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Dynamic flight stability of a hovering model dragonfly

Bin Liang, Mao Sun *

Ministry-of-Education Key Laboratory of Fluid Mechanics, Beijing University of Aeronautics & Astronautics, Beijing, China

HIGHLIGHTS

- Hovering flight of the model dragonfly is inherently unstable.
- The instability is caused by the horizontal-velocity/pitch-moment derivative.
- Damping force and moment derivatives weaken the instability considerably.
- Forewing/hindwing interaction has little effect on the stability properties.
- High stroke-plane angles affect how stability derivatives are produced.

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ABSTRACT

The longitudinal dynamic flight stability of a model dragonfly at hovering flight is studied, using the method of computational fluid dynamics to compute the stability derivatives and the techniques of eigenvalue and eigenvector analysis for solving the equations of motion. Three natural modes of motion are identified for the hovering flight: one unstable oscillatory mode, one stable fast subsidence mode and one stable slow subsidence mode. The flight is dynamically unstable owing to the unstable oscillatory mode. The instability is caused by a pitch-moment derivative with respect to horizontal velocity. The damping force and moment derivatives (with respect to horizontal and vertical velocities and pitch-rotational velocity, respectively) weaken the instability considerably. The aerodynamic interaction between the forewing and the hindwing does not have significant effect on the stability properties. The dragonfly has similar stability derivatives, hence stability properties, to that of a one-wing-pair insect at normal hovering, but there are differences in how the derivatives are produced because of the highly inclined stroke plane of the dragonfly.

1. Introduction

Dynamic flight stability is of great importance in the study of biomechanics of insect flight, and it also plays a major role in the development of insect-like micro-air vehicles (MAVs). This is because dynamic stability of a flying system represents the dynamic properties of the basic system, such as which degrees of freedom are unstable, how fast the instability develops, which variables are observable, and so on. In recent years, with the current understanding of the aerodynamic force mechanisms of insect flapping wings, researchers are beginning to devote more effort to understanding the area of dynamic flight stability in insects (e.g. Taylor and Thomas, 2003; Sun and Xiong, 2005; Sun and Wang, 2007; Hedrick et al., 2009; Faruque and Humbert, 2010a,b; Liu et al., 2010; Cheng and Deng, 2011).

This area is relatively new and research works in the area have been mainly on hovering flight. Sun and colleagues (Sun and Xiong, 2005; Sun et al., 2007; Zhang and Sun, 2010) studied the dynamic flight stability in several hovering insects (hoverfly, cranefly, dronefly, bumblebee, and hawkmoth). Faruque and Humbert (2010a,b) studied the dynamic flight stability in fruit flies. Cheng and Deng (2011) also studied the dynamic flight stability in several hovering insects (fruit fly, stalk-eyed fly, bumblebee and hawkmoth). In these studies, an 'averaged model' and the linear theory of aircraft flight dynamics were employed, greatly simplifying the analysis (in the averaged model, the wing-beat frequency was assumed to be much higher than that of the natural modes of motion of the insect, so that the insect could be treated as a flying body of only six degrees of freedom and the effects of the flapping wings were represented by wingbeat-cycle-average aerodynamic and inertial forces and moments that could vary with time over the time scale of the insect body). In order to compute the aerodynamic derivatives in the system matrices, Sun and colleagues (Sun and Xiong, 2005; Sun et al., 2007; Zhang and Sun, 2010) employed the method of computational fluid dynamics

* Corresponding author. Tel.: +86 1082313027; fax: +86 1082316100.
E-mail address: m.sun@buaa.edu.cn (M. Sun).

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(CFD) and Faruque and Humbert (2010a,b) and Cheng and Deng (2011) used the blade-element theory and the slopes of experimental lift and drag curves of a sweeping model fruit fly wing. The studies showed that although these insects were greatly different in size and wingbeat frequency (the mass of the insects ranged from 11 to 1648 mg and wingbeat frequency from 26 to 218 Hz), their hovering flight had qualitatively similar longitudinal stability properties (their longitudinal natural modes of motion were the same).

Insects considered in the above studies flap their wings approximately in a horizontal plane (called 'normal hovering'), and furthermore, they have only one pair of wings morphologically (the flies) or functionally (the bees and moths). Dragonflies flap their wings in highly inclined planes and they have two pair of wings morphologically and functionally. It is of great interest to know whether or not the stability properties of dragonflies are different from that of these insects.

In the present study, we conduct a quantitative analysis on the dynamic flight stability of the longitudinal motion of a hovering model dragonfly. Azuma and Watanabe (1988) measured the wing-kinematical data of the dragonfly *Anax parthenope julius* in free flight at very low speed and Norberg (1975) measured the data of the dragonfly *Aeschna juncea* in free hovering flight; these data are used for the model dragonfly. The required morphological data of the dragonfly *Anax parthenope julius* are measured by the present authors. The averaged model theory is used for the analysis. The method of computational fluid dynamics (CFD) is used to compute the flows and obtain the stability derivatives. Because of the unique feature of the motion, i.e. the forewing and the hindwing move relative to each other, the approach of solving the flow equations over moving overset grids is employed. The technique of eigenvalue and eigenvector analysis is used to obtain the dynamic stability properties.

