Journal of Theoretical Biology 264 (2010) 538–552

Contents lists available at ScienceDirect

Journal of Theoretical Biology

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

Dipteran insect flight dynamics. Part 1 Longitudinal motion about hover

Imraan Faruque *, J. Sean Humbert

University of Maryland, Department of Aerospace Engineering, College Park, MD 20742, USA

A R T I C L E I N F O

Article history:
Received 21 September 2009
Received in revised form
5 February 2010
Accepted 12 February 2010
Available online 17 February 2010

Keywords:
Insect flight
System identification
State-space models

A B S T R A C T

This paper presents a reduced-order model of longitudinal hovering flight dynamics for dipteran insects. The quasi-steady wing aerodynamics model is extended by including perturbation states from equilibrium and paired with rigid body equations of motion to create a nonlinear simulation of a *Drosophila*-like insect. Frequency-based system identification tools are used to identify the transfer functions from biologically inspired control inputs to rigid body states. Stability derivatives and a state space linear system describing the dynamics are also identified. The vehicle control requirements are quantified with respect to traditional human pilot handling qualities specification. The heave dynamics are found to be decoupled from the pitch/fore/aft dynamics. The haltere-on system revealed a stabilized system with a slow (heave) and fast subsidence mode, and a stable oscillatory mode. The haltere-off (bare airframe) system revealed a slow (heave) and fast subsidence mode and an unstable oscillatory mode, a modal structure in agreement with CFD studies. The analysis indicates that passive aerodynamic mechanisms contribute to stability, which may help explain how insects are able to achieve stable locomotion on a very small computational budget.

1. Introduction

In recent years, researchers have made much progress into the task of understanding the aerodynamic basis for and the control architecture involved in flapping insect flight, in particular the fruit fly *Drosophila melanogaster*. Advances in the field of flapping wing aerodynamics have largely relied on the ability of researchers to make detailed observations of the insects' flapping behavior. Early observations of tethered *Drosophila* by Vogel (1967) began to observe variations in certain "stroke parameters" defining wing kinematic patterns and variations in wing contour. Several years later, Weis-Fogh (1972) used Vogel's observations in the development of the "quasi-steady" postulate first introduced by Osborne (1951). Briefly, this approach asserts that the instantaneous lift and drag forces of an insect could be represented by drawing analogy to a similar wing translating at the same angle of attack and the same (steady) velocity, an analogy whose theory continues to find application in modern research.

The quasi-steady approximation has been extensively used as a foundation by researchers beginning with Ellington and Dickinson to develop the aerodynamic theory used in contemporary understanding and prediction of insect flight. A major use of the theory is in the prediction of baseline forces in order to elucidate the contributions of additional aerodynamic mechanisms, predominantly unsteady effects (Dickinson and Gotz, 1999). The quasi-steady concept has been applied to determine aerodynamic contributions by mechanisms such as "clap and fling" movements (Spedding and Maxworthy, 1986) and dynamic stall (Dickinson et al., 1999). Even so, the chief contribution of quasi-steady theory to the field of insect flight understanding has been as a means to reduce kinematic and force data taken from both tethered and in-flight recordings of wing kinematics, allowing reduction of in-flight data to nondimensional coefficients that may be interpreted from the perspective of more traditional aerodynamic mechanisms (Fry et al., 2003).

Despite the widespread usage of the quasi-steady model and the information that it can provide regarding insect aerodynamics, the theory is normally applied as a model operating at a single point. Placing the model in the context of perturbations from that operating point provides insight into the fundamental dynamic behavior, which can then be used to understand the sensing and feedback requirements for stable flight. These are precisely the goals of this paper.

Several attempts have been made to quantify the dynamic modes of an insect. Taylor and Thomas (2003a–c) used measurements taken of tethered locusts in forward flight to measure the locusts' forces in response to body pitch angle and velocity sweeps, and used these experimental derivatives to identify a stable subsidence mode, a stable oscillatory mode, and an unstable divergence mode. Sun and Xiong (2005) used perturbations in longitudinal state variables in a computational fluid dynamics study of bumblebee aerodynamic forces in hover to find

* Corresponding author. Tel.: +1 301 405 3282.
E-mail addresses: imraan@umd.edu (I. Faruque), humbert@umd.edu (J. Sean Humbert).

0022-5193/$ - see front matter © 2010 Published by Elsevier Ltd.
doi:10.1016/j.jtbi.2010.02.018

numeric estimates of its aerodynamic stability derivatives, finding a stable fast subsidence mode, a stable slow subsidence mode, and an unstable oscillatory mode.

This study will examine the implication of passive aerodynamic stability mechanisms associated with flapping flight. Euler rigid body dynamics are paired with quasi-steady aerodynamics modeling that includes effects of perturbations from the hover equilibrium. Results are based on analysis of the analytical equations as well as frequency-based system identification of the nonlinear simulation. The objective is a linearized state-space model valid for small motions about hover that may be used to understand sensing and feedback requirements (and directly provide modal insight as in Taylor and Sun et al.). Such a model is derived under the fundamental assumption that it is the averaged forces and moments over the wingstroke that are important up to timescales of the rigid body dynamics. Though the example insect used in the simulation uses *Drosophila*-like parameters, the theoretical approach is derived for a general insect exhibiting such a timescale separation in hover and the qualitative results are applicable to the translational effects of dipteran flapping wing flight.

