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Wing motion transformation to evaluate aerodynamic coupling in flapping wing flight☆

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HIGHLIGHTS

- A transformation is introduced that preserves the topology of recorded wing motions.
- The transformation is shown to be related to roll–yaw coupling in flapping flight.
- When applied to recorded insect flights, each trajectory shows proverse coupling.
- Proverse roll–yaw coupling could reduce the feedback demands of flapping flight.

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ABSTRACT

Whether the remarkable flight performance of insects is because the animals leverage inherent physics at this scale or because they employ specialized neural feedback mechanisms is an active research question. In this study, an empirically derived aerodynamics model is used with a transformation involving a delay and a rotation to identify a class of kinematics that provide favorable roll–yaw coupling. The transformation is also used to transform both synthetic and experimentally measured wing motions onto the manifold representing proverse yaw and to quantify the degree to which freely flying insects make use of passive aerodynamic mechanisms to provide proverse roll–yaw turn coordination. The transformation indicates that recorded insect kinematics do act to provide proverse yaw for a variety of maneuvers. This finding suggests that passive aerodynamic mechanisms can act to reduce the neural feedback demands of an insect's flight control strategy.

1. Introduction

Flapping wing flight in biological systems represents a dramatically more maneuverable form of flight than any man-made example. The simultaneous presence of aerial maneuverability and robust tracking in unknown environments in the insect world is made further more remarkable when one considers the incredibly limited neural processing available to an insect's flight control strategy. Many insects carry less than 100 mg worth of neural material distributed throughout the insect, of which 2/3 is devoted to visual processing (Egelhaaf et al., 2002), implying that their flight control strategies must be well-tuned to their flight dynamics so as to reduce the neural feedback demands. One Q2 possible means to reduce the demands on a flight control feedback system is to leverage passive aerodynamic mechanisms at this scale. Similar mechanisms to reduce feedback demands have been identified in cockroaches to reduce their neural control requirements by taking advantage of mechanical properties of the leg mechanism (Sponberg and Full, 2008).

Whether this remarkable flight performance is because insects leverage inherent physics at this scale or employ specialized neural feedback mechanisms is an open research question. An understanding of the balance between aeromechanical design and neural feedback could unlock decisive improvements in micro-aerial vehicle flight control. An aeromechanical flight platform that provides complementary (proverse) roll–yaw coupling via inherent passive aerodynamic mechanisms would require one less regulator in the feedback circuit. Conversely, an aeromechanical flight platform that provides antagonistic (adverse) yaw requires regulation of the two states separately. Because MAV flight controllers operate with very stringent size, weight, and power demands, reducing the computational demands of a controller is vital to successful flight, and a mechanical platform with

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low feedback control demands has a dramatic advantage to one that requires multiple complex control loops.

Despite the critical advantage, the inherent complexity of small-scale flapping flight aerodynamics has obscured a direct analysis of both biologically relevant and engineered wing kinematic perturbation strategies. Although the detailed aerodynamic mechanisms involved in small-scale flight are quite complex (Ramamurti and Sandberg, 2007), recent efforts have allowed extraction of reduced-order flight dynamics models, either for single degree of freedom experimental cases (Hesselberg and Lehmann, 2007a,b) direct analytic methods (Doman et al., 2010), or more general computationally (Sun et al., 2007) and spectrally derived models (Faruque and Humbert, 2010). As study progresses from hovering models to forward flight models, theoretical analysis and experimental measurements indicate that coupling increases (Dickson and Dickinson, 2004; Faruque et al., 2012), and the effect this coupling has on a control strategy is unknown.

This study addresses the balance of control requirements through consideration of the roll–yaw coordination required in maneuvering free flight, using both theoretical and experimental examples. Section 2 reviews the description of wing motions, introduces a transformation between recorded kinematic time histories and biologically relevant control inputs, and develops the aerodynamic basis for roll–yaw coupling using an empirically derived insect aerodynamics model (Sane and Dickinson, 2002). Both simplified wing motions and experimentally measured kinematic inputs are evaluated using the aerodynamics model in relation to lift and drag-based roll–yaw coupling in Section 3. Finally, the synthetic and experimentally measured wing motion time histories for a variety of maneuvering flight sequences are transformed and transformed onto a manifold representing proverse yaw to evaluate the degree to which insects harness aerodynamic roll–yaw coupling to reduce their neural feedback demands.

