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Achieving hover equilibrium in free flight with a flexible flapping wing

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HIGHLIGHTS

- A 3-way coupled body–wing–fluid motion insect flight simulator is presented.
- A trim algorithm that finds the hover equilibrium of a flapping flyer is derived.
- Trimmed wing motion and power agree closely with observation of live fruit flies.
- The hover equilibrium is influenced by the coupled wing-body dynamics.
- Flexible wings experience significantly reduced wing wake interaction.

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ABSTRACT

Recent discoveries in the fields of flapping wing aerodynamics and fluid–structure interaction have demonstrated that flexible wings can generate more lift than rigid wings. However, the implications of wing flexibility on the flight dynamics of flapping wing flyers is still an open research question. The main difficulty is that the free flight of flapping flyers with flexible wings is a result of the dynamic balance between unsteady aerodynamics, fluid–structure interaction, and flight dynamics. This study presents a fully coupled three-way flight simulator that solves the two-dimensional Navier–Stokes equations, tightly coupled to the Euler–Bernoulli beam equations of the wing and the nonlinear multi-body equations of motion for the dynamics at the fruit fly scale. A novel trim algorithm is used to determine the hover equilibrium in the longitudinal plane. The control inputs, i.e. the flapping amplitude, stroke plane angle, and flapping offset angle as well as the initial conditions are determined that effectively eliminate average body accelerations to less than 3% of gravitational acceleration. The resulting hover equilibrium control parameters flapping amplitude, stroke plane angle and the total power required agree well with the biological observation of fruit flies. Body oscillations in hovering free flight affect the flexible response of the wing compared to prescribed body motion without oscillation. The affected wing motion reduces the lift coefficient by up to 8.7% for the stiffest wing, necessitating slightly different control inputs to achieve trim. Finally, the power required to achieve hover equilibrium is 32%–94% lower for flexible wings than for rigid wings that are actively rotated to match the same passive pitch schedule.

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1. Introduction

Insects are capable of impressive aerial maneuvers. A host of research has been performed in recent decades to uncover what features of insect flight enable such remarkable performance. Not only are biologists interested in learning more about the natural world, but scientists and engineers are also interested in applying such insights to the design and fabrication of micro air vehicles. In addition to high speed flight, efficient cruise flight, rapid transient evasion maneuvers, and the ability to maintain course in the presence of significant turbulence relative to their own size and weight, the ability to hover and perch provides particular motivation for engineers to mimic their flight qualities. Many missions including surveillance of high-risk locations and even artificial pollination of crops have been envisioned (Shyy et al., 2013).

Despite the interest in developing such small robotic flyers, development has been hampered by many challenges. One such challenge is understanding the flight dynamics of insects, particularly in hover. A significant amount of attention has been paid to the longitudinal stability of an insect-like vehicle in hover, since the longitudinal dynamics include the largest source of unstable modes (Sun, 2014; Taha et al., 2012), and the longitudinal dynamics appear to be largely decoupled from the lateral-directional dynamics (Faruque and Humbert, 2010; Zhang and Sun, 2010a, b). Numerous flight dynamics models of varying fidelity have been proposed (Cheng and Deng, 2011; Faruque and Humbert, 2010; Liang and Sun, 2013; Orlowski and Girard, 2012; Sun and Xiong, 2005; Taha et al., 2015, 2014; Wu et al., 2009; Wu and Sun, 2012). However, none of these studies have considered flexible wings (Shyy et al., 2016; Sun, 2014; Taha et al., 2012) in spite of the fact that insects themselves feature flexible wings (Altshuler et al., 2005; Ennos, 1988; Fry et al., 2005; Shyy et al., 2013; Sunada et al., 1998; Young et al., 2009), and most flapping wing micro-air vehicles (FWMAVs) produced to date (Coleman and Benedict 2015; Desbiens et al., 2013; Keennon et al. 2012; Ma et al., 2013; Shang et al., 2009; Shyy et al., 2005; Tay and van Oudheusden, 2015) also have flexible wings.

Flexible wings have previously been shown to produce lift differently than their rigid counterparts. Recently, several studies (Kang et al., 2011; Kang and Shyy, 2014, 2013) have demonstrated the importance of considering wing flexibility in aerodynamic analysis and its significant impact on the aerodynamic force generation mechanisms (Kang and Shyy, 2013; Mountcastle and Combes, 2013), as well as efficiency and the timing of passive wing kinematics (Eldredge et al., 2010; Sridhar and Kang, 2015). Flexible wings tend to require less power to flap because the passive deflection produces less drag and torque penalties (Eldredge et al., 2010). Other studies have shown that the maximum efficiency of lift production in air occurs when the flapping frequency is below (approximately 50%) the first natural frequency of the wing (Heathcote and Gursul, 2007; Kang et al., 2011; Sridhar and Kang, 2015).

A key challenge with introducing wing flexibility in the flapping wing flight dynamics is the fact that it adds a set of dynamics to the already highly nonlinear, time varying system. Determining the flexible response of the wing in a numerical framework requires a converged solution of the coupled unsteady aerodynamics and flexible beam model. This has been successfully performed in recent studies that analyze the aerodynamics of insect flight (Kang et al., 2011; Kang and Shyy, 2013; Sridhar and Kang, 2015; Tobing et al., 2017), but free body motion is not considered in these studies. When free body motion is introduced, which is necessary for actual flight simulation, the potential exists for the body motion to affect the wing motion in addition to the typical arrangement of wing motion affecting body motion. Therefore, not only do the fluid and structural response need to converge, but the wing motion and resulting forces are now sensitive to body motion, which changes the wing motion and force, which change the body motion, etc.

The efficiency and performance of insect flight simulations also should be evaluated when the system is in equilibrium and forces are balanced. In particular, most stability analyses of insect flight dynamics begin with determining equilibrium. Linearization about an equilibrium point can provide valuable information about the stability of the system. Furthermore, flight path and control studies typically begin in an equilibrium condition. In each of these cases, it is important to establish equilibrium flight, yet a robust, systematic means of doing so for a coupled fluid/flexible wing / body system is not available in the literature.

The objective of this study is two-fold: (i) we present a three-way coupled flight simulation model that accurately models the fluid dynamics, the structural dynamics, and the flight dynamics; (ii) we develop a trim algorithm that efficiently determines hover equilibrium in free flight. We accelerate the trim-finding algorithm by evaluating the computationally expensive gradients on the quasi-steady (QS) approximation of the unsteady aerodynamics in an iterative scheme between the Navier–Stokes (NS) and QS solutions until convergence. We then demonstrate the ability of the trim algorithm to achieve hover equilibrium for various values of wing stiffness.

The outline of this paper is as follows. Section 2 covers the morphology, dimensions, and references frames of the fruit fly scale FWMAV used in this study. The flexible wing flight simulator that captures the three-way coupled dynamics is then presented along with the computational set up for both the NS and Euler–Bernoulli (EB) beam solvers. Power calculations, which are used in both validation and in discussion, are presented. The flight equations of motion and computational set up for the flight simulation are given as well. Finally, the trim algorithm is developed that efficiently uses a coupled QS–NS aerodynamics model. In Section 3, we present the control inputs required to trim the fruit fly for various values of wing stiffness, which closely match the flapping kinematics observed in live fruit flies. We then show that the oscillatory body motion in hover affects the motion of the flexible wing. We demonstrate the significantly reduced role that wing wake interaction plays in flexible wings. Finally, we discuss the power consequences of using flexible wings, showing that our simulation agrees with the average hover power reported in the literature for live fruit flies and that flexible wings require less power than rigid wings.