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A numerical study on the free hovering flight of a model insect at low Reynolds number

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ABSTRACT

The typical insect employs a flapping-wing mode of flight. In this paper we present numerical simulations on the low Reynolds number free hovering flight of a model fruit fly. A heuristic analysis shows that insect hovering flight tends to be poor in static stability. Stable quasi-periodic free hovering is achieved through active adaptation of wing kinematics during flight. The numerical model integrates the computational fluid dynamics of the flow with the three-dimensional Newtonian dynamics of the flyer and a generic PID-type kinematic control algorithm. The resultant wing and body motion of the flyer, which is evolved dynamically from variations to a basic set of sinusoidal wing kinematics, is quasi-periodic and quasi-steady. Two types of wing control are implemented here: an outer kinematic mode based primarily on the rotation of the wing stroke plane, and an inner kinematic mode based on adjustments of intra-stroke parameters. They allow the flyer to hover on a nearly horizontal stroke plane (*normal* hovering) and to hover with nearly horizontally poised body on a tilted stroke plane. The study is focused primarily on longitudinal stability (positional and pitching) in free hovering flight. The results obtained show good consistency and agreement with available published results. The present computational approach offers a promising line of investigation that could complement physical experiments in a wider study of the free flight aerodynamics of insect-like flyers.

1. Introduction

Flapping-wing insects depend on unsteady aerodynamics for their flight. They possess some remarkable flight characteristics and abilities that still intrigue and challenge our understanding of flight. To perform aerial manoeuvres, insects manipulate forces and moments produced by their wings with great precision. They can rapidly alter their wing kinematics in the course of flight to overcome airflow changes and navigate complex three-dimensional topography. These include changes to the stroke amplitude, deviation from mean stroke plane, angle-of-attack, wing-beat frequency, as well as timing and duration of wing rotation during stroke reversal [1]. Attempts to measure and characterize the complex range of wing motions even for simple flight mode, such as hovering, have proven to be highly challenging. The complex interplay of wing kinematics and nonlinear fluid dynamics also prevents simple correlations to be drawn about forces, flow structures and wing motion. The experimental studies of Ellington [2–7], Dickinson [8], Ellington et al. [9], Dickinson et al. [10], Sane and Dickinson [11], Birch and Dickinson [12] and others have found that the high lift generated by flapping-wing insects may be attributed to a number of unsteady fluid mechanisms. Foremost among these are a delayed stall mechanism characterized by the prolonged attachment of a leading-edge vortex (LEV), which causes reduced pressure over the top of the wings, and lift associated with strong rotational flows induced by the wings during stroke reversal. Wings may also take advantage of residual flows produced in a preceding stroke to generate extra lift as a form of wake capture. A clap-and fling mechanism was also been introduced earlier by Weis-Fogh [13] to explain the unusually high lift generated by some very small insects (such as the *Encarsia Formosa* – a tiny wasp). Recent experiments by Lua et al. [14] have also given particular attention to the highly transient aspects in flapping-wing flows to understand how short-lived flow effects may bear on the time-dependent lift and drag forces. Computer-based studies have also begun to play a bigger role in recent years to help unravel the intricacies of insect flight, most notably through the works of Liu et al. [15], Wang [16], Ramamurti and Sandberg [17], Sun and Tang [18] and Aono et al. [19]. The important role of rapid wing acceleration was also highlighted by Sun and Tang [18]. These efforts have been successful in identifying and clarifying the high lift mechanisms available to flapping-wing insects to overcome their weight in flight.

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Adequacy of lift represents the most fundamental necessary condition for airborne flight. However, it is not sufficient on its own to explain the ability of insects to fly, not to mention their agility in flight. This is because flight is quintessentially a dynamic condition; and more so in the present instance (than in conventional aerodynamics) because an insect has to contend with very large unsteady forces (force peaks larger than its weight) and moments generated by its wings as a *free* flying body. For free flapping-wing flight to be possible, the highly unsteady and large forces and moments generated by the flapping wings must remain in some form of overall dynamic balance most of the time. This suggests that some elements of active intervention may be required during free flight. At a basic level, control would be needed to keep the flight stable against potential aerial disturbances, and at higher levels, to address more complex flight needs of the insect. If the flyer has strong static (or passive) stability, i.e., possessing a strong self-equilibrating or self-recovery tendency against disturbances in the flying condition, then it would be easy for it to maintain stable flight. The term *passive* is sometimes used here to emphasize its stability *in the absence of control*. If the flyer system is only weakly stable, or even unstable, then responsive intervention through adjustments of force-generating surfaces will be necessary. Typically, the forces, moments and flight configuration of the flyer are coupled, and they need to be controlled in tandem to achieve stable flight.