The organization of the paper is as follows. Section 2 introduces the kinematics, control inputs, aerodynamics model, and aerodynamics averaging. Section 3 uses the rigid body equations of motion to compute trim solutions for hover and extends the quasi-steady model to include perturbations from the hover point, while Section 4 describes a nonlinear simulation environment encoding the perturbation velocities concept and describes the system identification procedure. Section 5 investigates the handling qualities of the system, the properties and accuracy of the heave and longitudinal dynamics, and compares the haltere-on dynamics to bare-airframe identification. Supplementary Bode plots of measured and identified transfer functions are provided in an Appendix.

2. Background

In this section, a review of quasi-steady aerodynamic theory and the governing equations for the analysis and simulation is presented. For a more complete treatment of insect aerodynamics, refer to Sane (2003).

2.1. Kinematics

The description of the insect flapping motion requires a family of axes centered at the insect wing hinge. Approximating the wings as rigid bodies, measured insect kinematics exhibit a roughly planar flap motion which will be represented using 2–3–2 Euler angles. Define by reference to Fig. 1a a set of stability axes $\mathcal{S}=\{\hat{s}_x,\hat{s}_y,\hat{s}_z\}$ passing through the insect center of mass G, the stroke plane angle β as the angle about the pitch axis to an idealized planar stroke motion, and a coordinate axes set aligned with this plane the stroke plane axes $\mathcal{P}=\{\hat{p}_x,\hat{p}_y,\hat{p}_z\}$. Define $\mathcal{R}=\{\hat{r}_x,\hat{r}_y,\hat{r}_z\}$ a set of axes that move along with the right wing, with $\hat{r}_z=\hat{p}_z$ and $\hat{r}_y$ to extend toward the wing tip as in Fig. 1 b. Similarly, define $\mathcal{L}=\{\hat{l}_x,\hat{l}_y,\hat{l}_z\}$ for the left wing, with $\hat{l}_y$ extending inboard along the left wing spanline. The additional definition of the geometric angle with respect to the stroke plane as α_g provides the notation necessary to describe the orientation of two rigid wings at an instant in time.

For a flapping insect in or near hover, the flap angle ϕ_r undergoes a harmonic motion represented as a sinusoid

$$\phi_r(t)=-\Phi_r\cos(2\pi f_r t)+\phi_{\mathrm{off,r}}, \tag{1}$$

where Φ_r gives the amplitude of each wingstroke, $\phi_{\mathrm{off,r}}$ the deviation of the point about which the wing oscillates, and f_r the right wing flap frequency. Since this study addresses longitudinal motion, we will describe the behavior of the right wing motion and assume the complementary behavior in the left wing frame by dropping the r subscript. The geometric angle of attack α_g exhibits a harmonic motion roughly resembling a modified square wave, which allows the advancing and retreating strokes to both share a positive angle of attack.

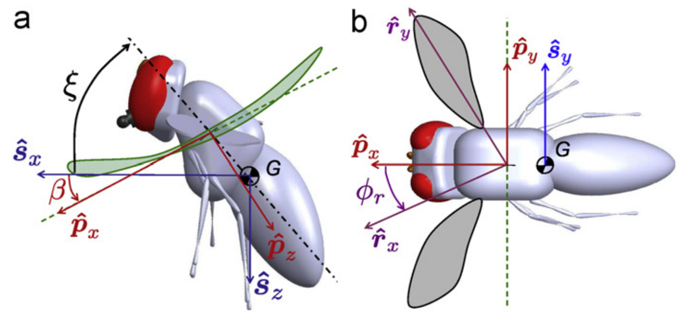

Fig. 1. Axes and angle definitions. (a) Stroke plane axes/angle β, body hovering angle ξ. (b) Stroke angle ϕ_r- and $\mathcal{R}$−axes.

2.2. Control parameters

As postulated by Vogel (1967) and later quantified experimentally by Fry et al. (2003), insects modulate the time forces and moments applied to wingstrokes by modification of several wingstroke parameters. Parameter variations remain remarkably small, even for aggressive maneuvers such as fast 90° collision avoidance maneuvers known as saccades (Fry et al., 2003), but are nonetheless fundamental for the control of the insect. The control inputs considered in this study are the biologically motivated choice of flap frequency f in Hz, the flap amplitude Φ as defined in Section 2.1, stroke plane angle β, and the mean position (center) of wing oscillation ϕ_{off}. In addition to the mathematical definitions in Section 2.1, several control parameters may be seen graphically in Fig. 2.

2.3. Aerodynamics

A variety of effects, predominantly unsteady, are known to be active during an insect's flight. A thorough treatment of these effects is outside the scope of this paper and may be found in Ansari et al. (2006). Instead, this treatment will review the largest contribution to in-flight insect forces: "translational" lift.

2.3.1. Translational lift and drag

Wing "translational lift" is the largest component (approximately 65–85%) of an insect's lift production in hover and the most straightforward of the lift mechanisms known to be active, but includes a number of unsteady effects via experimental coefficients. The translational component of insect lift can be represented using (Ellington, 1984b)

$$L(t)=\tfrac{1}{2}\rho S|u_t(t)|^2\hat{r}_2^2 C_L[\alpha(t)], \tag{2}$$

where the instantaneous lift force L is written as a function of the air density ρ, the wing area S, tip velocity u_t, nondimensional second moment of area $\hat{r}_2^2$, and an experimentally determined lift curve slope (Sane and Dickinson, 2002)

$$C_L[\alpha(t)]=0.225+1.58\sin(2.13\alpha_g-7.2). \tag{3}$$

The second moment of area may be defined in terms of the normalized chord $\hat{c}=1/2\mathcal{R}\, c/R$ and normalized radius $\hat{r}=r/R$ as $\hat{r}_2^2=\int_0^1\hat{c}\,\hat{r}^2\,d\hat{r}$ (Ellington, 1984a).