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Within-wingstroke body oscillations shape the aerodynamic force and power of wild silkmoths

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1 Introduction

Centimeter-scale flapping flight poses force, power, and stability challenges to insects and flapping-wing micro air vehicles (FW-MAVs). The great diversity of biological flight can inspire various solutions that might be best suited for engineering design goals. Hawkmoths and similar fliers such as hummingbirds are popular models for flapping-wing micro air vehicles (FW-MAV) design because they excel at agile flight [1–3]. They can hold different stroke-plane tilts to control forward thrust and generate weight support during both halves of the wingstroke [4]. Hence, their steady forward flight aerodynamics are specified by how wings move relative to the thorax. Similar fixed stroke planes are used in many current FW-MAVs.

Silkmoths are closely related to hawkmoths but fly differently. They generally have lower wingbeat frequencies and larger wings [5], similar to larger flapping-wing robots [6]. Some silkmoths have large oscillations in body pitch angle and vertical speed coupled to their flapping wing motion. This flight behavior has been observed in butterflies as well. It is hypothesized to help avoid predators due to its erratic nature [7]. It also helps differentiate the roles of downstroke and upstroke to prioritize weight support and forward thrust respectively [8], which is different from hawkmoth flight.

The oscillations in body pitch and vertical speed can impact aerodynamics by changing the overall wing motion and the airflow velocity around the wing. For successful forward flight, wing's elevation relative to the horizontal (α_h), angle of attack (α_v) and relative airflow (v) must be controlled during a wingstroke (Figure 1a) because these three parameters determine the magnitude and direction of the aerodynamic force. Body oscillations, if not well coordinated with the wing flapping motion, may push these critical parameters outside the regime of stable flight or available power. Yet these fliers excel at forward flight. In this study, we explore how body pitch and vertical speed oscillations affect wing-airflow interaction and flight performance of forward flying silkmoths. Examining how body oscillations shape aerodynamic forces could reveal alternative strategies of small-scale flapping flight. This can inspire designs of FW-MAV that fly at lower wingbeat frequencies or have larger wings.

2 Methods

A total of four silkmoth species were studied: *Actias luna* (AL), *Antheraea polyphemus* (AP), *Callosamia angulifera* (CA) and *Hyalophora euryalus* (HE) (Figure 1b). Wing morphology of 9 silkmoth individuals and their steady forward flight kinematics from a total of 15 wingstrokes (2 to 3 m/s flight speed) were digitized using R and MATLAB. Moths were filmed at 1000-2000 FPS using three Photron cameras under IR light. Time-varying body pitch angle (χ), forward (u) and vertical (w) body speeds, stroke-plane angle (β), and wing kinematic angles were extracted for each wingstroke. A quasi-steady blade element method was used to calculate the aerodynamic force which was resolved into its fore-aft (F_x) and vertical (F_z) components [5]. The instantaneous aerodynamic power was calculated as the dot product of aerodynamic force and airflow velocity relative to wing. To analyze the effects of within-wingstroke body oscillations on the aerodynamics and to investigate the relative phase dependence of body oscillations and wing flapping, three models of kinematic configurations were used (Figure 1c-d). Model 1 incorporates fully time-varying unmodified measurements of u , w , χ and β . Model 2 assumes their wingstroke-averaged constant values. Model 3 assumes the time series of measured body kinematics (model 1) shifted by half wingstroke period.

3 Results and Discussion

By comparing results from the three models, we found that during forward flight of these four silkmoth species, body pitch oscillation couples with flapping wing motion to improve flight performance. This coupling lowers the aerodynamic power requirement by reducing drag and enhancing lift on the wings, without compromising weight support. To explain the mechanisms behind the improved flight performance, we first compare the three models applied to an average wingstroke of silkmoth HE.

Compared to the other two models, the angle of attack α_v (averaged over all blade elements) is not just lower in model 1 (the unmodified body kinematics), it stays close to 45° in the middle part of the wingstroke (Figure 1e) where most of the aerodynamic force is generated (Figure 1h). This decreases drag and increases lift at the same time because drag reduces for low α_v and lift is maximum near $\alpha_v = 45^\circ$ [9]. A reduced drag together with higher lift enhances the lift-

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to-drag ratio (Figure 1f), which is crucial in determining flight efficiency. A smaller drag also lowers the aerodynamic power requirement to improve flight performance.

