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Numerical studies of the hysteresis in locomotion of a passively pitching foil*

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Abstract: The direct-forcing fictitious domain method is extended to simulate the locomotion of a passively pitching foil. Our study focuses on the hysteresis phenomenon that the critical frequency for the reverse of the locomotion direction of the wing in case of decreasing frequency is smaller than that in case of increasing frequency. In our simulations, the hysteresis phenomenon is produced by imposing different initial conditions at a same frequency. Our results indicate that the ratio of the heaving amplitudes of two foil edges is crucial to the direction of the foil's horizontal motion, and the amplitude of the leading edge is generally smaller. The critical frequencies for the reverse of the locomotion direction are increased, when the foil-fluid density ratio is decreased or the spring constant is increased. The critical frequencies in the bi-stability regime also depend on the initial velocity imposed, and the hysteresis loop generally becomes larger if the initial velocities are closer to the terminal locomotion velocities of the foil.

Key words: flapping foil, passively pitching, hysteresis, fictitious domain method

Introduction

The flapping locomotion of insects, birds and fishes was extensively studied[1-3]. At the early stage, the focus is on the production of the thrust and the lift on a wing model fixed in the streamwise direction and subject to a prescribed lateral flapping motion[4-6]. In recent years, the self-propelled flight or swimming was studied. Vandenberghe et al.[7,8] experimentally investigated the dynamics of a rigid symmetric foil that flaps vertically and moves freely in the horizontal direction in a fluid. They observed the locomotion of the foil above a critical flapping frequency. The dynamics of the self-propelled body under a given vertical flapping motion were numerically studied by Alben and Shelley[9], Lu and Liao[10], Zhang et al.[11] and Hu and Xiao[12].

Spagnolie et al.[13] experimentally examined the locomotion of a flapping foil which pitched passively. One edge of the foil was driven to heave vertically, and the wing was able to passively pitch with a restoring torque from a torsional spring and to translate in the horizontal direction. They observed a hysteresis phenomenon: the foil reversed its motion direction as the heaving frequency was increased or decreased, but the critical frequency in the case of decreasing frequency was smaller than that in the case of increasing frequency. The dynamics of such a model was numerically studied by Spagnolieet al.[13], Zhang et al.[14] and Xiao et al.[15], but the hysteresis phenomenon has not been reproduced and studied. The aim of the present study is to numerically reproduce the hysteresis phenomenon, elucidate its mechanism, and examine the effects of the density ratio and the spring constant.

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1. Physical model and numerical method

1.1 *Physical model*

The flapping foil is modeled as a two-dimensional elliptic body (as shown in Fig.1). The major and minor axis lengths are $2a$ and $2b$, respectively. The right edge of the elliptic wing is driven to heave vertically, with the position given as

$$y_p(t) = A\cos(2\pi f t) \tag{1}$$

where A and f are the amplitude and the frequency of the oscillating motion.

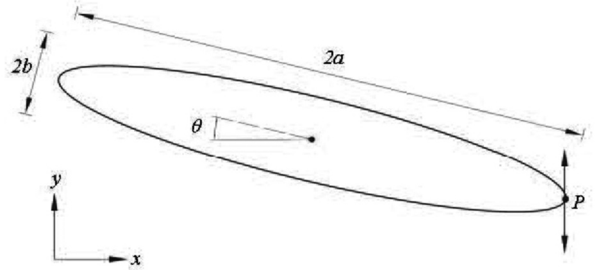

Fig.1 Schematic diagram of a two-dimensional elliptic body as a model of the foil. The right edge point is driven to move with a given vertical displacement $y_p(t)$. θ is the pitching angle between the elliptic major axis and the horizontal plane

The foil can rotate freely, and a torsional spring is introduced to produce a restorative torque, whose amplitude is linearly proportional to θ,

$$\tau = -k^*\theta \tag{2}$$

where k^* is the spring's torsional coefficient and θ is the pitching angle between the elliptic major axis and the horizontal plane.

