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Generation of Control Moments in an Insect-like Tailless Flapping-wing Micro Air Vehicle by Changing the Stroke-plane Angle

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Abstract

We propose a control moment generator to control the attitude of an insect-like tailless Flapping-wing Micro Air Vehicle (FW-MAV), where the flapping wings simultaneously produce the flight force and control moments. The generator tilts the stroke plane of each wing independently to direct the resultant aerodynamic force in the desired direction to ultimately generate pitch and yaw moments. A roll moment is produced by an additional mechanism that shifts the trailing edge, which changes the wing rotation angles of the two flapping wings and produces an asymmetric thrust. Images of the flapping wings are captured with a high-speed camera and clearly show that the FW-MAV can independently change the stroke planes of its two wings. The measured force and moment data prove that the control moment generator produces reasonable pitch and yaw moments by tilting the stroke plane and realizes a roll moment by shifting the position of the trailing edge at the wing root.

Keywords: insect-like Flapping-wing Micro Air Vehicle (FW-MAV), control mechanism, stroke plane, beetle flight

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1 Introduction

There has been an upsurge in interest in the development of small-scale flyers with flapping wings, or Flapping-wing Micro Air Vehicles (FW-MAVs)[1], to mimic birds[2–5] and insects[6–13]. Nature's flyers, such as birds and insects, flap their wings to produce their flight force. Insects differ from birds in that they do not have a control surface, which would be the tail for birds. Thus, they must actively modify their wing kinematics during flapping flight to produce control forces or moments along with the flight force. Therefore, the engineering design of an insect-like tailless FW-MAV is a challenging task in that the principles of insect flight control should be fully adopted and realized.

The principles of attitude control in insect flight are well summarized in Ref. [14], which provides a very useful reference for extracting the bio-inspiration of novel designs capable of mimicking the principles in question. In addition to the principles of attitude control, understanding the principles of insect flight including leading edge vortex generation[15–17], clap-and-fling[17,18], rotational circulation [19–21] and wing-wake interaction[17,21] has contributed to the development of FW-MAVs. In brief, an insect has the ability to manipulate its wing kinematics by changing the flapping angle[14,22], flapping frequency[23], stroke-plane angle[24], and posture[25] during its flapping wing motion. An example shown in Fig. 1 indicates that shifting the flapping angle ranges of the two wings simultaneously with respect to the mid-stroke while maintaining the flapping angle amplitude produces a pitch moment. A differential flapping angle shift between the two wings may generate other control moments. This principle was adopted in Ref. [26], which presented the design of a flapping-wing mechanism that can change the flapping angle while simultaneously producing thrust and a pitch moment. Changing the amplitudes of the two wings, or differential flapping angles, is a good strategy for generating the control moments and is therefore adopted for RoboBee[6] and a robotic hummingbird[27].

However, manipulating the flapping angle may require the mechanism to apply a relatively large actuation force. Even a slight change in the wing morphology

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during fast flapping can create a sufficiently large asymmetric force to apply a control moment. Adopting this principle would make it easier to fabricate and maintain a tailless FW-MAV because the control moment generation mechanism that modifies the wing kinematics can be independent of the vehicle's flapping mechanism[7,28,29].

Allomyrina dichotoma is a beetle that can modify its wing kinematics by changing its wing stroke-plane angle during flight. We set up a situation where the beetle initiated forward flight while facing a wall so that it immediately noticed the presence of the wall. To avoid collision, it applied every means of moment generation available to slow down its flight speed, climb, or a quick turn. We traced some of the images of the flight captured with a high-speed camera (2,000 fps) and found that this particular beetle instantly changes the angle between the axis of its body and the tip path planes or stroke plane, as shown in Fig. 2. The change in stroke plane redirects the resultant aerodynamic forces to generate control moments during flight.

