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Recent progress in flapping wing aerodynamics and aeroelasticity

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ABSTRACT

Micro air vehicles (MAVs) have the potential to revolutionize our sensing and information gathering capabilities in areas such as environmental monitoring and homeland security. Flapping wings with suitable wing kinematics, wing shapes, and flexible structures can enhance lift as well as thrust by exploiting large-scale vortical flow structures under various conditions. However, the scaling invariance of both fluid dynamics and structural dynamics as the size changes is fundamentally difficult. The focus of this review is to assess the recent progress in flapping wing aerodynamics and aeroelasticity. It is realized that a variation of the Reynolds number (wing sizing, flapping frequency, etc.) leads to a change in the leading edge vortex (LEV) and spanwise flow structures, which impacts the aerodynamic force generation. While in classical stationary wing theory, the tip vortices (TiVs) are seen as wasted energy, in flapping flight, they can interact with the LEV to enhance lift without increasing the power requirements. Surrogate modeling techniques can assess the aerodynamic outcomes between two- and three-dimensional wing. The combined effect of the TiVs, the LEV, and jet can improve the aerodynamics of a flapping wing. Regarding aeroelasticity, chordwise flexibility in the forward flight can substantially adjust the projected area normal to the flight trajectory via shape deformation, hence redistributing thrust and lift. Spanwise flexibility in the forward flight creates shape deformation from the wing root to the wing tip resulting in varied phase shift and effective angle of attack distribution along the wing span. Numerous open issues in flapping wing aerodynamics are highlighted.

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Abbreviations: AoA, angle of attack; LEV, leading edge vortex; MAV, micro air vehicle; MTV, molecular tagging velocimetry

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1. Introduction

Micro air vehicles (MAVs) have the potential to revolutionize our sensing and information gathering capabilities in areas such as environmental monitoring and homeland security. Numerous vehicle concepts, including fixed wing, rotary wing, and flapping wing, have been proposed [1–8]. As the size of a vehicle becomes smaller than a few centimeters, fixed wing designs encounter fundamental challenges in lift generation and flight control. There are merits and challenges associated with rotary and flapping wing designs. Fundamentally, due to the Reynolds number effect, the aerodynamic characteristics such as the lift, drag and thrust of a flight vehicle change considerably between MAVs and conventional manned air vehicles [1–8]. And, since MAVs are of light weight and fly at low speeds, they are sensitive to wind gust [1–9]. Furthermore, their wing structures are often flexible and tend to deform during flight. Consequently, the fluid and structural dynamics of these flyers are closely linked to each other. Because of the common characteristics shared by MAVs and biological flyers, the aerospace and biological science communities are now actively communicating and collaborating. Much can be shared between researchers with different training and background including biological insight, mathematical models, physical interpretation, experimental techniques, and design concepts.

In order to handle wind gust, object avoidance, or station keeping, highly deformed wing shapes and coordinated wing–tail movement in the biological flight are often observed. Understanding the aerodynamic, structural, and control implications of these modes is essential for the development of high performance and robust flapping wing MAVs for accomplishing desirable missions. Moreover, the large flexibility of the wings leads to complex fluid–structure interactions, while the kinematics of flapping and the spectacular maneuvers performed by natural flyers result in highly coupled nonlinearities in fluid dynamics, aeroelasticity, flight dynamics, and control systems.

Insect wing structures are inherently anisotropic due to their membrane–vein configurations, with the spanwise bending stiffness being approximately 1–2 orders of magnitude larger than the chordwise bending stiffness in a majority of insect species [10,11]. In general, the spanwise flexural stiffness scales with the third power of the wing chord, while the chordwise stiffness scales with the second power of the wing chord [10,11]. Insect wings exhibit substantial variations in aspect ratio and configuration but share a common feature of a reinforced leading edge. A dragonfly wing has more local variations in its structural composition and is more corrugated than the wing of a cicada or a wasp [1,12]. It has been shown in the literature [1–3,12] that wing corrugation increases both warping rigidity and flexibility. Furthermore, specific characteristic features have been observed in the wing structure of a dragonfly which help prevent fatigue fracture [1,12]. The thin nature of the insect wing skin structure makes it unsuitable for taking compressive loads, which may result in skin wrinkling and/or buckling, i.e., large local deformations that will interact with the flow. On the aerodynamics side, in a fixed wing set-up, wind tunnel measurements show that corrugated wings are aerodynamically insensitive to the Reynolds number variations, which is quite different from a typical low Reynolds number airfoil [1,4,6,7,12].

As highlighted above, biological flyers showcase desirable flight characteristics and performance objectives [1,12–23]. The strategies exhibited in nature have the potential to be utilized in the design of flapping wing MAVs [1–8,24–27]. In particular, wing flexibility is likely to have a significant influence on the resulting aerodynamics. Based on a literature survey, it was found that several questions in flexible wing aerodynamics have not been adequately addressed in existing literature, among which, the key ones include: (i) How do geometrically nonlinear effects and the anisotropy of the structure impact the aerodynamics characteristics of the flapping wing? (ii) How can flapping flight be stabilized passively via flexible structures?

Furthermore, even though the rigid wing aerodynamics have been explored in more detail than the flexible wing aerodynamics, several questions still remain, among which, the key ones include: (i) How can the unsteady flow features be manipulated to enhance performance? As the sizing, flapping kinematics, flapping frequency, and flight speed vary, which fluid physics mechanisms are important? (ii) How can the observations from high fidelity simulations or experimental studies be distilled into reduced order models so that they are fast enough to execute for MAV control development? Since all of the above are not necessarily independent topics, a comprehensive understanding of the role of flapping wing kinematics, aerodynamics, and flexibility is central to the success of future flapping wing MAV designs.

As evidenced in the references cited, a number of publications exist to address numerous aspects of these issues. Furthermore, recently, many researchers have taken serious efforts in investigating these topics. There seems to be a need to consolidate the fast developing information to help update and benefit the community. The purpose of this paper is to complement the recent work presented by Shyy et al. [1] to review the recent progress in flapping wing aerodynamics and aeroelasticity at low Reynolds numbers, namely, ($O(10^1)$–$O(10^4)$). In addition to present established information, open issues in both aerodynamics/aeroelasticity are highlighted so as to encourage future community-wide efforts.

The rest of the paper is organized as follows:

Flapping wing kinematics, governing equations, and scaling laws are presented in Section 2. Unsteady flight mechanisms associated with flapping wings and frequently encountered in the literature are described in Section 3. A literature survey focusing on flapping wing aerodynamics and aeroelasticity is presented in Sections 4 and 5 while emphasizing computational efforts of the authors to highlight selected flapping wing physics. Finally, concluding remarks and areas warranting further study are made in Section 6.