1.2 *Numerical method*

Yu and Shao[16] proposed a direct-forcing fictitious domain method for the simulation of the particle motion in a fluid, by modifying the original fictitious domain method proposed by Glowsinki et al.[17]. The key idea of the fictitious domain method is that the interior domain of the solid body is assumed to be filled with the fluid and the inner fictitious fluid is constrained to move as a rigid body by a pseudo body force (i.e., Lagrange multiplier)[17]. In the present study, we further extend the fictitious domain method to deal with the flapping foil with passive pitching and translational motions as introduced earlier.

1.2.1 Governing equations

The original momentum equation for the fluid field can be written as follows

$$\rho_f \frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}t} = \nabla \cdot \sigma \quad \text{in} \quad \Omega_f \tag{3}$$

and the Newton's equations of motion for the foil are:

$$m\ddot{x}_0 = F_{Hx} \tag{4}$$

$$m\ddot{y}_0 = F_D + F_{Hy} \tag{5}$$

$$J\dot{\omega} = -k^*\theta + a\cos(\theta)F_D + T_H \tag{6}$$

where ρ_f is the fluid density, $\boldsymbol{u}$ the fluid velocity, σ the fluid stress tensor, Ω_f the fluid domain outside the foil, x_0 and y_0 are the positions of the foil mass center, F_{Hx} and F_{Hy} the hydrodynamic force components in the x and y directions, respectively, F_D is the external vertical driving force on the right point of the foil, ω the angular velocity of the foil, T_H the hydrodynamic torque on the foil, m the foil mass, and J the foil moment of inertia. From Eq.(1) and $y_0 = y_p - a\sin\theta$, the vertical translational velocity and acceleration of the foil center are

$$\dot{y}_0 = \dot{y}_p - a(\cos\theta)\omega \tag{7}$$

$$\ddot{y}_0 = \ddot{y}_p + a[(\sin\theta)\omega^2 - (\cos\theta)\dot{\omega}] \tag{8}$$

In the following, we deduce the fictitious domain formulation based on its key idea introduced earlier. First, we extend the fluid momentum Eq.(3) from the real fluid domain Ω_f to the entire domain Ω including Ω_f and the foil domain $P(t)$, and a pseudo body force $\boldsymbol{\lambda}$ is introduced to make the fictitious fluid inside the foil satisfy the rigid body motion constraint,

$$\rho_f \frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}t} = \nabla \cdot \boldsymbol{\sigma} + \boldsymbol{\lambda} \quad \text{in} \quad P(t) \tag{9}$$

$$\boldsymbol{u} = \boldsymbol{U} + \boldsymbol{\omega}_s \times \boldsymbol{r} \quad \text{in} \quad P(t) \tag{10}$$

in which $\boldsymbol{U}$ represents the foil translational velocity and $\boldsymbol{r}$ the position vector with respect to the foil mass center. Considering that

$$\boldsymbol{F}^H = \int_{\partial P} \boldsymbol{n} \cdot \boldsymbol{\sigma} \,\mathrm{d}\boldsymbol{x}, \quad \boldsymbol{T}^H = \int_{\partial P} \boldsymbol{r} \times (\boldsymbol{n} \cdot \boldsymbol{\sigma}) \,\mathrm{d}\boldsymbol{x} \tag{11}$$

and integrating Eq.(9) and $\boldsymbol{r} \times$ Eq.(9) over the foil domain $P(t)$, we obtain

$$\boldsymbol{F}_H = \rho_f V_p \dot{\boldsymbol{U}} - \int_P \boldsymbol{\lambda} \,\mathrm{d}\boldsymbol{x} \tag{12}$$

$$T_H = \frac{J}{\rho_r}\dot{\omega} - \int_P \boldsymbol{r} \times \boldsymbol{\lambda} \,\mathrm{d}\boldsymbol{x} \tag{13}$$

where V_p is the foil volume, and ρ_r is the density ratio, defined as $\rho_r = \rho_s / \rho_f$, with ρ_s being the foil

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