The Significance of Moment-of-Inertia Variation in Insect Flight Maneuvers

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I. Introduction

Micro-aerial vehicles (MAVs) are being designed for a variety of missions including environmental monitoring, search-and-rescue, and reconnaissance. In developing these MAVs, there is much that can be learned from insects because evolution has created an incredible variety of flying insects that have successfully colonized almost all known terrestrial habitats. A better understanding of insect flight maneuvers:

- would assist biologists studying insect flight dynamics.
- has practical significance for designers of micro-aerial vehicles (MAV).

One area where MAV design could learn from insects is in stabilization and maneuverability. The established method for studying these features in insects is to develop dynamic models that incorporate relevant details regarding the mass properties, wing kinematics, and aerodynamic forces. These models are then used to explore the stability (Sun et al., 2007; Gao et al., 2009; Taylor et al., 2003) and maneuverability of insects.

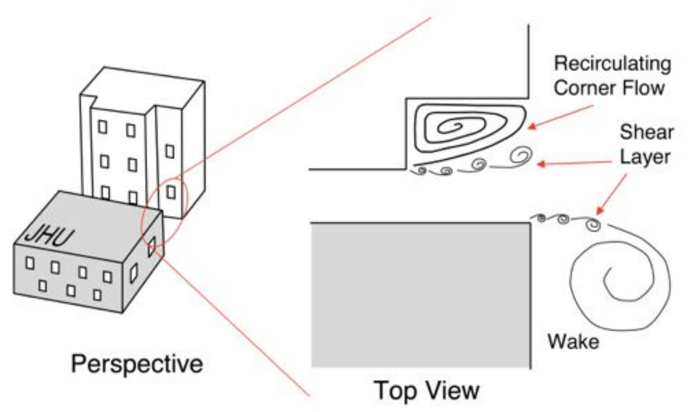

Fig. 1a. MAVs will have to operate in complex urban environments

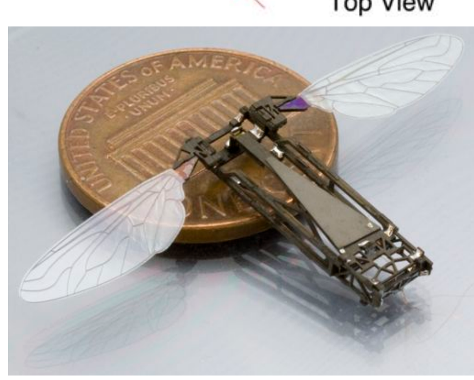

Fig. 1b. Example of an insect-inspired flapping-wing MAV under development at Harvard [1]

In all of the above studies however, the moment-of-inertia (MoI) of an insect is assumed to a constant in time; this assumption is based on the very small mass of the wings. However, they might account for a larger fraction of the MoI since the moment arm about the center-of-mass (CoM) of the insect may be large. The objective of the current study is to assess the importance of MoI variation in insect flight maneuvers. The balance of angular momentum states that,

$$\tau = [I]\ddot{\theta} + [\dot{I}]\dot{\theta} \qquad (1)$$

Torque (τ) — *MoI* ([I]) — *Angular Velocity* ($\dot{\theta}$)

If the MoI is assumed to be constant, then the second term on the RHS vanishes. If however, the rate-of-change of the MoI is significant enough such that the second term is non-negligible, then it can potentially have an effect on the dynamics of flight.

II. Methods

The insect species chosen for this research is the Painted Lady butterfly (*Vanessa cardui*). In order to assess the significance of the MoI variation, measurements must be made of the:

1. Mass properties (dissection).
Estimation of the CoM and MoI of the insect requires an estimation of the CoM of each component of the insect body. In order to find the CoM of each wing, it is assumed to be a lamina for which the plumb-line method can be used.

