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A fluid–structure interaction model of insect flight with flexible wings

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ABSTRACT

We present a fluid–structure interactions (FSI) model of insect flapping flight with flexible wings. This FSI-based model is established by loosely coupling a finite element method (FEM)-based computational structural dynamic (CSD) model and a computational fluid dynamic (CFD)-based insect dynamic flight simulator. The CSD model is developed specifically for insect flapping flight, which is capable to model thin shell structures of insect flexible wings by taking into account the distribution and anisotropy in both wing morphology involving veins, membranes, fibers and density, and in wing material properties of Young's modulus and Poisson's ratios. The insect dynamic flight simulator that is based on a multi-block, overset grid, fortified Navier–Stokes solver is capable to integrate modeling of realistic wing-body morphology, realistic flapping-wing and body kinematics, and unsteady aerodynamics in flapping-wing flights. Validation of the FSI-based aerodynamics and structural dynamics in flexible wings is achieved through a set of benchmark tests and comparisons with measurements, which contain a heaving spanwise flexible wing, a heaving chordwise-flexible wing with a rigid teardrop element, and a realistic hawkmoth wing rotating in air. A FSI analysis of hawkmoth hovering with flapping flexible wings is then carried out and discussed with a specific focus on the in-flight deformation of the hawkmoth wings and hovering aerodynamic performances with the flexible and rigid wings. Our results demonstrate the feasibility of the present FSI model in accurately modeling and quantitatively evaluating flexible-wing aerodynamics of insect flapping flight in terms of the aerodynamic forces, the power consumption and the efficiency.

1. Introduction

Insects fly by flapping their wings to generate high aerodynamic forces to keep them aloft and to achieve remarkable maneuvers by sophisticated movement and interaction with surrounding air. Because of the inherent flexibility of insect wings, the aerodynamic and inertial forces acting on insect wings can consequently induce considerable elastic deformations during flapping flight [55]. This usually leads to a strongly coupled, complex fluid–structure interaction (FSI) problem associated with the aerodynamics and structural dynamics of flapping wings. Recently there is a remarkable increasing of studies on this topic, which are carried out by means of high-tech-based methods including the high speed digital camera for the wing kinematics reconstruction [49–51,58,60], the digital particle image velocimetry (DPIV) for flow measurement [4,36,45], the dynamically scaled robotic insect models with man-made flexible wings [61,62] and the computational fluid and structural dynamics for simplified FSI analysis [10,15,26,34,48,53,59,63]. Although these studies have deepened our

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understanding of the flapping flexible wing aerodynamics, it still remains unclear yet how three-dimensional and passive changes of wing kinematics due to the inherent flexibility of insect wings affect the unsteady aerodynamics and the energetics in insect flapping flight.

Experimentally, it is of great difficulties to tackle this aero-elastic problem of the flexible wing aerodynamics because it usually requires a direct measurement of the wing kinematics, the wing deformation, the flow fields and the aerodynamic forces either for a real flexible insect wing or for a dynamically-scaled robotic wing model in a simultaneous way. An integrated method that combines the direct measurement of wing-body kinematics and wing deformation as well as flow fields in real insect flight with a computational fluid dynamic analysis can be an approach to predict how the wing deformation affects the aerodynamic performance [60,63]. This method, however, does not couple solutions to flows and wing structures and hence cannot deal with the mutual interactions between aerodynamics and structural dynamics in flexible wings. Recently, several FSI-based analyses report some interesting results associated with the flexible wing aerodynamics by using either a two-dimensional foil or a highly idealized single three-dimensional wing model [10,22,26,34,48,53,59,64]. However, there is still no any study dealing with a realistic insect model with flexible wings, which is desired to integrate the body-wing morphology and kinematics, the unsteady aerodynamics and the wing structural dynamics, and the energetic evaluation on aerodynamic forces, power and efficiency.