Both peak and wingstroke-averaged aerodynamic forces are much smaller for model 1—the unmodified body kinematics (Figure 1h). This could significantly reduce the moth's forward thrust and body weight support. However, this does not occur. Despite a much smaller total aerodynamic force generated for model 1, the differences in forward thrust during upstroke (Figure 1i) and body weight support during downstroke (Figure 1j) are negligible between the three models. This is a consequence of how the elevation of the wing (α_h) relative to the horizontal varies because the aerodynamic force is roughly normal to the wing chord. Both body pitch and wing pitch rotations act together and specify time variation of α_h to direct the aerodynamic force more effectively during both half-strokes. During downstroke, a lower and minimally varying α_h (Figure 1g) keeps the wing chord nearly horizontal and thus makes the aerodynamic force vector incline more vertically upward. This means a larger portion of the aerodynamic force is providing weight support instead of backward force (negative thrust). Whereas, during upstroke, a higher α_h (Figure 1g) directs the force more horizontally so that most of the aerodynamic force provides forward thrust. Hence, α_h is controlled in a way that distributes the aerodynamic force more effectively to support body weight, reduce backward force, and enhance forward thrust. This kinematic mechanism also explains why butterflies (with similar erratic flight and body-wing morphology) shoot vortices in different directions to generate weight support during downstroke and forward thrust during upstroke [8].

Extending our three-model analysis to the aerodynamic power and lift-to-drag ratio of the other three silkmoth species (Figure 1k-m) reveals similar and consistent results. This demonstrates an important role for within-wingstroke body kinematics, particularly body pitch oscillations, which are common in some insect families. Additionally, body oscillations can couple with flapping wing motion to improve flight performance—evident from the poor performance of model 3 in which body kinematics were shifted by half wingstroke. However, the differences in the aerodynamics of models 1 and 3 suggest that an active control on the phase of the body oscillation can expand the flight envelope by generating aerodynamic forces over a larger range of magnitudes and directions. All these results have important performance implications for FW-MAVs adopting slower wing-beat frequencies or larger wings.

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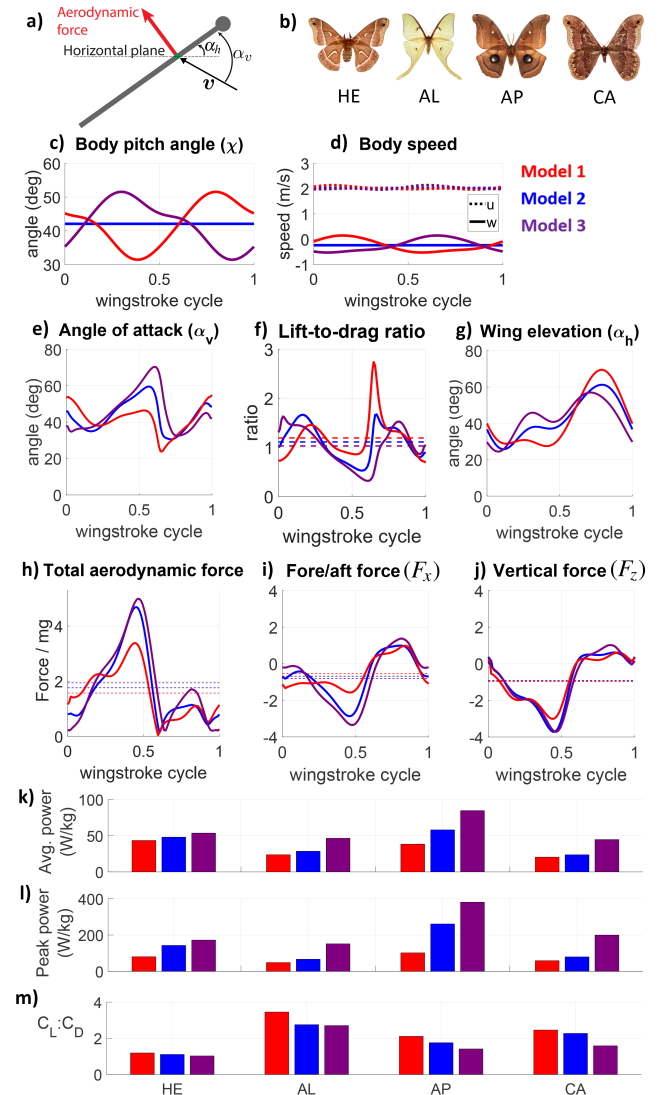


Figure 1: a) α_h , α_v and v . b) Silkmoth species in this study. c-d) Body kinematics for models 1, 2 and 3 over an averaged wingstroke of HE. First half is downstroke. e-j) Time series of α_v , $C_L : C_D$, α_h , total aerodynamic force, F_x and F_z over HE's wingstroke. Dashed lines represent wingstroke-averaged values. k-m) Mean and peak body mass-specific aerodynamic power, and mean $C_L : C_D$ for averaged wingstrokes of all silkmoth species in this study.