Inspired by this feature, we first created an engineering design for a Stroke Plane Change (SPC) mechanism, which was previously reported in Ref. [30] by us. In the following sections, we describe the engineering design of the control moment generator to mimic the beetle's SPC and provide experimental data to prove that the mechanism can produce pitch and yaw moments.

2 Design of the stroke plane change mechanism

2.1 Definition of rotational angles

Fig. 3 defines the rotational angles, which follows the method adopted in Ref. [7]. The proposed mechanical design can independently modify the flapping stroke planes of the left and right wings during a flapping motion to generate pitch and yaw moments about the *y* and *z* axes, respectively. This is referred to as the SPC mechanism in this paper.

2.2 Design of SPC mechanism

The SPC mechanism was assembled in a FW-MAV, as shown in Fig. 4. The flapping mechanism itself can be of any type, such as that used in Ref. [28]. In this work, we used a flapping mechanism based on the four-bar linkage and pulley-belt mechanism introduced

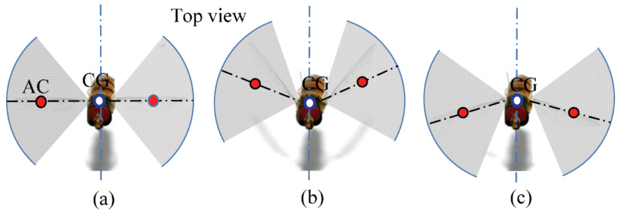

Fig. 1 A top view for generating a pitch moment by shifting the flapping angle range (AC: mean aerodynamic force center; CG: center of gravity). (a) No control moment is generated; (b) shifting up the flapping angle range results in the pitch-down moment for forward flight; (c) shifting down the flapping angle range creates pitch-up moment for backward flight.

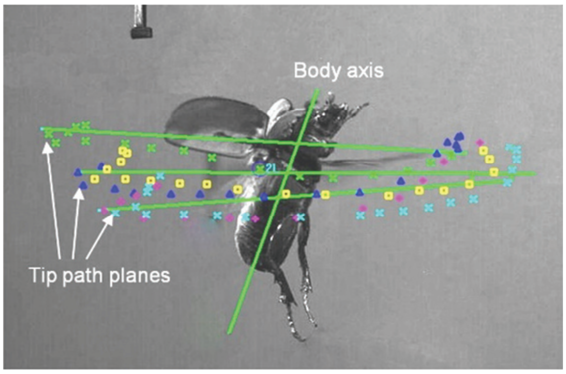

Fig. 2 Change in beetle's wing stroke plane during flight. The marked points represent the instant locations of the wing tip during flapping motion. Different symbols and colors show the difference in the flapping stroke.

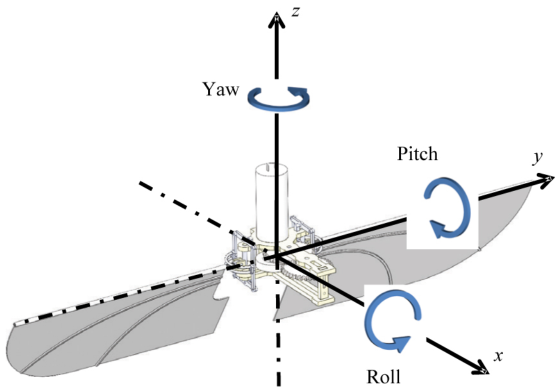

Fig. 3 Definition of rotational motion about the three axes.

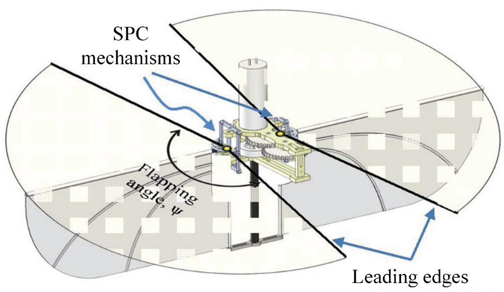

Fig. 4 Assembly of flapping wing and SPC mechanisms.