A Bio-inspired Wing Driver for the Study of Insect-Scale Flight Aerodynamics

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Abstract. Insect flight studies have advanced our understanding of flight biomechanics and inspire micro-aerial vehicle (MAV) technologies. A challenge of centimeter or millimeter scale flight is that small forces are produced from relatively complex wing motions. We describe the design and fabrication of a millimeter-sized wing flapping mechanism to simultaneously control pitch and stroke of insect and MAV wings. Using micro-fabrication techniques we construct this wing driver and observe that wing motion matches the natural degrees of freedom of insect wings. We actuate wing stroke-position and pitch in open-loop at frequencies relevant to Dipteran and Hymenopteran flight (100-200Hz) and describe the advancements and limitations of this system.

Keywords: Biomimetics, Insect flight, Micro-robotics, Aerodynamics.

1 Introduction

Combined robotic and biological experiments have advanced our knowledge of the world of insect flight, and serve as a source of inspiration for the future design of micro-aerial vehicles (MAVs). Furthermore, the study of robotic and biological flapping wing flight has highlighted a need to understand unsteady aerodynamics [1]. However, despite the myriad laboratory experiments on flapping wing aerodynamics, major open questions of flapping wing flight remain unanswered.

Insect wings are heterogeneous structures with non-linear elasticity and complex structural design [2]. The functional consequences of features such as wing flexibility, shape, or material properties are largely open questions in flapping wing aerodynamics. While recent studies have highlighted the importance of wing flexibility in a dynamically scaled experiment [3], at-scale experimental approaches are necessary since inertial forges cannot be accurately captured by dynamically scaled models. Inertia is a key factor in aeroelastic deformations of wings during flapping and thus at-scale laboratory experiments are needed to explore form and function of insect wings.

Advances in micro-robotic manufacturing, such as the smart-composite manufacturing process [4], have enabled the development of insect-scale actuated

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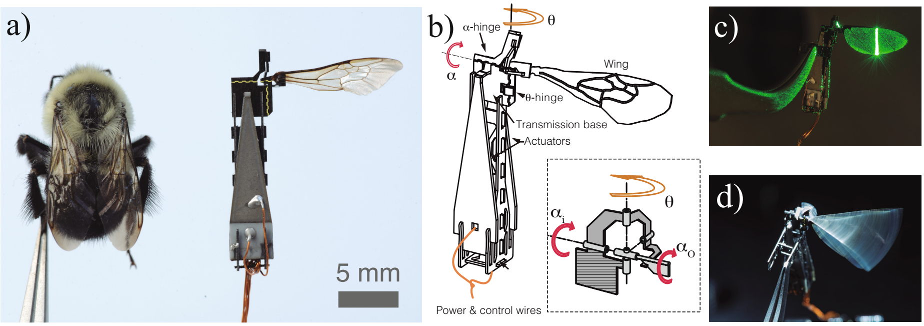

Fig. 1. Insect inspired study of flapping wing aerodynamics. a) A bumblebee (*Bombus impatiens*) (left) and wing driver (right). A bumblebee wing is attached to the driver. b) Schematic of the wing driver. Inset shows spherical 5-bar mechanism. c) Laser sheet illumination. d) Wing motion during flapping at 100Hz.

mechanisms. We present the design of a micro-robotic wing flapping mechanism capable of actuating the millimeter sized wings of MAVs and the bumblebee (*Bombus impatiens*) for aerodynamics study. This wing driver is inspired by the motion of real insect wings during flight. We construct and test the wing driver and discuss the future outcomes of these experiments.

2 Driver Design

Our design goal is a wing driver that generates bumblebee scale (*Bombus impatiens*) wing kinematics (Fig. 1a). During hover, bumblebees flap their wings at approximately 170 Hz with a mean stroke amplitude of 140°. During a typical wing stroke the position (θ), pitch (α), and vertical excursion are all modulated. Previous flapping mechanisms to study bumblebee scale aerodynamics utilized a passive hinge to modulate wing pitch. Here we present a mechanism capable of actuating a bumblebee sized wing in θ and α over ranges of $\theta \in [-70°,\ 70°]$ and $\alpha \in [-45°,\ 45°]$. For manufacturing considerations we require this mechanism to be minimally complex, and be lightweight for time resolved force measurements.

We laser cut and fold planar sheets of carbon fiber and polymer flexures into their designed shapes to construct this mechanism [4]. The driver is actuated by two piezo-electric bimorphs (Fig. 1b). A spherical five bar linkage provides two degree of freedom control (Fig. 1b and inset). A feature of this linkage is the minimal coupling between θ and the α output [5].

3 Experiments and Outlook

We tested wing motion under open-loop control in both θ and α. A laser sheet illuminated the mid-plane of the wing normal to the span-wise direction in the neutral position (Fig. 1c). We tracked the motion of this laser line in high-speed

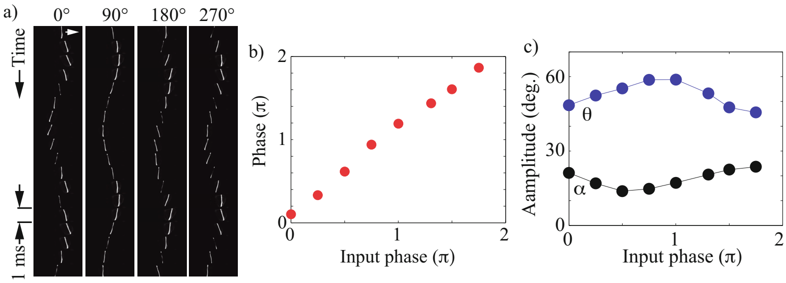

Fig. 2. Wing kinematics. a) High-speed video from four experiments at 100 Hz. Phase offset denoted above. Frames are 1 ms apart. b) Input and measured phase difference in wing stroke and pitch. c) Peak-to-peak amplitude of wing stroke and amplitude of angle of attack.

video. Wings were oscillated sinusoidally at a frequencies of 100 Hz (Fig. 1d) with varied phase-lag between α and θ (Fig. 2a). The mechanism was capable of wing frequencies of up to 200 Hz.

We fit sin curves to the measured α and θ. The output phase lag between α and θ increased with the commanded phase lag approximately linearly, with a small positive offset (Fig. 2b). However, the output amplitudes of α and θ varied with phase lag (Fig. 2c) likely due to the rotational inertia of the wing during stroke reversal. These results highlight the need for closed-loop control to compensate for the non-uniform output kinematics associated with the variation of wing control signals.

The development of a two degree of freedom wing driver capable of matching the wing kinematics of millimeter sized insects will give valuable insight into the functional consequences of insect wing form. Through closed-loop control on θ and α we will systematically vary wing and kinematic parameters in our at-scale experiments in the near future.

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