Unsteady Aerodynamics in High-Frequency Flapping Wings of Insects and Robots

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Abstract

To produce the aerodynamic forces required for flight, insects and bio-inspired flying robots beat their wings back-and-forth at high frequencies. These rapid oscillatory motions result in significant accelerations, leading to acceleration-based aerodynamic forces, namely added-mass forces and Wagner-effect-based forces. The added-mass forces arise from the acceleration of fluid around the wings, while the Wagner effect describes the delay in the build-up of bound circulation in accelerating wings. Surprisingly, many aerodynamic models for flying insects and bio-inspired robots ignore these mechanisms, considering them negligible or unsuitable for quasi-steady aerodynamic modelling.

Here, we used computational fluid dynamics simulations of accelerating wings to systematically study how added-mass and the Wagner effect influence aerodynamic force production and airflow dynamics. Based on this, we developed a novel quasi-steady aerodynamic model that accurately captures the stroke-acceleration forces based on wing-beat kinematics and wing morphology. Our findings revealed that previous added-mass models fail to accurately predict the added-mass forces on insect wings due to their simplified semi-empirical nature, which overlooks the Wagner effect. Consequently, we present a novel Wagner-effect model that accounts for the interaction between stroke rate and stroke acceleration, effectively predicting the delay in Leading-Edge Vortex development in both accelerating and decelerating wings.

By applying our aerodynamic model to the wingbeats of a fruit fly and a malaria mosquito, we demonstrate that acceleration-based forces significantly contribute to aerodynamic lift and drag production, particularly in high-frequency flapping flyers like the mosquito. These findings emphasize the importance of considering acceleration-based aerodynamic forces when modelling flight of insects and bio-inspired robots, as they play a vital role in powering and controlling flapping-wing-based flight in both systems.

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