The free flight of insect flyers has begun to attract attention in recent years. Hedrick and Daniel [20] employed a micro-genetic selection algorithm to recreate numerically the free flight kinematics of hawkmoth. The aerodynamic forces in their model were approximated by a quasi-steady blade-element model, incorporating coefficients derived from experiments of others. They found that free hovering is consistent with a multiplicity of wing kinematics or solutions. The hovering solutions differ in their time histories of body position and orientation; leading them to conclude that there is no unique free-hovering state, and that insects may also be able to dynamically adapt their hovering kinematics to situational needs. Given the oscillatory nature of free hovering flight, Wu et al. [21] systematically sought and obtained cyclic/periodic solutions to the coupled equations of fluid and body dynamics for hawkmoth and drone-fly. Their results show centre-of-mass oscillations that are consistent with published results. Wu and Sun [22] subsequently showed that those cyclic/periodic states were actually *unstable*; they employed a Floquet-based analysis, which accounted for variation of the solution states over the wing cycle. These works considered only the two-dimensional dynamics of free hovering in the sagittal or symmetry plane.

In this paper we present a computational study on the free hovering flight of a model fruit fly, with low Reynolds number in the range of 150–185. Hovering flight is considered because it is the most basic mode of flapping wing flight. A heuristic argument shows that free hovering flight of insects is inherently weak in static/passive stability, and hence also dynamically unstable. Dudley [23] commented that even "steady flight (of insects) is perhaps best viewed as a sequence of consecutively unstable but controlled aerodynamic conditions; (where) compensatory course correction must continuously characterize flight with flapping wings." This comment unequivocally underscores the highly unstable and dynamic character of insect flight in general. From this perspective, dynamical control appears to be indispensable concomitant of insect flight, and this need motivated the approach that has been adopted in this work.

The present numerical model integrates the computational fluid dynamics of the flow with the three-dimensional Newtonian dynamics of the flyer and an active feedback control system to achieve stable quasi-periodic hovering flight. It differs from recent works of Hedrick and Daniel [20] and Wu et al. [21,22] in a number of aspects; foremost being in the modelling of free hovering here as a *real-time* dynamic event, presided over by a simple kinematic control algorithm that actively adapts the kinematics of the wings to position and orientate the flyer at a pre-set location. The wing kinematics employed in this work is allowed to evolve in time from variations made to a basic set of sinusoidal wing actions by the control algorithm to achieve sustained free hovering; as compared to other computational studies, where strictly unchanging periodic wing kinematics are prescribed from experimental sources. In this work, we are focused primarily on longitudinal stability (asserting stable pitching and displacement control). Two modes of free hovering control are explored in this study, i.e. a *stroke-plane* mode and an *intra-stroke* mode. However, as the dynamical model is three-dimensional, rolling and yawing motions of the model insect (excited by numerical noise accumulated over prolonged simulation) are not suppressed unless they lead to diverging flight behaviour. Normal hovering (with nearly horizontal mean stroke plane) and inclined-body hovering (with body profile approaching a horizontal posture) of the fruit fly model are simulated.

The present work has been conducted from a fundamentally aerodynamic and dynamic stability perspective. Many simplifying assumptions have by necessity been made to render even feasible such a study, when viewed in the context of a real insect flyer. In this regard, the model fruit fly in the present study may be regarded as the surrogate for a generalized low-Re flapping-wing flyer. The present work may also have relevance for the design of micro aerial vehicles that are modelled after flapping-wind insects.

The contents of the paper are organized as follows. Section 2.1 presents morphological data on the fruit fly model that are required for the simulation; with a description of the geometric and kinematic parameters defining the motion of the body and flapping wings. The basic methodology and numerical setup for computational fluid simulation and its implementation for coupled fluid–body interactions are briefly outlined in Sections 2.2–2.3, as much of the details have already been published elsewhere. The main contributions of the paper begin in Section 3.1, where a heuristic analysis first shows that passive flapping-wing hoverer (on fixed periodic wing kinematics) is inherently weak in static stability. Section 3.2 outlines the requirements of kinematic control for quasi-steady free hovering flight. Sections 3.3–3.4 describe two types of kinematic wing actions that are subsequently used; a stroke-plane (or outer kinematics) control mode for normal hovering flight, and an additional intra-stroke (or inner kinematics) mode which controls the angle-of-attack of the wings within the wing stroke for inclined-body hovering. Section 3.5 briefly outlines the implementation of a standard proportional–integral-derivative type algorithm that adjusts the wing kinematics to achieve quasi-steady hovering flight. Results for quasi-steady normal and inclined-body hovering are presented in Sections 4.1–2 respectively. Further analyses on forces, momentum and power are given in Section 4.3. Section 4.4 reviews some of the assumptions and analyses concerning hovering stability that were made in Section 3.1 in the light of the hovering results that have been obtained; while Section 4.5 highlights some qualitative aspects of the fluid dynamics that were observed. The key conclusions arising from the present work are summarized in Section 5.

2. Materials and methods

2.1. Morphological and kinematic model

For the present work, we have adopted the morphological data on fruit fly *Drosophila melanogaster* from Fry et al. [24] for our computer model of a low-Reynolds number flapping-wing flyer. The geometric model of the flyer itself, see Fig. 1A, was constructed