Fig. 2a. Painted Lady butterfly

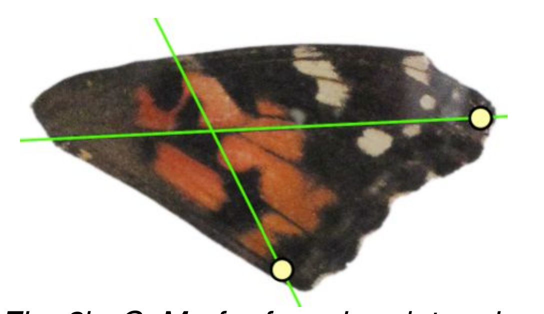

Fig. 2b. CoM of a forewing determined using two plumb-lines (circles indicate the two hinge points)

2. Kinematics (videogrammetry).
The butterflies fly inside the main glass chamber – three synchronized high-speed cameras are pointed at a small region in the chamber, and are used to capture videos of the butterflies' flight maneuvers. The three cameras are calibrated in three dimensions with a rig that is photographed at the end of each recording session.

Because the flapping frequency of the Painted Lady butterfly is about 25 Hz, a recording frame rate of 3,000 frames per second and a shutter speed of 150 µs are used to capture a sharp image of the butterfly at each frame. A lens f-stop of at least f/11 is used to maintain an appropriate depth-of-field in each of the videos.

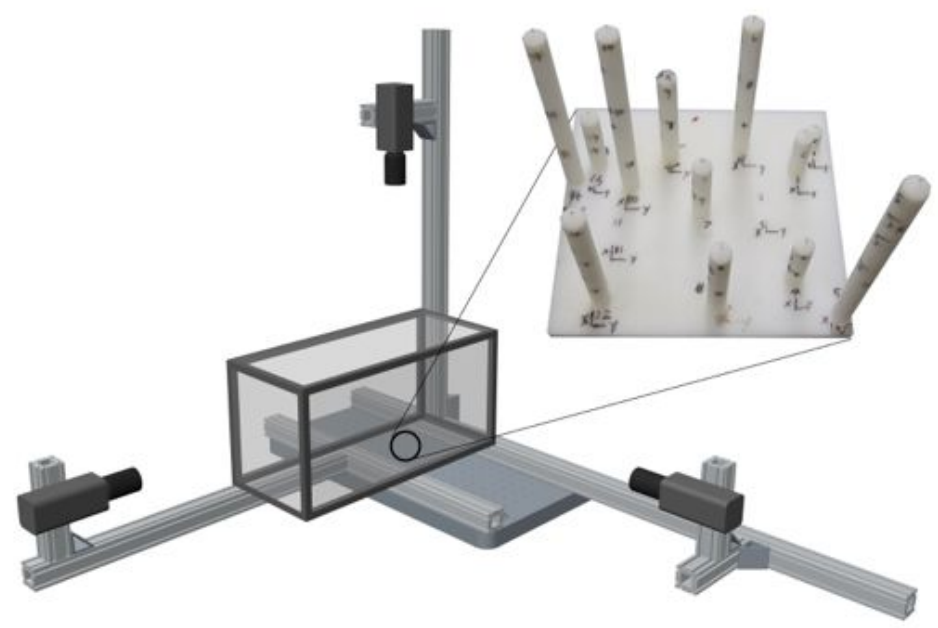

Fig. 3. Videogrammetry setup showing three high-speed cameras and the flight chamber. Inset shows the calibration rig used for defining the spatial coordinates in the glass chamber for analysis with the Direct Linear Transformation (DLT) algorithm.

III. Discussion & Results

Our analysis of MoI variation is based primarily on the simplest flight mode: forward flight. Due to the bilateral anatomical symmetry of the butterfly about its sagittal plane, the principal axes obtained from a spectral decomposition of the MoI tensor constitute the roll, pitch, and yaw axes, and the eigenvalues are the corresponding MoI values.

