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Modeling and analysis of insect-like flexible wings at low Reynolds number

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A B S T R A C T

Much of the aerodynamic research conducted on insects to date has assumed that their wings are predominantly flat and rigid. In this paper, we investigate the effects of wing flexibility on the aerodynamic performance of a simple wing modeled after that of the Fruitfly, at the Reynolds number of 150. Analyses were first carried out to understand how distribution of stiffness property influences its deformation/deflection under simple static, inertial and inertial-cum-aerodynamic loadings. A class of leading-edge reinforced (LER) wings with stiffness that is sharply reduced towards the wing tip and trailing edge was found to exhibit deformations that resemble well those observed for insect wings in flight. The LER-type wings are shown to be aerodynamically superior to rigid wing and wings of uniform stiffness in terms of their improved cycle-mean lift-to-drag and lift-to-power ratios. The positive roles played by wing deformation in the aerodynamics and the beneficial energetics of elastic wing storage are discussed.

1. Introduction

Back in 1980s, Wootton (1981) was among the first to draw attention to the deformable quality of insect wings and its potential role in flight. He realized that there were strong correlations among wing morphology, kinematics and flight behavior. He explained how interaction between active torsion (muscle torque) and passive torsion (aerodynamic and inertial loads) determined the way the wing twists via the relative positions of the point of actuation, center of pressure and center of mass. Torsion often introduces camber which is found in many insects during the downstroke, potentially giving rise to enhanced lift.

In another comprehensive study, C. Ellington (1984) investigated the benefits of elastic energy storage to flying insects. He agreed with Weis-Fogh (1972) that, in terms of power requirement, insect flight is not possible without elastic power storage. He argued that almost all the inertial power developed during the acceleration phase of each stroke is absorbed, and released during the second half of the stroke. The result is that insects would expend very little net power to overcome inertia.

In the experimental camp, efforts had also been made to better understand and characterize the flexibility and deformability of insect wings. Ennos (1988) studied the role of torsion in insect wing designs and concluded that a corrugated structure with serial branching veins from the leading edge can set up appropriate camber automatically under

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aerodynamic and inertial loads to optimize the performance of the wing. His study assumed that the wing spars are rigid in bending, thus neglecting the effect of transverse deflection. Real insect wings, in contrast, exhibit varying degrees of bending especially towards the wing tip. Significantly, Combes and Daniel (2003) analyzed 16 insect species with differing wing shapes and structures and concluded that insect wings have anisotropic properties. Spanwise stiffness scales with the cube of wing span, while chordwise flexural stiffness only with the square of chord length. Thus the wings of the larger insects would tend to deflect more along the chord direction than they do along the span. Static load experiments also revealed that wing deflection is proportional to the exponential and second-degree variations of stiffness along the span and chord directions, respectively.

Computational studies that account for the deformation and deflection of insect-type wings under inertia and aerodynamic loads have only emerged in recent years. Yin and Luo (2010) studied the effects of inertia on the hovering performance of two-dimensional (2D) parameterized flexible flapping wing models. They found that low mass-ratio wings perform well at low frequency relative to the resonant frequency of the wing, whereas high mass-ratio wings perform well better at frequency close to the resonant frequency. They cited an optimal frequency ratio of 0.35. Dai et al. (2012) extended Yin and Luo (2010)'s study to three dimensions by carrying out a fluid–structure interaction study on flexible rectangular plates with rigid leading, but otherwise uniform properties, which deflected only along the chord. They obtained an optimal frequency ratio of about 0.3, close to Yin and Luo (2010)'s results. Also, higher mass-ratio wings tended to exhibit a range of flexibility with improved performance. In these studies, their wings displayed only negative camber, which is not characteristic of typical insect wings during flight. Observed wing deformation in nature is generally more complex with combined span and chord deflections. Nakata and Liu (2012) may be the first to apply a comprehensive 3D wing model to the study of hawkmoth wings. The hawkmoth wings are treated in terms of shell elements, with variations of stiffness and thickness over the surface to mimic the properties of the actual wings. Spanwise bending agreed quite well with the literature, whereas twisting and cambering were more moderate, with a maximum twist of 12° and a camber of 2%. In terms of aerodynamic performance, there was an approximate increase of 20% in vertical force and 13% in aerodynamic power. The increase in force production was explained by a prolonged attachment of the leading edge vortex. Overall, they concluded that there was an enhancement in going from rigid to flexible wings.

In other numerical studies, Shoele and Zhu (2013) examined the effects of vein strengthening on an idealized 2D wing model. Wing stiffness is governed by a number of reference points, which represents the effect of vein reinforcement. The superior performance of a leading-edge strengthened wing over the rigid wing and a uniformly flexible wing was illustrated in terms of lift production and lift-to-power ratio. They explained that although the uniformly flexible wing can generate large camber, it is the leading edge stiffness that plays a crucial role in stabilizing deformation and maintaining optimal pitch angle, which are beneficial to stable and efficient lift production. Zheng et al. (2013) also demonstrated improved efficiency brought about by prescribed deformation on butterfly wings in forward flight. In this case the varying twist and camber of Painted Lady butterfly (Vanessa cardui) wings were measured by high-speed photography, and replayed on a set of model wings and numerically solved by a Navier–Stokes solver. They reported an impressive improvement of at least 29% in lift and 46% in lift-to-power ratio. Genuine fluid–structure interaction is absent from this study.

It is amply clear from the above-mentioned studies that properly-configured flexible wings would be superior to their kinematically-equivalent rigid counterparts in terms of aerodynamic performance. Some studies, such as Ennos (1988) and Combes and Daniel (2003) had emphasized the structural aspects while others, such as Zheng et al. (2013) had considered only the aerodynamics of prescribed deformation. Dynamic fluid–structure interaction had also been investigated (Yin and Luo, 2010; Shoele and Zhu, 2013; Dai et al., 2012), though under fairly restrictive assumption of 2D flow or simplified deformation. Nakata and Liu (2012) carried out a comprehensive dynamic fluid–structural analysis for a hovering Hawkmoth; however their structural wing model exhibited relatively small twisting deformation compared to the actual wings. The typical insect wing is an approximately planar structure comprising a complex network of veins with connecting membrane-like material. The larger veins, the primary and secondary branching ones, confer stiffness and form to the wing. The venal formation (which can differ significantly among insect types) governs how a wing deflects and deforms in 3D under loading, both inertial and aerodynamic. The capture of these structural details in a model may be important for reproducing the correct dynamic response of an insect wing along its span and chord in flight. From a modeling perspective, two structural features of insect wings stand out from the research that has been done so far; namely decreasing spanwise stiffness towards the wing tip and decreasing chordwise bending stiffness towards the trailing edge. These should also be consistent with the maintenance of a relatively stiff leading edge for the wing, which is a prominent property of most insect wings.

The present paper is concerned with numerical modeling and aerodynamic performance of an insect wing modeled after that of the fruit fly (Drosophila melanogaster) in the order of Dipteran. The choice is motivated to a large extent by the structural simplicity of its wings, which contains a small number of load-bearing veins and limited secondary branching. The wing is modeled as a 3D deformable solid by a dynamic finite element model. The latter is implicitly coupled to a full Navier–Stokes solver. The model is able to accept sharp variations in material properties to distinguish regions of stiff veins from soft adjacent membrane for a more faithful mechanical representation of the wing. The performance of the wing vis-à-vis rigid wing and wings of uniform mechanical properties under conditions of static, inertial and combined inertial-aerodynamic loading is studied.