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Three-dimensional effects on the translational locomotion of a passive heaving wing

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ABSTRACT

This study was carried out on a three-dimensional wing with a freedom in translational direction under a prescribed up and down heaving motion. The investigation focused on how the system kinematics and structural parameters affect the dynamic response of a wing with a relatively small span length. The induced wing motion is a result of the system stability breakdown, which has only been observed by previous researches in the two-dimensional case. The results obtained indicate that the evolution of the wing locomotion is controlled not only by the flapping frequency but also influenced by the system inertia as well as the wing aspect ratio and density ratio. Moreover, initial perturbation effect on wings flexibility plays a role in the evolution development.

1. Introduction

The term “flapping” is always mentioned and employed in the study of wing motion of various animal species. In the classic studies, it is simplified to a combined pitching and heaving motion, and propulsion performance can be observed by examining the lateral fluid forces under a prescribed heaving or pitching motion numerically and experimentally (Triantafyllou et al., 1992; Lewin and Hajhariri, 2003; Dong et al., 2006; Heathcote and Gursul, 2007; Young and Lai, 2007; Tian et al., 2013).

In recent decades, attention has been focused on the propulsion mechanism under a coupled interaction between animal locomotion and its surrounding viscous fluid. In this context, the propulsion motion of animal is purely determined by the fluid force and moment generated by its forced locomotion. This is usually called, passive and self-propelled locomotion (Vandenberghe et al., 2004, 2006; Alben and Shelley, 2005; Lu and Liao, 2006; Spagnolie et al., 2010; Hu et al., 2011). Investigations are carried out by the foils with simple geometries, covering various system kinematic and structural parameters, such as foil shape, plunging frequency (f), amplitude (hc) and density ratio (σ). Results from these studies showed that the forced plunging motion leads to a symmetric foil moving in the direction perpendicular to the prescribed motion.

Although some research has been done in this self-propelled foil area, most of the above studies are focused on a large aspect ratio flapping wing. Therefore, a two-dimensional (2-D) assumption is reasonably valid, which significantly reduces the computational challenge and time. However, real aquatic animal fins may have relatively small aspect ratios such as the aspect ratios of four species of labrid fishes ranging from about 1.5 to 3.5 (Walker and Westneat, 2002), whereas bluegill sunfish and ratfish having pectoral fins with aspect ratios of about 2.4 (Drucker and Lauder, 1999) and 2.2 (Combes and Daneil, 2001), respectively, where three-dimensional (3-D) effect must be taken into account. Limited research on a 3-D

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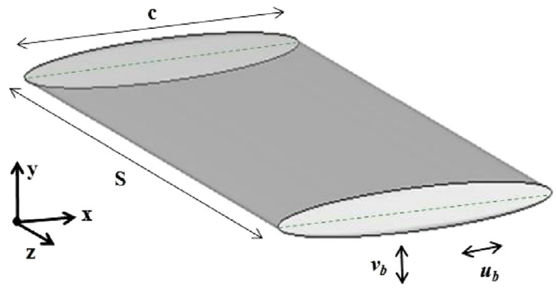

Fig. 1. Sketch of wing with an elliptical cross-section. The span is S and chord length c. The ratio of thickness to chord length is 0.1. It has a prescribed transverse velocity v_b and an induced translational velocity u_b.

tethered flapping wings shows that the wing with low aspect ratio generates high propulsion efficiency and reduced bending moment relative to the large aspect ratio wings (Walker and Westneat, 2002; Dong et al., 2006; Visbal et al., 2013).

The aim of present study is therefore to extend our recent work for a 2-D flapping foil with one degree of freedom (1-DoF) in translational direction, to a 3-D wing under low aspect ratio condition. Fig. 1 shows the wing under current investigation, a 3-D rectangular wing with an elliptical cross-section. The ratio of thickness to chord length is 0.1, and the aspect ratio is defined as $\mathrm{AR}=S/c$, where S is the wing span (wing tip to tip distance) and c is the chord length. Instead of a tethered flapping motion, the wing is allowed to move in lateral direction. It has a freedom in in-line (x) direction, which is solely determined by the fluid-motion coupling between fluid and wing.

Investigation is first carried out on comparing the evolution process of left-right symmetric wing with large and medium aspect ratios, which are treated by 2-D and 3-D respectively. As the wing propulsion performance can be determined by variation of flapping wing′s kinematics and structural dynamic parameters, the examination on how such phenomena are influenced by structural and kinematic parameters are important. Therefore, we further discuss this self-propelled phenomenon in the aspects of 3-D effect, density ratio effect and perturbation effect on the induced in-line(x) direction locomotion ability. Wake structures of wings are presented with different aspect ratios, and the dynamic behaviors and propulsive properties of passive plunging wing is further analyzed in terms of typical kinematic quantities, such as the mean horizontal speed and the Strouhal number (St). To simplify the problem, at this stage, only the in-line freedom of wing is considered, while the freedom in pitch direction is not allowed. Detailed investigations on a 3-D wing with combined pitch and in-line freedom are published on another relevant paper (Xiao et al., 2014).

2. Mathematic models and validations

2.1. Fluid-motion coupling model

Referred to Fig. 1, the wing motions $\mathbf{u}_b=(u_b, v_b, 0)$ are explained as follows:

1. A specified sinusoidal plunging motion v_b:

$$v_b(t)=hc\omega\ \sin\ (\omega t), \tag{1}$$

where h is the non-dimensional flapping amplitude, ω is the flapping angular frequency, and $\omega=2\pi f$, where f is the flapping frequency;

2. An induced velocity u_b which is solely determined by the unsteady fluid forces through Newton′s second law:

$$m_b\frac{du_b}{dt}=F_x, \tag{2}$$

where m_b is the mass of wing, F_x is the hydrodynamic force in X direction including both pressure force and viscosity force. The density ratio σ is defined as the ratio between the density of wing and fluid, and $m_b=\sigma\rho V$, where V is the volume of the wing.

The instantaneous propulsion velocity u_b is obtained by integrating Eq. (2) with a first-order explicit scheme

$$u_b^t=\frac{{F_x}^{t-\Delta t}}{m_b}\Delta t+u_b^{t-\Delta t}, \tag{3}$$

where u_b^t and $u_b^{t-\Delta t}$ are X direction velocities at time instants t and $t-\Delta t$.

The fluid motion is governed by 3-D incompressible continuity and momentum equations as

$$\nabla\cdot\mathbf{u}=0,$$
$$\frac{\partial\mathbf{u}}{\partial t}+\mathbf{u}\cdot\nabla\mathbf{u}=-\frac{1}{\rho}\nabla p+\frac{\mu}{\rho}\nabla^2\mathbf{u}, \tag{4}$$

where $\mathbf{u}=(u, v, w)$ is the fluid velocity, p is the fluid pressure, μ is the fluid viscosity and ρ is the fluid density.