Computers & Fluids 97 (2014) 1–20

Contents lists available at ScienceDirect

Computers & Fluids

journal homepage: www.elsevier.com/locate/compfluid

Numerical study on hydrodynamic effect of flexibility in a self-propelled plunging foil

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A R T I C L E I N F O

Article history:
Received 15 October 2013
Received in revised form 17 February 2014
Accepted 31 March 2014
Available online 13 April 2014

Keywords:
Fluid–structure interaction
Passive flexibility
Self-propulsion
Plunging foil
Immersed boundary method
Vortex street

A B S T R A C T

The present study is a numerical investigation of the hydrodynamic effects of passive flexibility on a self-propelled plunging foil. In the model problem, the flow is two-dimensional, incompressible and laminar, while the flexible foil is treated as an inextensible filament. The leading-edge of the foil undergoes a prescribed harmonic oscillation in the vertical direction. In the horizontal direction, the foil is free to move and no constraint is imposed. The simulations are performed by using a solver which couples the immersed boundary method for the flow and the finite difference method for the structure. A systematic parametric study has been conducted to investigate the effects of flexibility on important physical quantities such as the cruising speed, swimming power and propulsive efficiency. It is found that optimal cruising speed is always achieved in foils with some passive flexibility and not the rigid ones. Another important finding is that optimum performance is always achieved at a forcing frequency much lower than the resonance point. Based on the simulation results, three dynamical states of a self-propelled foil have been identified with the increase of bending rigidity, i.e., non-periodic movement, periodic backward-movement and periodic forward-movement. For a flexible foil in forward movement, depending on the range of bending rigidity, either a deflected or a symmetric vortex street arises as the characteristic wake structure. It is found that moderate flexibility is beneficial to symmetry preservation in the wake, while excessive flexibility can trigger symmetry-breaking. The results obtained in the current work shed some light on the role of flexibility in flapping-based biolocomotion.

1. Introduction

Flapping motions of wings/fins are used by animals (such as birds, insects, bats and fishes) to generate lift or thrust to keep them aloft or propel themselves in the surrounding fluid. Researches in this area are not only motivated by the fundamental interest of understanding the mechanism of animal flight and swimming, but also the development of micro air vehicles (MAVs) and autonomous underwater vehicles (AUVs) based on biomimetics. A foil in steady forward motion and a combination of harmonic plunging and pitching has served as a simplified model for the study of efficient locomotion in animals. Till now extensive researches on flapping foils have been conducted, both experimentally and computationally.

Although (passive) flexibility of wing/fin has long been recognized as an important factor in the aerodynamic (hydrodynamic) performance of insect flight or fish swimming, it has received little attention until recently (see [1,2] for a comprehensive review). By using a combination of computational and analytic methods, Daniel and Combes [3] have shown that the deformation in flapping wings was dominated less by aerodynamic loading than by inertial and elastic forces. In a series of experimental studies, chordwise and spanwise flexibility have been shown to increase propulsive efficiency in flapping-based propulsion [4–6]. In the works by Ishihara et al. [7] and Zhao et al. [8], a dynamically scaled mechanical model of flapping flight was used to measure the aerodynamic forces on flapping wings of variable flexural stiffness. Due to the complexity of fluid–structure interaction (FSI) problems, in computational simulations simplifications are usually made, either in the model for the fluid or for the structure. For example, Katz and Weihs [9] and Michelin and Llewellyn Smith [10] have used the potential flow theory to describe the interaction between an inviscid flow and a flexible flapping wing; whereas a reduced-order model has been used for the structures in other works [11–13]. With the availability of better computing power and more sophisticated numerical methods, simulations which include the interaction of viscous fluid and solid continuum were performed in some more recent studies [14–22].

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http://dx.doi.org/10.1016/j.compfluid.2014.03.031
0045-7930/

One point has to be underlined here: in most studies concerning flapping foils, the interaction between a flapping body held static and an oncoming flow driven independently is considered. However, the decoupling of the flapping dynamics and the forward speed makes those systems very dissimilar to free-flying (or free-swimming) animals. Thus the utilization of 'self-propelled' device is preferable in the study of biolocomotion [23]. Till now, only limited studies have been conducted to understand the behaviors of 'self-propelled' flapping-foil systems. For rigid flapping foils, experimental studies on a model mounted on a 'merry go round' can be found in Vandenberghe et al. [24] and Vandenberghe et al. [25]; numerical simulations of simplified models can be found in Alben and Shelley [26], Lu and Liao [27], and Zhang et al. [28]. For flexible flapping foils, Spagnolie et al. [29] and Zhang et al. [30] used the 'lumped-torsional' model to mimic the flexibility of the structure (i.e., a plunging rigid plate with a torsion spring acting about the pivot at the leading edge to produce passive pitching). Eldredge and Pisani [31] and Wilson and Eldredge [32] have also performed simulations of a self-propelled flexible swimmers represented by an articulated system of linked rigid bodies. Recently, self-propelled flapping devices with realistic flexible wings were built to investigate the role of resonance in optimizing the performance [33, 34] and the scaling of cruising speed with foil length and bending rigidity [35]. A numerical study of such system was also performed in [35], where the foil is treated as an elastica and a 'body-vortex-sheet' model is used for the fluid. This fluid model is still based on the potential (inviscid) flow theory, although some empirical models were used to include the effect of viscous drag. Despite of the encouraging agreements between the experiments and the inviscid predictions, the range of validity of the inviscid assumption is still limited by the onset of dynamic stall. This is particularly true at low Reynolds numbers typically required in the flights of MAVs. Moreover, although some physical insights have been gained by using reduced-order models for the structures, the behavior of a dynamical system consisting of torsional springs and rigid components is still very different from that of an elastica. Thus we believe FSI simulations that use the Navier–Stokes equations for the fluid and the equation of solid continuum for the flexible foil are essential for elucidating the effect of flexibility on the performance of a self-propelled flapping system. We also noticed a most recent work by Lee and Lee [36], where numerical simulations of such system have been conducted by using the lattice Boltzmann method. Their work only focused on the effect of flexibility on propulsive velocity. To the best of our knowledge, a *thorough and systematic* study regarding the role of flexibility in such system still lacks in the literature.