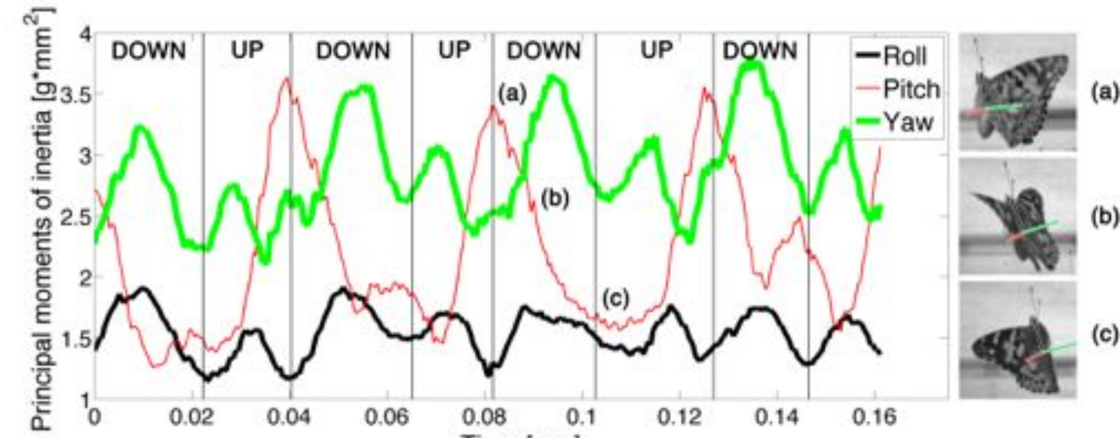

Fig. 4. Moments-of-Inertia, forward maneuver

To extend this analysis to assess the potential impact of a changing MoI on the maneuvering of the insect, we estimate the relative magnitude of the terms on the RHS of Eq. 1 for a pitching maneuver – specifically, the transition from forward to climbing flight. We estimate the pitch MoI and pitch MoI variation for this maneuver with the data corresponding to forward flight.

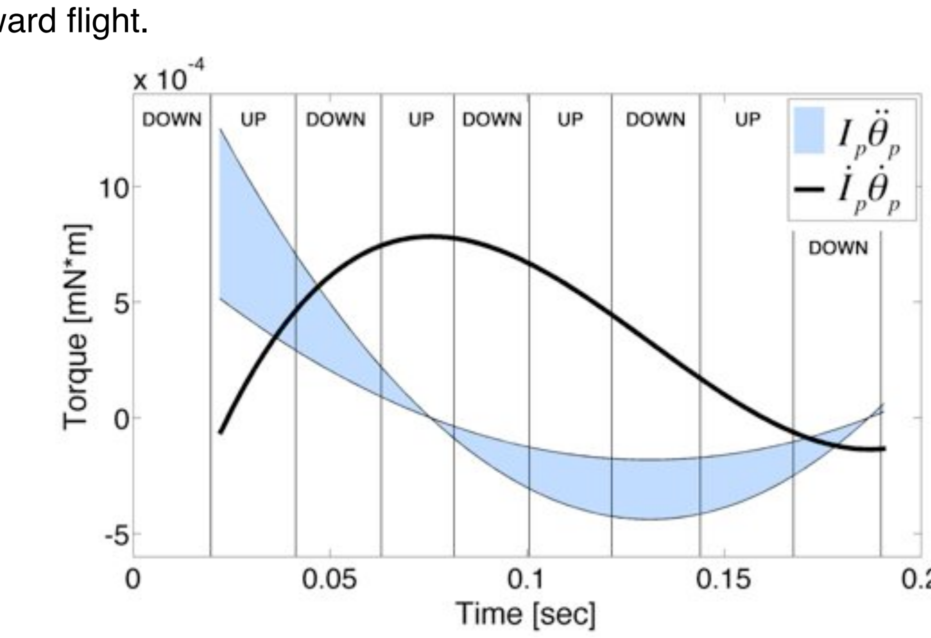

Fig. 5. Components of rate of change of pitch angular momentum estimated using the upper and lower bound of pitch MoI and the maximum time rate of change of pitch MoI

The above plot shows that the torque component due to angular acceleration and the torque component due to MoI variation are similar in magnitude. Even though the wings of the butterfly only contribute to about 7% of the mass of the insect, the MoI changes induced by the movement of the wings may potentially have a non-negligible effect on the dynamics of insect flight maneuvers.

Acknowledgements

[1] Pratheev Sreetharan, Microrobotics Lab, Harvard University.
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