Available online at www.sciencedirect.com

ScienceDirect

Journal of Bionic Engineering 11 (2014) 439–448

Lateral Flight Stability of Two Hovering Model Insects

Na Xu, Mao Sun

Ministry-of-Education Key Laboratory of Fluid Mechanics, *Beihang University*, *Beijing* 100191, *P. R. China*

Abstract

The longitudinal disturbance motion of different insects at hovering flight has the same modal structure. Here, we consider the case of lateral motion. The lateral dynamic flight stability of two model insects, hoverfly and honeybee, at hovering flight is studied. The method of computational fluid dynamics is applied to compute the stability derivatives. The techniques of eigenvalue and eigenvector analysis are used to solve the equations of motion. Results show that the lateral disturbance motion of the hoverfly has three natural modes of motion: an unstable divergence mode, a stable oscillatory mode and a stable subsidence mode, and the flight is unstable; while the honeybee has a different modal structure (a stable slow subsidence mode, a stable fast subsidence mode, and a nearly neutrally stable oscillatory mode) and the flight is nearly neutrally stable. The change in modal structure between the two insects is due to their roll-moment/side-velocity derivative having different sign, and the sign difference is because that the hoverfly has a relatively small, but the honeybee has a relatively large, distance between the wing roots and the center of mass. Thus, unlike the case of longitudinal motion, for lateral motion, some insects have different modal structures and stability properties from others.

Keywords: insect, hovering flight, dynamic flight stability, modal structure

doi: 10.1016/S1672-6529(14)60056-1

---

1 Introduction

Insect flight stability is of great interest to researchers who study the biomechanics of insect flight and to engineers who try to make insect-like Micro Aerial Vehicles (MAVs). Because this area is relatively new, research works in the area have been mainly on hovering flight. For longitudinal stability of hovering flight, it has been shown that for a bumblebee, there exist three natural modes of motion: one unstable slow oscillatory mode, one stable fast subsidence mode and one stable slow subsidence mode[1]. Because of the unstable oscillatory mode, the longitudinal motion is unstable. Studies on many species of insects (bumblebee, fruit fly, hoverfly, cranefly, stalk-eyed fly, dronefly and hawkmoth) by several research groups[2–8] have shown that hovering insects have the same longitudinal modal structure and that the longitudinal motion is unstable.

For lateral stability of hovering flight, studies were also made for some insects by several research groups[5,9–12]. Hawkmoth was considered by both Zhang *et al.*[12] and Cheng and Deng[5], but Zhang *et al.* predicted that the lateral motion was unstable, whilst Cheng and Deng predicted that it was stable. Xu and Sun[11] pointed out that the difference was because that their roll-moment/side-velocity derivative had different sign (positive in Zhang *et al.*'s study but negative in Cheng and Deng's study). The cause of the sign difference was analyzed by Xu and Sun[11]. In a side-slip, an insect sees a lateral wind. The chordal component of the lateral wind will change the relative velocity of the wing and the change at the left wing is different from that at the right wing, resulting in different aerodynamic forces on the wings. This is called as "changing-relative-velocity" effect. On the other hand, the spanwise component of the lateral wind will change the axial velocity of the Leading-Edge-Vortex (LEV) of a wing, increasing it on one wing and decreasing it on the other wing, which makes the LEV of one wing to be more concentrated than that of the other wing, and results in different aerodynamic forces on the left and right wings. This is called as "changing-LEV-axial-velocity" effect. The "changing-relative-velocity" effect produces a side force that is in the opposite direction of the side motion, and because

---

Corresponding author: Na Xu
E-mail: xuna@ase.buaa.edu.cn

the wings are above the center of mass, the side force produces a roll moment, which gives a negative contribution to the roll-moment/side-velocity derivative. The "changing-LEV-axial-velocity" effect produces a force couple about the roll axis, giving a positive contribution to the roll-moment/side-velocity derivative. Because the positive contribution by the "changing-LEV-axial-velocity" effect is larger than the negative contribution by the "changing-relative-velocity" effect, the roll-moment/side-velocity derivative is positive. In Cheng and Deng's study[5] the derivatives were computed by a simple aerodynamic model which could not take the "changing-LEV-axial-velocity" effect into account, thus the computed roll-moment/side-velocity derivative was negative.

