Dynamic Modeling and Simulation of Flapping-Wing Micro Air Vehicles

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Sep. 20, 2019

Abstract

Birds and insects inspired us to develop flying machines such as airplanes and helicopters. However, the development of artificial flapping-wing flyers falls far behind other aircraft due to the complexities of unsteady aerodynamics, bidirectional actuation, stability and control, etc. To aid the practical design of insect-sized robotic micro air vehicles (MAVs), we aimed to develop a set of tools for analyzing the unsteady aerodynamics and flight dynamics of flapping-wing flyers.

The robotic design of MAVs with wings connected to the body through flexure hinges is able to reduce the number of the actuation degrees of freedom and the complexity of the transmission design. In this design, the wing is partially actuated and the passive pitching motion of the wing is dynamically determined under the interactions among inertial, hinge elastic and aerodynamic forces. Both the wing motion itself and the dynamics of the entire MAV define the fluid-structure interaction (FSI) procedures.

To estimate the aerodynamic forces on a single wing under passive pitching, the dynamics model of one wing is derived and first simulated by integrating the equations of motion with a CFD solver. To achieve physical insights and quick force estimation, revised empirical formulas are proposed to extend the adaptability and improve the accuracy of existing quasi-steady (QS) models. Preliminary modeling on the hinge angle limit by geometry is proposed for actual mechanical design. The validity of the weakly decoupled FSI assumption is discussed with the FSI simulation of a wing immersed under water.

Full dynamics model of the entire MAV is formulated with our proposed alternative form of the Euler-Lagrange equations. In the alternative form, repeated terms are removed to enable the manual derivation of compact equations of motion for the MAV to achieve efficient numerical computations. The integrated simulation with CFD solver provides us with high-fidelity numerical predictions for the dynamic behavior of the flapping-wing MAVs in open-loop or closed-loop simulations. The fast full dynamics models with QS formulas are formulated and the results are compared with the results by CFD solvers. The full dynamics model with QS formulas are experimentally validated with both underwater tests and jump tests in the air. Highly satisfactory matching between the simulated and experimental results are achieved. The full dynamics model is proved to be effective in the dynamic behavior prediction for the robotic MAVs.

To compensate for the incapability of the proprietary CFD solver in flexibility and computing efficiency, a unified CFD solver based on the overset grid method is proposed and implemented for moving boundary problems at low Reynolds number. To achieve efficient and accurate simulations with the overset grid method, fast search-based hole-cutting algorithm, hybrid automatic parallel multigrid generation and consistency improved schemes for the segregated solving process are proposed. Finally, testing examples are provided to demonstrate the capability of the in-house solver on unsteady and moving boundary problems.