peskin (2006). The approach proposed here is based on the method described by Huang et al. (2007), and provides enhanced numerical stability with respect to the approach suggested in Kim and Peskin (2006) by avoiding the spring-like discretization of the filament and the penetration velocity given in Eq. (15) of the same paper. The 1D porous filament can be considered as a model for the flow in one plane perpendicular to a 3D permeable sheet. The porous filament can also be considered as a model for a three dimensional flow past an impermeable fiber, where the leakage through the porous filament corresponds to the flux past the filament in the 3D problem (see e.g. Wexler et al., 2013).

The paper is organized as follows. Section 2 describes the numerical model, while Section 3 contains a comparison between our model for porosity and Darcy's law. In Section 4 the numerical scheme is validated using an analytical stability criterion based on the slender body theory. Numerical and theoretical results are presented in Sections 5 and 6, respectively. Finally conclusions are drawn in Section 7.

2. Problem formulation

We consider a one-dimensional incompressible elastic filament of length L^*, with mass per unit length ρ_S^* and bending rigidity K_b^*, exposed to a viscous incompressible fluid of density ρ_F^*, viscosity ν^* with a uniform velocity U_∞^*. The governing equations for the fluid are the Navier–Stokes equation (1) considered together with an appropriate volume forcing $\mathbf{f}(\mathbf{x}, t)$ to enforce the no-slip condition on the filament,

$$\begin{cases} \dfrac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \dfrac{1}{\mathrm{Re}} \nabla^2 \mathbf{u} + \mathbf{f} \\ \nabla \cdot \mathbf{u} = 0 \end{cases}, \tag{1}$$

where $\mathbf{u}(\mathbf{x}, t)$ is the velocity field, $p(\mathbf{x}, t)$ is the pressure field and Re is the Reynolds number. Here $\mathbf{x} = (x, y) \in \Omega$ is the Cartesian physical coordinates, with Ω denoting the physical domain, x and y are the stream-wise and cross-stream direction, respectively.

The filament dynamics is considered in Eqs. (2) and (3), where the first is d'Alembert elastic string equation and the second introduces the tension as a Lagrange multiplier in order to enforce incompressibility (Huang et al., 2007),

$$\frac{\partial^2 \mathbf{X}}{\partial t^2} = \frac{\partial}{\partial s}\left(T \frac{\partial \mathbf{X}}{\partial s}\right) - \frac{\partial^2}{\partial s^2}\left(\gamma \frac{\partial^2 \mathbf{X}}{\partial s^2}\right) + \mathrm{Fr}\frac{\mathbf{g}}{g} - \mathbf{F}, \tag{2}$$

$$\frac{\partial \mathbf{X}}{\partial s} \frac{\partial^2}{\partial s^2}\left(T \frac{\partial \mathbf{X}}{\partial s}\right) = \frac{1}{2} \frac{\partial^2}{\partial t^2}\left(\frac{\partial \mathbf{X}}{\partial s} \frac{\partial \mathbf{X}}{\partial s}\right) - \frac{\partial^2 \mathbf{X}}{\partial t \partial s} \frac{\partial^2 \mathbf{X}}{\partial t \partial s} - \frac{\partial \mathbf{X}}{\partial s} \frac{\partial}{\partial s}(\mathbf{F}_b - \mathbf{F}). \tag{3}$$

Here, $s \in \Gamma$ is the Lagrangian curvilinear coordinate, with Γ denoting the body surface; $\mathbf{X}(s, t) = (X_1(s, t), X_2(s, t)) \in \Gamma$ denotes the physical position of each material point of curvilinear coordinate s at time t and $T(s, t)$ represents the tension. In particular, on the right hand side of Eq. (2) the first two terms represent the tensional ($\mathbf{F}_s$) and bending terms ($\mathbf{F}_b$). The last term are the Lagrangian forces exerted by the fluid on the structure, obtained by means of Eqs. (4) and (6), where the first is Goldstein's feedback law (Goldstein et al., 1993) and the latter is the reduction due to porosity, whose meaning will be explained in Section 2.4. Notice that the non-slip condition is enforced implicitly by means of

$$\mathbf{F}_{imp}(s, t) = \alpha \int_0^t \left(\mathbf{U}_{ib} - \frac{\partial \mathbf{X}}{\partial t}\right) dt' + \beta \left(\mathbf{U}_{ib} - \frac{\partial \mathbf{X}}{\partial t}\right), \tag{4}$$

$$\mathbf{U}_{ib}(s, t) = \int_\Omega \mathbf{u}(\mathbf{x}, t) \delta(\mathbf{x} - \mathbf{X}(s, t))\, d\Omega, \tag{5}$$

$$\mathbf{F} = (1 - \lambda) \cdot (\mathbf{F}_{imp} \cdot \mathbf{n})\mathbf{n} + (\mathbf{F}_{imp} \cdot \boldsymbol{\tau})\boldsymbol{\tau}. \tag{6}$$