2. Background and approach

2.1. Kinematics measurement

2.1.1. Coordinate definitions

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 is 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. 1b. Similarly, define $\mathbf{L}=\{\hat{l}_x,\hat{l}_y,\hat{l}_z\}$ for the left wing, with $\hat{l}_y$ being extending inboard along the left wing spanline. The additional definition of the geometric angle with respect to the stroke plane as wing pitch angle α_g provides the notation necessary to describe the orientation of two rigid wings at an instant in time.

Both experimental kinematics measured in Section 2.1.2 and simplified synthetic kinematics introduced in Section 2.3 were used for analysis.

2.1.2. Experimental apparatus

An experimental test rig shown in Fig. 2 was used to make detailed measurements of freely maneuvering flies. The experimental apparatus consists of three Vision Research Phantom V710 high speed video cameras and lighting array, orthogonally mounted about a 10 in. × 10 in. × 8 in. a Plexi-Glass test section. Camera calibration was accomplished with direct linear transformation (Hedrick, 2008). The 11 DLT coefficients identified in this calibration (Abdel-Aziz and Karara, 1971) allowed reconstruction with 0.1–0.2 pixel errors, indicating that lens distortion was a minor factor in the experimental setup and that the pinhole camera model assumed in the DLT method provided an acceptable model. Background subtraction was used to identify profiles and coefficients and generate a visual hull. Regions of volume pixels, or "voxels," are then identified as wing or body using intensity segmentation, and a principal component analysis is performed

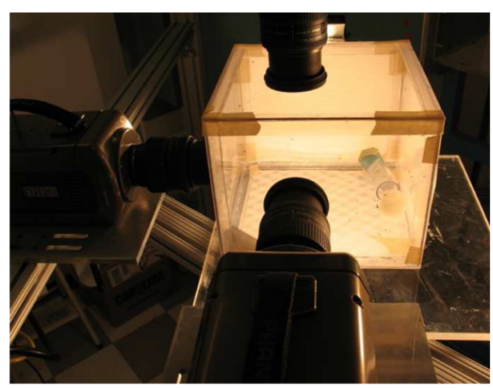

Fig. 2. Freely flying insects in the flight chamber were imaged at 7002 Hz to study straight and level flight.

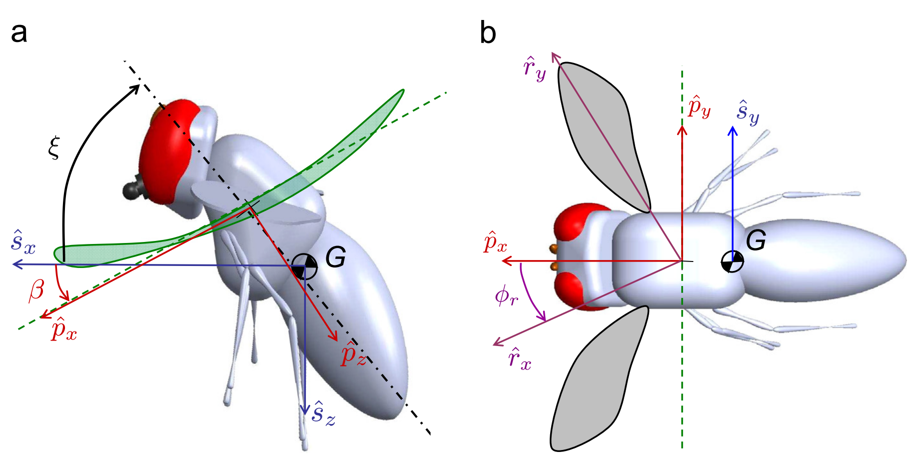

Fig. 1. Axes and angle definitions. (a) Stroke plane axes/angle β, body hovering angle ξ; (b) stroke angle ϕ_r and $\mathcal{R}$ axes.

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