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Flapping wing aerodynamics of a numerical biological flyer model in hovering flight

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A B S T R A C T

Flapping flyers showcase excellent flight performances under many flight environments. In particular, hovering is a miracle of insects that can be seen for most of sizes of flying insects. Understanding of sizing or Reynolds numbers effects in hovering flights on the aerodynamics is not only of interest to the micro-air-vehicle ommunity but also of importance to comparative morphologists. In this study, a computational study of such size effects on insect hovering aerodynamics is conducted, which is performed using an integrated numerical framework consisting of the modeling of realistic wing-body morphology, the modeling of flapping-wing and body kinematics, and an in-house Navier–Stokes solver. Computational results of four typical insects in hovering flight including a thrips, a fruitfly, a honeybee, and a hawkmoth over a wide range of Reynolds numbers from $O(10^1)$ to $O(10^4)$ are presented. Furthermore the correlation among the near-and far-field flow features, the aerodynamic force production, and the wing kinematics is highlighted.

1. Introduction

Birds, bat, and insect flight has fascinated humans for many centuries [1]. In Earth nearly a million species of flying insects, and of the living 13,000 birds and mammals, and 1000 bats have taken to the skies. With respect to maneuvering a body efficiently through space, birds represent one of nature's finest locomotion experiments. While aeronautical technology has advanced rapidly over the past centuries, nature's flying machines, which have evolved over 150 million years, are still impressive. Considering that humans move at top speeds of 3–4 body lengths per second, a supersonic aircraft such as the SR-71 traveling near Mach three covers about 32 body lengths per second, it is remarkable that a common pigeon frequently attains 75 body lengths per second, and various species of swift are even more impressive, over 140 body lengths per second. The primary reasons for such superior maneuvering and flight characteristics include scaling laws with respect to a vehicle's size, as well as intuitive but highly developed sensing, navigation, and control capabilities. As McMasters and Henderson put it, humans fly commercially or recreationally, but animals fly professionally [2].

Compared to flapping wings, conventional airplanes with fixed-wings are relatively simple; the forward motion relative to the air causes the wings to produce lift. However, in biological flapping flight the wings not only move forward relative to the air; they also flap up and down, plunge, and sweep [1]. While, in earlier days of flight of efforts regarding the flapping wing aerodynamics, much of the analysis is based on the analogy to fixed-wing counterpart, it was known that this approach encounters qualitative difficulties, for example, the airplane were considered as a similar size of a bee, moving as slowly as a bee, could not fly. However, bees can fly. This story suggested in simple fashion the implied conclusion-that the theory of fixed wing aerodynamics cannot explain certain critical aspects of the flapping wing aerodynamics. The aforementioned framework essentially considers the flapping wing dynamics as a series of *snapshots* by neglecting the influence of the aerodynamics and wing motion at an earlier moment on the aerodynamics at a later time, based on the so-called quasi-steady approach [3]. In reality, in order to generate the desirable lift and thrust under various conditions, a small flyer can often benefit from manipulating unsteady fluid flows via flapping wing.

Commonly, flapping wing aerodynamics characterizes time-dependent wing motions, flexible wing structure, and low Reynolds numbers (characterizing the relative importance between inertia and viscous effects of fluid). As highlighted in Fig. 1, it is observed that the Reynolds numbers are the order of 10^1 for a tiny thrips up to order of 10^4 for a moth. Many studies have significantly contributed to understanding aerodynamic mechanisms of the flapping flight. For instance, numerical and physical experiments with dynamically-scaled biological rigid wing models under hovering condition reveal several unsteady aerodynamic mechanisms, namely, delayed stall of leading-edge vortex (LEV) [4], active wing rotation [5], an interaction between the LEV and tip

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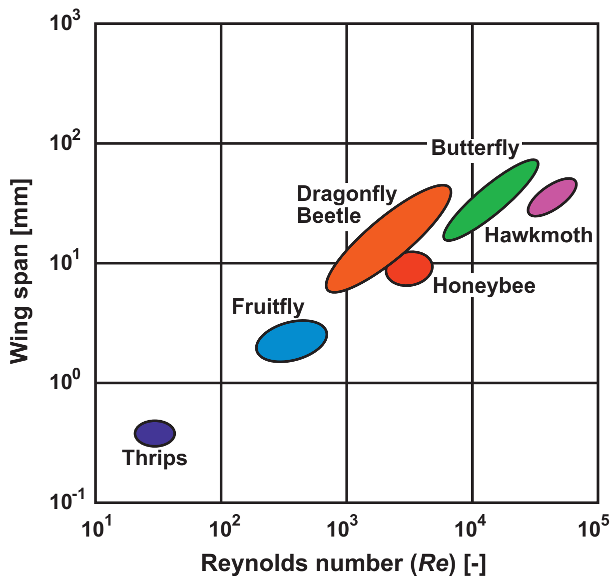

Fig. 1. Diagram of relationship between Reynolds number and wing span in biological flights.

vortex (TV) [7], as well as recapturing vortices in a wake [5,6]. Most of them substantially play a role in enhancing lift generation in the flapping flight while some of them such as the wake capture and tip vortices may lead to a decrease in the aerodynamic performance when the wing orientation and the vortical structure are not well coordinated. Moreover, the effects of wing flexibility on unsteady aerodynamic mechanisms are an ongoing topic and recently actively investigated [8]. More importantly, the effectiveness of these unsteady mechanisms is strongly linked with resultant flapping wing movement including passive wing motion, the Reynolds number, and the flight environment. Therefore, a concrete explanation and implication on the unsteady aerodynamic mechanisms still remains unclear, especially in terms of the effects of sizing or *Re* and the wing flexibility. Furthermore modeling of morphology and kinematics based on real insects and birds is no doubt a must but have not been studied systematically yet, which is not only of great interest to the micro air vehicle (MAV) community but also of importance to comparative morphologists when considering how physics constrains biological design [1,8].