We thus see that the modal structure of the lateral motion can be changed by variation in the sign of the roll-moment/side-velocity derivative, and that this derivative is contributed by two moments of opposite sign, i.e. the roll moment produced by the side force due to the "changing-relative-velocity" effect and that produced by the force couple due to the 'changing-LEV-axial-velocity' effect. For the model hawkmoth in the above study[12], the magnitude of the roll moment produced by the side force due to the 'changing-relative-velocity' effect are smaller than that by the force couple due to the "changing-LEV-axial-velocity" effect, so that the roll-moment/side-velocity derivative is positive and the lateral motion is unstable. However, it should be noted that the roll moment produced by the side force is dependent on the vertical distance between the wing roots and the center of mass of the insect. For some insects, this distance can be relatively large and so is the magnitude of the roll moment produced by the side force. In this case, the magnitude of the roll moment produced by the side force due to the 'changing-relative-velocity' effect might become larger than that by the force couple due to the "changing-LEV-axial-velocity" effect. As a result, the roll-moment/side-velocity derivative would become negative, and the flight would become stable. That is, unlike the case of longitudinal disturbance motion, some insects might have different lateral modal structure from others. This hypothesis is examined in the present study.

We consider the lateral dynamic stability of hovering flight in two model insects, a model hoverfly and a model honeybee. The reason we choose these two insects is as following. Available morphological data[13–17] show that the non-dimensional vertical distance between the wing roots and the center of mass is relatively small for a hoverfly and large for a honeybee. Thus they are representative. The averaged model theory is used for the analysis and the method of computational fluid dynamics is used to compute the stability derivatives. Our analysis shows that the roll-moment/side-velocity derivative is positive for the model hoverfly and negative for the model honeybee, and that the two insects have different modal structure and stability properties, confirming the above hypothesis.

2 Methods

2.1 Equations of motion

In the averaged model theory[1,10,18], the insect is modeled as a rigid body with six degrees of freedom and the action of the flapping wings is represented by the wingbeat-cycle-average forces and moments. Thus the equations of motion of the insect are identical with that of a rigid aircraft. The longitudinal and lateral small disturbance motion can be decoupled and be solved separately (see e.g. [19]). For the convenience of describing the lateral motion, we define a right-handed, non-inertial, body-fixed coordinate system, $oxyz$, (Fig. 1). The origin o is at the center of mass of the insect. At equilibrium flight, the x-axis and y-axis are horizontal, with x-axis pointing forward, and y-axis pointing to the right side of the insect. The lateral motion of insect consists of four state variables v, p, r and γ (Fig. 1). The variable v is the translation velocity along y-axis; p and r are the angular velocities around the x-axis and z-axis (also being called as roll velocity and yaw velocity), respectively; and γ is the angle between the y-axis and the horizontal, i.e. roll angle. The linearized equations of lateral motion are given as (see e.g. Ref. [19]):

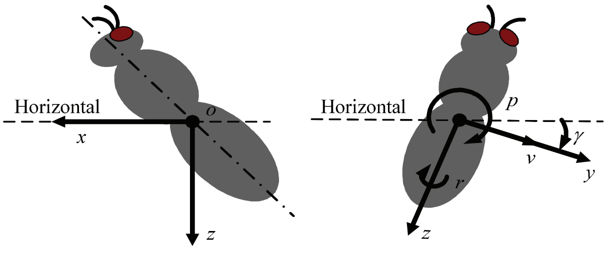

Fig. 1 Definition of the state variables, v, p, r and γ, and sketches of the reference frames.