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A Search for Optimal Wing Strokes in Flapping Flight: Can Engineers Improve Upon Nature?

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ABSTRACT

Computational modeling is used to explore the efficiency of hovering flight in a hawkmoth (*Manduca Sexta*). While flying insects such as hawkmoths are excellent flyers, their wing-strokes are constrained by a number of factors including anatomy, developmental requirements, biological material properties and evolutionary history. Engineered micro-aerial vehicles are not subject to similar constraints and this suggests the possibility that bioinspired flapping wings could be designed to aerodynamically outperform equivalent biological flyers. In this study we use a composite modeling approach that combines blade-element and Navier-Stokes flow models to explore the wing kinematics parameter space for this insect. Our study demonstrates that wing-strokes can indeed be synthesized which exceed the power loading (the ratio of lift to power) of the insect wing by over 30%. This study reinforces the notion that while engineers can learn from Nature's designs, they do not need to be constrained by them.

Introduction

In the past four decades, insect flight has attracted much interest and substantial progress has been made in revealing the various underlying aerodynamic mechanisms of flapping flight. Weis-Fogh[1, 2] discovered the "clap-and-fling" mechanism. Ellington[3] revealed the importance of leading edge vortex in lift generation. Dickinson[4, 5] and coworkers identified three distinct mechanisms during insect flight: delayed stall, rotational circulation and wake capture. Mittal[6] studied the wing-wing interaction in four-winged insects. Recently, Sun et al.[7, 8] studied the dynamic flight stability and controllability of different insect models. Wang[9] analyzed a two-stroke model in the quasi-steady limit to seek the simplest efficient flapping wing motions. With increases in computational power and the development of photogrammetric techniques, additional attention has been paid to the wing flexibility. Vanella et al.[10] investigated the performance of a two-dimensional hovering wing section and found the flexibility can be beneficial in terms of enhancing aerodynamic performance. Miller et al.[11] used the immersed boundary method to simulate clap-and-fling in rigid and flexible wings.

Approach

Currently, we are focused on gaining a comprehensive understanding of hovering flight in large insects and our particular focus here is on the hawkmoth (*Manduca Sexta*) which is known for its ability to hover. The approach used here is one that integrates biological flight experiments/measurements with computational fluid dynamics. The 3-D kinematics of the freely flying insect are measured from high-speed videogrammetry; Figure 1 shows the high-speed insect flight videogrammetry setup used in this study. This approach produces images similar to the sample frames shown in Figure 2. Following extraction of the 3-D surfaces from the flying animal, we then simulate the model using a high fidelity CFD solver that has been developed to simulate complex biological flows[12].

This experimental framework, running from recordings of living animals in untethered, free flight through to CFD simulations is capable of revealing complex flow dynamics, offers a wealth of opportunities for exploration of many aspects of animal flight. For instance, ongoing analysis of experiments similar to Figure 3, which shows the aerodynamic perturbation of a hovering moth through application of a directed vortex ring followed by recovery wingbeats from the moth, will reveal interactions

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