In this paper, we proposed to model such system by considering the interaction of a self-propelled inextensible filament with a two-dimensional viscous flow. We developed a solver by coupling the Navier–Stokes equations for the fluid and a geometrically nonlinear equation for the structure. The model problem is then systematically investigated by means of numerical simulations. The purposes of the current work are twofold. First, by using the data from the numerical simulations, we would like to clarify the speculation regarding the connection between performance optimum and occurrence of resonance. Second, we would like to uncover some information which are lacking in inviscid simulations or simulations using the 'lumped-torsional' model, e.g., the mode shape of the flexible foil during flapping and the true wake structure behind the foil in forward movement. Such information are crucial for understanding the role of flexibility in propulsive performance of a flapping-foil system.

The rest of the paper is arranged as follows. In Section 2, the model problem and governing equations are presented. In Section 3, the numerical methods and simulation set-up are described. Section 4 presents the results and discussions. Finally, some conclusions are drawn in Section 5.

2. Model problem and governing equations

We consider the model problem of a self-propelled flexible foil driven by the plunging motion (see Fig. 1). The foil is clamped at the leading-edge which undergoes a harmonic oscillation in the vertical direction, but is free to move horizontally.

The fluid flow is assumed to be laminar and incompressible. The governing equations are written in the dimensionless form as

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{u}) = -\nabla p + \frac{1}{\mathrm{Re}_f}\nabla^2 \mathbf{u} + \mathbf{f}, \tag{1}$$

$$\nabla \cdot \mathbf{u} = 0, \tag{2}$$

where $\mathbf{u}$ is the fluid velocity, p the pressure. Re_f is the flapping Reynolds number which is defined as $\mathrm{Re}_f = \rho_f U_{ref} L/\mu$, with ρ_f, $Uref$, L and μ being the density of fluid, reference velocity, chord length of the foil and dynamic viscosity of the fluid, respectively. $\mathbf{f}$ is the (dimensionless) Eulerian forcing that is used to mimic the effect of the immersed object on the fluid flow. The reference velocity used in this work is $U_{ref} = 2\pi A f$, where f is the frequency of the plunging motion and A is the oscillation amplitude of the leading edge. Thus the reference velocity is equivalent to the maximum flapping velocity.

In this study, we consider a two-dimensional flow interacting with a flexible foil. Due to its small thickness–length-ratio, the flexible foil is treated as an inextensible filament. The governing equations for the motion of the filament can be written in a dimensionless form as

$$\beta\frac{\partial^2 \mathbf{X}}{\partial t^2} - \frac{\partial}{\partial s}\left(\zeta\frac{\partial \mathbf{X}}{\partial s}\right) + \frac{\partial^2}{\partial s^2}\left(\gamma\frac{\partial^2 \mathbf{X}}{\partial s^2}\right) = \beta Fr\frac{\mathbf{g}}{g} - \mathbf{F}, \tag{3}$$

$$\frac{\partial \mathbf{X}}{\partial s}\cdot\frac{\partial \mathbf{X}}{\partial s} = 1, \tag{4}$$

where s is the Lagrangian coordinate along the arc length; $\mathbf{X}$ is the displacement vector; β, ζ and γ are the mass ratio, dimensionless tension coefficient and dimensionless bending rigidity respectively. $\mathbf{F}$ is the (dimensionless) Lagrangian forcing term due to the interaction with the fluid; $\mathbf{g}$ is the acceleration of gravity and $g = |\mathbf{g}|$. Fr is the Froude number defined as gL/U_{ref}^2. The gravitational term in Eq. (3) is zero for all simulations performed in this paper except one validation case for the structural solver (see Section 3.2 for the details).

The dimensionless parameters, β, ζ and γ, are defined as

$$\beta = \frac{\rho_s}{\rho_f L}, \quad \zeta = \frac{T}{\rho_f U_{ref}^2 L}, \quad \gamma = \frac{B}{\rho_f U_{ref}^2 L^3}, \tag{5}$$

where ρ_s is the linear density of the filament; T and B are the dimensional tension and bending rigidity respectively. Eq. (3) is equivalent to those used by Zhu and Peskin [37], Connell and Yue [38] and Huang et al. [39] for flexible structures. Eq. (4) is the inextensibility condition which acts as a constraint on the

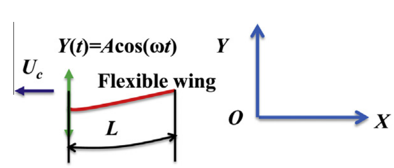

Fig. 1. Schematic depiction of the model problem: a self-propelled flexible foil of length L driven by a harmonic plunging motion at the leading-edge.