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Force production and asymmetric deformation of a flexible flapping wing in forward flight

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ABSTRACT

Insect wings usually are flexible and deform significantly under the combined inertial and aerodynamic load. To study the effect of wing flexibility on both lift and thrust production in forward flight, a two-dimensional numerical simulation is employed to compute the fluid–structure interaction of an elastic wing section translating in an inclined stroke plane while pitching around its leading ledge. The effects of the wing stiffness, mass ratio, stroke plane angle, and flight speed are considered. The results show that the passive pitching due to wing deformation can significantly increase thrust while either maintaining lift at the same level or increasing it simultaneously. Another important finding is that even though the wing structure and actuation kinematics are symmetric, chordwise deformation of the wing shows a larger magnitude during upstroke than during downstroke. The asymmetry is more pronounced when the wing has a low mass ratio so that the fluid-induced deformation is significant. Such an aerodynamic cause may serve as an additional mechanism for the asymmetric deformation pattern observed in real insects.

1. Introduction

The membranous wings of flying insects usually possess significant structural flexibility and deform considerably during flight (Combes and Daniel, 2003; Wootton, 1999). Such wing elasticity has recently become an important topic of research in the area of the flapping-wing aerodynamics. Observations of the kinematics of insect wings have shown that the deformation generally includes both chordwise and spanwise deflections (Ennos, 1988). In many studies, these two types of deformation have been decoupled in the structural representation of the wing so that the model complexity can be reduced and the aerodynamic effect of each type can be investigated separately.

Experiments on the wing flexibility have been carried out using heaving-only airfoils or membranous wings in rotational motion (Heathcote et al., 2004, 2008; Mazaheri and Ebrahimi, 2010), and they have demonstrated that both chordwise and spanwise deformations can have positive impact on the thrust performance of the wing. A recent experiment (Ramananarivo et al., 2011) using a mechanical wing self-propelled in air showed that the flapping frequency needs to be significantly lower than the natural frequency of the wing structure in order to achieve maximum thrust and power efficiency.

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On the computational side, several models of cruise flight have been developed to simulate the fluid–structure interaction between an elastic wing and its surrounding air. In Zhu (2007) and Michelin and Llewellyn Smith (2009), an oscillatory plate at low angles of attack was used to study thrust production of the wing. Inviscid flow was assumed in their models, and the unsteady wake was accounted for by introducing discrete vortices coming off the trailing edge. Zhang et al. (2010), Spagnolie et al. (2010), and Unger et al. (2012) performed two-dimensional (2D) simulations of the viscous incompressible flow to study the passive pitching of elastically mounted panels or deformable airfoils. Full three-dimensional (3D) studies were also carried out for flexible plunging airfoils to incorporate chordwise and spanwise deformations (e.g., Chimakurthi et al., 2009). In these models, the wing moves in the transverse direction with respect to the flow, and thrust production of the wing is the main focus of the study. In spite of specific wing models being adopted, all these studies have shown that processing some level of structural flexibility may significantly enhance thrust production.

For flapping wings, hovering motion is often used as the flight mode in a study of lift production. If the actuation kinematics of the wing remains the same, then hovering flight can be viewed as the limiting case of forward flight where the free stream velocity (or flight speed) is zero. Using a two-link model representing a chordwise section, Vanella et al. (2009) found that the flexibility can enhance the wing performance by increasing the lift-to-drag and lift-to-power ratios, and that the best performance is obtained when the flapping frequency is near one-third of the natural frequency of the wing structure. With a similar model, Eldredge et al. (2010) investigated the effect of wing flexibility in a range of hovering kinematic parameters. They found that a mildly flexible wing has robust and good performance for a wide range of phase differences between pitching and heaving. Using a dimensionless mass ratio to characterize the relative importance of the inertial force with respect to the aerodynamic force, Yin and Luo (2010) and Dai et al. (2012) performed respectively 2D and 3D simulations to study the performance of a hovering wing at different load combinations. They showed that the dynamic pitching of the wing chord depends largely on the mass ratio and when the aerodynamic torque is comparable to the inertial torque in twisting the wing, the lift efficiency can be further improved significantly.

Insects obviously need both lift and thrust during forward flight. The two force components can be simply achieved by adjusting the angle between the forward direction and the stroke plane, i.e., the plane spanned by wing strokes. However, the details of force production are more complicated than re-orientation of the force vector. The reason is that when the stroke plane angle is less than 90° and the free stream velocity is non-zero, the flow becomes asymmetric between upstroke and downstroke, which leads to the net lift and drag that cannot be calculated through trivial force re-orientation. This argument is illustrated in Fig. 1, where it can be immediately seen that even if the wing kinematics is symmetric in a rotated coordinate system, the resultant aerodynamic force during downstroke would be higher than that during upstroke due to the presence of the free stream.

A direct consequence of the flow asymmetry is that the wing deformation may differ between the two half-strokes if the aerodynamic torque around the torsional axis is large enough to twist the wing. In fact, insect wings typically exhibit significant asymmetric deformation patterns, with the magnitude during upstroke greater than during downstroke (Wootton, 1993). Such a feature is beneficial for the aerodynamics since it reduces the projected wing area and leads to less negative lift during upstroke. Previously, this asymmetry has been mainly attributed to the directional bending stiffness in the wing structure, e.g., one-way hinge (Wootton, 1981), or a pre-existing camber in the wing surface (Wootton, 1993). So far it is still not clear whether the aerodynamic force plays a significant role in this problem. As illustrated in Fig. 1, the aerodynamic force on the wing has a higher magnitude during downstroke. However, instantaneous deformation of the wing chord depends on a combination of the asynchronous aerodynamic and inertial forces, and its asymmetry is therefore not straightforward to predict.

In order to investigate the issues raised here, we propose to study the elastic wing section illustrated in Fig. 1 and consider the stroke plane angle and free stream velocity two variable parameters in addition to the material properties of the wing. While studying lift, thrust, power, and the effect of wing flexibility on these quantities, we will discuss the possible asymmetry in the wing deformation.

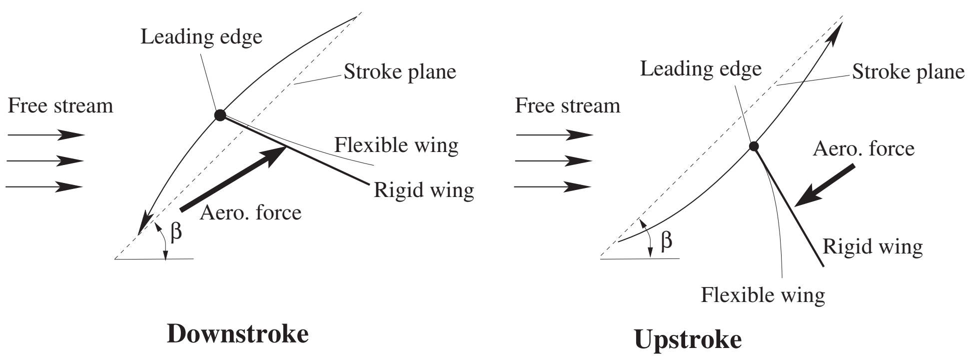

Fig. 1. A schematic illustration of the aerodynamic force on a wing chord in a free stream during downstroke and during upstroke, where β is the stroke plane angle.