The objective of present paper is twofold: (i) to provide an insight of how different morphology and kinematics in insect flight are; and (ii) to show how morphology and kinematics influence the aerodynamics in terms of either sizing or Reynolds number.

2. Materials and methods

2.1. Numerical framework of flapping flight: a biology-inspired dynamic flight simulator

Current study utilizes a numerical framework for analyzing flapping wing flight, namely, a biology-inspired dynamic flight simulator. This simulator is versatile and established based on the modeling of realistic wing-body morphology, realistic flapping-wing and body kinematics, and unsteady aerodynamics in flapping flights. A morphological model is built based on an effective differential geometric method for reconstructing geometry of and an in-house grid generator for the wing and body; and a multi-blocked, overset-grid method is utilized to deal with complicated wing-body geometries and time-dependent flapping movements with multiple degrees of freedoms. A kinematic model is constructed to be capable of mimicking the realistic wing-body kinematics of flapping flight; and an efficient analytical method combined with three coordinate systems is employed for the dynamic re-gridding. A fortified finite-volume method-based Navier–Stokes solver for the dynamically moving multi-blocked, overset-grid system is developed and verified to be self-consistent by a variety of benchmark tests. The evaluation of flapping energetics is established on both instantaneous and period-averaged inertial and aerodynamic forces, torques, and powers.

Furthermore this simulator has been validated by the comparisons of aerodynamic force-production with experimental measurements in terms of the instantaneous and flapping cycle averaged lift and drag forces. The results of four typical insect hovering flights (a hawkmoth, a honeybee, a fruitfly, and a thrips) over a wide range of Reynolds numbers from $O(10^1)$ to $O(10^4)$ have been demonstrated its feasibility in accurately modeling and quantitatively evaluating the unsteady aerodynamic mechanisms in insect flapping flight. Further details on description of numerical methods can be found in Aono et al. [7], Liu and Aono [9], Liu et al. [10], Liu and Kawachi [11], and Liu [12].

2.2. Modeling of morphology and kinematics of a biological flyer

Wing-body morphological models of four typical insects, namely a hawkmoth, a honeybee, a fruitfly, and a thrips, are constructed. In the morphological modeling the special attention is received for the fact that multiple morphologies of a two- or four-winged body and unique wing-body geometry feature in biological flapping flights. To deal with such complexity a chimera grid scheme-based overset-grid method is adopted. The grid is clustered to the wing-and body-surface with the minimum grid spacing adjacent to the wing surface controlled by a formula $0.1c_m/\sqrt{Re}$, where c_m is mean chord length and Re is the chord-based Reynolds number. The body grid is sufficiently large, which has a distance between the body surface and the outside boundary of approximately twenty times the mean chord length c_m, whereas the wing grid has an outside boundary of two times the mean chord length c_m.

Fig. 2 illustrates computational grid systems of four typical insects. Kinematics of flapping flight, in general, consists of wing beat and body kinematics. The insect body, if it is assumed to be rigid during flapping motion, can be represented by the inclination of the body to the ground (or, body angle χ) and the stroke plane angle (β), which varies according to the variation in flight speeds. While the wing-beat kinematics can be described by three basic rotational angles within the stroke plane as shown in Fig. 3. Here, a general definition of the positional angle (or the stroke angle), the elevation angle (or the deviation angle) and the feathering angle in terms of the geometric angle of attack of a wing, all in degrees, are expressed using the Fourier series, such as:

$$\varphi(t) = \sum_{n=0}^{3} \varphi_{cn}\cos(n\omega t) + \varphi_{sn}\sin(n\omega t) \tag{1}$$

$$\vartheta(t) = \sum_{n=0}^{3} \vartheta_{cn}\cos(n\omega t) + \vartheta_{sn}\sin(n\omega t) \tag{2}$$

$$\alpha(t) = \sum_{n=0}^{3} \alpha_{cn}\cos(n\omega t) + \alpha_{sn}\sin(n\omega t) \tag{3}$$

where t is a dimensional time, ω the angular frequency, n an integer varying from 0 to 3, and the coefficients φ_{cn}, φ_{sn}, ϑ_{cn}, ϑ_{sn}, α_{cn}, α_{sn} can be determined from the measured kinematic data [13,14]. Fig. 4 depicts hovering kinematic models of four insects.

Consider flying in the air ρ_{air}, the mean chord length c_m as the reference length L_{ref}, the mean wing tip velocity U_{tip} in hovering flight the reference velocity U_{ref}, which is proportional to $U_{tip} = 2\Phi fR$, where Φ is the wing tip peak-to-peak amplitude, f is the