2. Methods

2.1. Equations of motion

With the averaged model theory, the equations of motion of the insect are the same of that of an airplane or a helicopter. For stability analysis, the equations of motion are linearized by approximating the body's motion as a series of small disturbance from a steady, symmetric reference flight condition. As a result of the linearization, the longitudinal and lateral small disturbance equations are decoupled and can be solved separately (see e.g. Etkin and Reid, 1996). Let *oxyz* be a non-inertial coordinate system fixed to the body. The origin *o* is at the center of mass of the insect and axes are aligned so that at equilibrium, the *x*- and *y*-axes are horizontal, *x*-axis points forward, and *y*-axis points to the right of the insect (Fig. 1). The variables that define the longitudinal motion are the components of velocity along *x*- and *z*-axes (denoted as u and w, respectively), the angular-velocity around the *y*-axis (denoted as q), and the angle between the *x*-axis and the horizontal (denoted as θ). Let X and Z be the *x*- and *z*-components of the wingbeat-cycle-average aerodynamic force (due to the wings and the body), respectively, and M is the wingbeat-cycle-average aerodynamic pitching moment. At reference flight (hovering), u, w, q, θ are zero (θ is zero because the *x*-axis is aligned with horizontal at reference flight), and $X_E=0$, $Z_E=-mg$ and $M_E=0$ (the forces and moments are in equilibrium; the subscript "E" denotes equilibrium). The linearized equations of longitudinal motion (linearized about the symmetric reference flight, see e.g. Taylor and Thomas, 2003; Etkin and Reid, 1996) are

$$\delta\dot{u}=X_u\delta u/m+X_w\delta w/m+X_q\delta q/m-g\delta\theta \tag{1a}$$

$$\delta\dot{w}=Z_u\delta u/m+Z_w\delta w/m+Z_q\delta q/m \tag{1b}$$

$$\delta\dot{q}=M_u\delta u/I_y+M_w\delta w/I_y+M_q\delta q/I_y \tag{1c}$$

$$\delta\dot{\theta}=\delta q \tag{1d}$$

where X_u, X_w, X_q, Z_u, Z_w, Z_q, M_u, M_w and M_q are the stability derivatives (they represent partial derivatives of the forces and moments with respect to the state variables); m is the mass of the insect; g is the gravitational acceleration; I_y is the pitching moment of inertia about *y*-axis; "·" represents differentiation with respect to time (t); the symbol δ denotes a small disturbance quantity.

Let c, U and t_w be the reference length, velocity and time, respectively; here c is the mean chord length of the forewing; U is the mean flapping velocity at the radius (r_2) of the second moment of forewing area, defined as $U=2\Phi nr_2$ where Φ is the stroke amplitude of the forewing and n is the stroke frequency (forewing and hindwing have the same stroke frequency), and t_w is the period of the wingbeat cycle ($t_w=1/n$). The non-dimensional form of Eq. (1) is

$$\begin{bmatrix}\delta\dot{u}^+\\ \delta\dot{w}^+\\ \delta\dot{q}^+\\ \delta\dot{\theta}\end{bmatrix}=\mathbf{A}\begin{bmatrix}\delta u^+\\ \delta w^+\\ \delta q^+\\ \delta\theta\end{bmatrix} \tag{2}$$

where $\mathbf{A}$ is the system matrix

$$\mathbf{A}=\begin{bmatrix}X_u^+/m^+ & X_w^+/m^+ & X_q^+/m^+ & -g^+\\ Z_u^+/m^+ & Z_w^+/m^+ & Z_q^+/m^+ & 0\\ M_u^+/I_y^+ & M_w^+/I_y^+ & M_q^+/I_y^+ & 0\\ 0 & 0 & 1 & 0\end{bmatrix} \tag{3}$$

where the superscript "+" denotes the non-dimensional quantity; the non-dimensional forms are: $\delta u^+=\delta u/U$, $\delta w^+=\delta w/U$, $\delta q^+=\delta q t_w$; $X^+=X/(\rho U^2 S_t/2)$, $Z^+=Z/(\rho U^2 S_t/2)$, $M^+=M/(\rho U^2 S_t c/2)$; $t^+=t/t_w$, $m^+=m/(\rho U S_t t_w/2)$ (ρ denotes the air density and S_t denotes the area of the four wings), $I_y^+=I_y/(\rho U^2 S_t c t_w^2/2)$ and $g^+=g t_w/U$ [using the flight data given below, m^+, I_y^+ and g^+ are computed as $m^+=10.98$, $I_y^+=4.18$, $g^+=0.1315$ (ρ is 1.25 kg/m^3 and g is 9.81 m/s^2)].

In order to specify $\mathbf{A}$, morphological parameters (m, I_y, etc.) and stability derivatives (X_u, X_w, etc.) need to be determined.

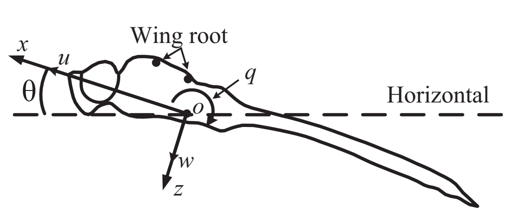

Fig. 1. Definition of the state variables u, w, q and θ and sketches of the reference frames.

2.2. Morphological data

Azuma and Watanabe (1988) measured morphological parameters of the dragonfly *Anax parthenope julius* that were useful for flight performance study (e.g. insect mass, wing length and area, etc.). But morphological parameters required for flight dynamics analysis (e.g. pitching moment of inertia, wing mass, etc.) are not available. In the present study, we measure the morphological parameters of this species. Our method of measurement follows, for the most part, that given by Ellington (1984a), whose paper can be consulted for a more detailed description of the method.