In this study, we present an integrated computational model of insect flapping flight with flexible wings, which is based on a three-dimensional and unsteady FSI analysis and is capable to evaluate the flexible-wing aerodynamic performances in terms of the aerodynamic forces, the power consumption and the efficiency. This FSI model being specified for insect hovering flight is achieved by coupling a recently developed finite element method (FEM)-based computational structural dynamic (CSD) solver with a rigorous computational fluid dynamics (CFD)-based insect dynamic flight simulator [29]. The CFD method based on a fortified Navier–Stokes (NS) solver for dynamically moving multi-block and overset-grid systems integrates the modeling of the realistic wing-body morphology, the realistic flapping-wing and body kinematics, and the unsteady aerodynamics in insect flight. The FEM-based CSD method is developed to simulate dynamic and large deformations of insects' flexible wings due to inertial and aerodynamic forces. In the following we demonstrate that the present coupled model has capability to accurately predict aerodynamics and energetics in insect flapping flight with flexible wings.

2. Fluid–structure interaction modeling of flexible wings in flapping flight

2.1. A CFD-based insect dynamic flight simulator

This study employs a biology-inspired, dynamic flight simulator [29], which is versatile, easily integrating the modeling of realistic wing-body morphology, realistic wing-body kinematics, and unsteady aerodynamics in insect flight. A morphological model is built based on an effective differential geometric method for reconstructing the geometry of wings and a body, and a specific grid generator; and a multi-block, overset-grid method is utilized to deal with the complex wing-body geometries and the complicated flapping movements. A kinematic model is constructed to be able to mimic the realistic wing-body kinematics of flapping flight; and an efficient analytical method combined with three coordinate systems is employed for the dynamic regridding.

2.1.1. Morphological and kinematic models of a hovering insect

A realistic morphological model of a hovering insect is constructed on a basis of two-dimensional digitized images of hawkmoth, *Agrius convolvuli*, as shown in Fig. 1, which is used for generation of both CFD grids and CSD meshes. For the CFD model a uniform thickness is taken for the wing but with elliptic smoothing at the leading and trailing edge as well

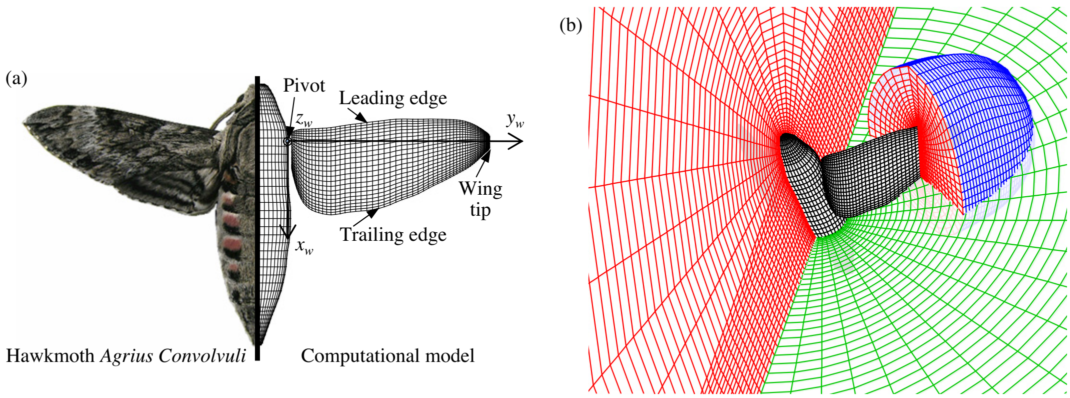

Fig. 1. A morphological hawkmoth model. (a) A hawkmoth *Agrius Convolvuli* with a computational model for CFD analysis superimposed on the right half. (b) Multi-block grid systems of a wing-body hawkmoth model (body: 45 × 43 × 65; wing: 45 × 65 × 25) with an outside boundary of $15c_m$ from body surface.