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Integrated modeling of insect flight: From morphology, kinematics to aerodynamics

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ABSTRACT

An integrated and rigorous model for the simulation of insect flapping flight is addressed. The method is very versatile, easily integrating the modeling of realistic wing–body morphology, realistic flapping-wing and body kinematics, and unsteady aerodynamics in insect flight. A morphological model is built based on an effective differential geometric method for reconstructing geometry of and a specific grid generator for the wings and body; and a kinematic model is constructed capable to mimic the realistic wing–body kinematics of flapping flight. A fortified FVM-based NS solver for dynamically moving multi-blocked, overset-grid systems is developed and verified to be self-consistent by a variety of benchmark tests; and evaluation of flapping energetics is established on inertial and aerodynamic forces, torques and powers. Validation of this integrated insect dynamic flight simulator is achieved by comparisons of aerodynamic force-production with measurements in terms of the time-varying and mean lift and drag forces. Results for three typical insect hovering flights (hawkmoth, honeybee and fruitfly) over a wide rang of Reynolds numbers from $O(10^2)$ to $O(10^4)$ demonstrate its feasibility in accurately modeling and quantitatively evaluating the unsteady aerodynamic mechanisms in insect flapping flight.

1. Introduction

1.1. Overview of insect flight

Flying insects, in general, perform flapping wing flight because they have to create not only lift to stay airborne but also thrust for forward and darting flight, in achieving remarkable maneuvers with rapid accelerations and decelerations. Aerodynamics associated with the insect flapping wing flight prominently features unsteady motions at moderate Reynolds numbers ranging over $O(10^1)$ to $O(10^4)$, which is normally characterized by large-scale vortex structures, complicated flapping wing kinematics and flexible-wing structures [1–4]. Thus a challenging problem in uncovering aerodynamic mechanisms in insect flight is to answer a central question of how the large-scale vortex dynamics and complicated wake topology are generated and how they correlate to the force-production.

Studies [4,6–11,13,14,18,19,21–26] on aerodynamics of a single flapping wing model have been the main subject till now; and a general conclusion is that insects keep them aloft by using a high-lift, unsteady aerodynamic mechanism based on the sophisticated vortices. Experimental studies using robotic insect wing models have made significant contributions in quantifying some of the unsteady aerodynamic effects including the leading edge vortex mechanisms, the wing rotation and the wake capture mechanisms and so forth [7,8,11,13]. Recent direct measurements of the vortical structures around real insects and birds [7,8,11,13,15–17,21–25,27,29] further enhance our insights into quantitative description on such vortex dynamic-

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based aerodynamics in flapping wing flight. However, limited to specific insects of hawkmoth and fruitfly and to specific focus on the near-field flows around non-realistic hovering models [7,8,11,13,16], or, tracking on the footprint of the vortex dynamics in a manner of the far-field flow fields around real animals [15,17,26,28,30], a universal explanation on insect flapping wing aerodynamic mechanisms still remains controversial [13,34]. This leads to recognition that an integrative study is necessary for systematically and quantitatively investigating the effects of sizing or Reynolds number, morphology and kinematics on flapping wing flight.

1.2. Integrated modeling of insect flight

To tackle this difficult problem one needs to deal with unsteady aerodynamics about an insect-like multi-body system with consideration of dynamically oscillating boundaries of flapping wings and complicated wing–wing and wing–body interactions. While flows around flying insects obey the Navier–Stokes equation a comprehensive answer to the question depends upon multi scale solutions of the problem that integrate the vortex dynamics of all scales in terms of the near- and far-fields and that establish an essential three-dimensional mechanism of flapping wing aerodynamics. To reveal such an essential three-dimensional mechanism [31,32], a systematic and quantitative study of insect flapping wing flight is a must, which need to be established on the basis of realistic morphology and kinematics and is capable to quantify the vortex dynamics, the wake topology and their correlation with the force-production.

We here address an integrated and rigorous model for the simulation of insect flapping flight. The majority of the current insect-like model is the integrated modeling methodology from realistic body–wing morphology, the flapping-wing and body kinematics to the unsteady aerodynamics as well as the quantitative evaluation of flapping energetics on inertial and aerodynamic forces, torques and powers. Till now most CFD-based models employ non-realistic wing models in a fashion of single or paired wings in 2D or 3D [14,18,19,28] with a specific focus on how important the flapping motions influence the viscous vortex flows but with less attention to the modeling efficiency and the integrated correlation between the near- and far-field vortex dynamics and the force-production. Some studies focus on efficient algorithms development capable for treating arbitrary boundaries with complex geometries of wing and/or body [24,27] by means of immersed boundary methods, etc in Cartesian coordinate systems but using some simple kinematic models. To date, no model has been reported which is versatile to easily construct a morphological model with realistic geometries of both wings and body, which is capable to accurately mimic complicated movements of realistic flapping wings and body kinematics, and which is able to efficiently solve the Navier–Stokes (NS) equations for a multi-blocked, overset-grid system with dynamically moving boundaries and meshes. In the following we demonstrate that the current model has such capability and the results of insect hovering flight can be obtained in a reasonable amount of time.

2. Integrated modeling methodology

2.1. A brief overview of current model

The current model integrates the modeling of morphology-kinematics-aerodynamics in insect flapping flight; and three typical insect hovering models covering a range of *Re*s from $O(10^2)$ to $O(10^4)$ demonstrate its feasibility in efficiently and accurately modeling and evaluating the insect flapping flight. The morphological modeling is based on a differential geometric method for reconstructing wing–body geometry with each cross-section approximated as an ellipse, a specific structured-grid generator, and a multi-blocked overset-grid system in dealing with complex wing–body geometries and complicated flapping movements. The kinematic modeling is capable to mimic realistic wing–body kinematics in terms of the body angle, the stroke plane angle, and the positional–feathering–elevation angles, which is combined with an analytical method for dynamic regridding. A fortified finite volume method (FVM)-based NS solver for the dynamically deforming multi-blocked, overset-grid system is developed and verified; and validation is implemented through an extensive study of aerodynamic force-production by comparison with experimental results in terms of the time-varying and mean lift and drag forces. The computing performance is further confirmed by testing on a PC (Dell Precision 690) with DuralCore Intel(R) CPU (3.0 GHz) and a memory of 4.0 GB, which takes approximately 10 h of CPU time for a hawkmoth-like wing–body model undergoing hovering for four complete beat cycle, with approx. 340,000 grid points of two wing blocks and a body block.

2.2. Coordinate systems in modeling of insect flapping flight

We define three coordinate systems in modeling of insect flapping flight, as depicted in Fig. 1: (1) a wing-fixed system (x_w, y_w, z_w) with its origin at the pivot point of the right wing and 'flapping' with the flapping wing; (2) a body-fixed system (x_b, y_b, z_b) with its origin at the center of mass of and moving together with the object; and (3) a global system (X, Y, Z) as an inertial system being fixed horizontally. Body posture (Fig. 1a) is described by the stroke plane angle η and the body angle χ, relative to horizontal; the angles of pitch β, roll ψ, and yaw γ with respect to the body-fixed system. Wing position parameters are defined (Fig. 1b) within the stroke plane: the wingtip path is indicated by the closed circle composed of a solid for downstroke and a dashed for upstroke, respectively; the positional angle ϕ is the angle between the y_{sp} axis and the projection $y_{w'}$ of the y_w axis onto the stroke plane; the elevation angle θ describes the rotation about the axis z_w between the wing axis y_w and the stroke plane $y_{w'}$; and the angle of attack α is defined as the feathering (rotation) of the wing axis y_w.