Journal of Fluids and Structures 42 (2013) 130–151

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Wing performance and 3-D vortical structure formation in flapping flight

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A R T I C L E I N F O

Article history:
Received 28 November 2011
Accepted 7 April 2013
Available online 5 July 2013

Keywords:
Flapping wings
Insect flight
Vortices
Three-dimensional numerical simulations

A B S T R A C T

Numerical simulations of the three-dimensional flow around a modelled insect wing were performed to investigate the performance in flapping flight and to provide insight into the vortex dynamics and associated force generation. Different parameters relevant for three-dimensional flapping wing aerodynamics have been studied, notably the angle of attack in mid-stroke, the Rossby number, the Reynolds number and the stroke kinematic pattern. A parametric study has been made for these parameters, notably for the hovering flight regime. The leading-edge vortex is confirmed to be important for the gain in lift, it being larger and more stable at angles of attack larger than about 30°. At smaller angles of attack, the leading-edge vortex development is insufficient to increase the lift, instead the lift decreases. It is observed that the trend of the force development over the cycle and the effect of the angle of attack is similar for revolving and translating wings. However, a flapping wing motion with a revolving character has an important lift-enhancing effect, at a small penalty of drag. Although the variations in lift and drag with Reynolds number are found to be larger at lower Rossby numbers, the lift-enhancing effect of the revolving wing appears not strongly dependent on Reynolds number. Application of a 'trapezoidal angle of attack' pattern with increased angular rotation at stroke reversal showed a significant performance increase. It was further shown how the variation in lift and drag can be significantly influenced by introducing deviation in the stroke pattern. A comparison between the three-dimensional simulations and two-dimensional simulations (for forward flight conditions) displayed similar trends with respect to the influence of the angle of attack. However, the latter do not account for finite wing and tip vortex effects which were found to have an important impact on the LEV development.

1. Introduction

To understand the aerodynamic performance of flapping wings at low Reynolds numbers, relevant for insect flight, it is important to obtain insight into the vortex dynamics and its influence on force development. The most important feature in flapping wing aerodynamics has been established to be the generation of a stable leading-edge vortex (LEV) on top of the wing, which is responsible for the unexpectedly large force augmentation in hovering insect flight (Dickinson et al., 1999; Ellington et al., 1996; Lentink and Dickinson, 2009b; Maxworthy, 1979; Srygley and Thomas, 2002). In order to gain insight into the flow field induced by the flapping wings, several two-dimensional studies have been performed (Bos et al., 2008; Dickinson, 1994; Dickinson and Götz, 1993; Wang, 2005). It was shown that the leading-edge vortex generated by a

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http://dx.doi.org/10.1016/j.jfluidstructs.2013.04.002

two-dimensional moving foil is shed after several travelled chord lengths, whereas a three-dimensional LEV remains stably attached to a three-dimensional revolving (Usherwood and Ellington, 2002) or flapping (Birch et al., 2004; Dickinson et al., 1999; Lehmann, 2004) model wing, which rotates around its base. Those results indicate that three-dimensional flow effects are essential for the LEV stability. Suggestions have been forwarded as to the possible analogy between the LEV stability on flapping wings and the stable LEV generated by swept and delta wings (Ellington et al., 1996; Van Den Berg and Ellington, 1997). The spiral leading-edge vortex generated by a translating swept or delta wing is stabilised by the induced spanwise flow, which could suggest that a spanwise flow may play an important role concerning the LEV stability in insect flight as well (Ellington et al., 1996; Van Den Berg and Ellington, 1997). Lentink and Dickinson (2009b) discussed that the stability of the LEV growth specifically might be increased by the spanwise flow through the LEV core, driven by either the dynamic pressure gradient on the wing's surface, the centrifugal acceleration of the boundary layer or the induced velocity field of the spiral vortex lines (Ellington et al., 1996). Additionally, the LEV stability may be enhanced by a reduction of the effective angle of attack as a result of the tip vortex generation (Birch and Dickinson, 2001; Shyy et al., 2008). However, Birch and Dickinson (2001) found no significant effect of the spanwise flow on the LEV strength and stability, using plates at different spanwise locations to block the spanwise flow, but they did not completely explain the LEV stability in their experiments.

The objective of the present investigation is to study the vortex dynamics and the stability of the leading-edge vortex in particular, by means of accurate three-dimensional flow simulations around a flapping wing. In view of the discussion about LEV stabilisation due to wing revolving effects (Birch et al., 2004; Lentink and Dickinson, 2009a,b; Usherwood and Ellington, 2002), a three-dimensional model wing is used that performs a flapping motion around a rotation base of which the relative distance to the wing can be varied. In this way the influence of the revolving strength (expressed in terms of the Rossby number) as well as the effect of the tip vortices can be studied.

Following the experimental work of Lentink (2008) the Rossby and Reynolds numbers are systematically varied. In addition, recent two-dimensional simulations (Bos et al., 2008) suggested that the wing kinematics may also have a large influence on the flapping performance in three-dimensional hovering. Therefore, variations of the baseline harmonic wing motion kinematics are investigated, including the addition of a deviation and a modified 'trapezoidal' pattern for the angle of attack variation.

2. Material and methods

2.1. Modelling and parameter selection

Most flapping wing studies have conformed to the modelling and nomenclature convention as previously described by Sane and Dickinson (2002) and Dickson and Dickinson (2004), as applied for example in the experiments with the Robofly, a dynamically scaled robotic fruit fly wing, see Fig. 1.

In the current investigation a simplified model wing is used, which has an ellipsoidal planform with 10% thickness, since Lentink and Gerritsma (2003) showed that airfoil shape was of minor influence on the forces and the flow field. Also, Luo and Sun (2005) showed that the airfoil corrugation, such as present in dragonfly wings, for example, did not influence the force development significantly. The length scales of the corrugation are orders of magnitude smaller compared to the length scale of the separated flow region or the leading-edge vortex, such that significant effect of corrugation on the flow can be neglected.

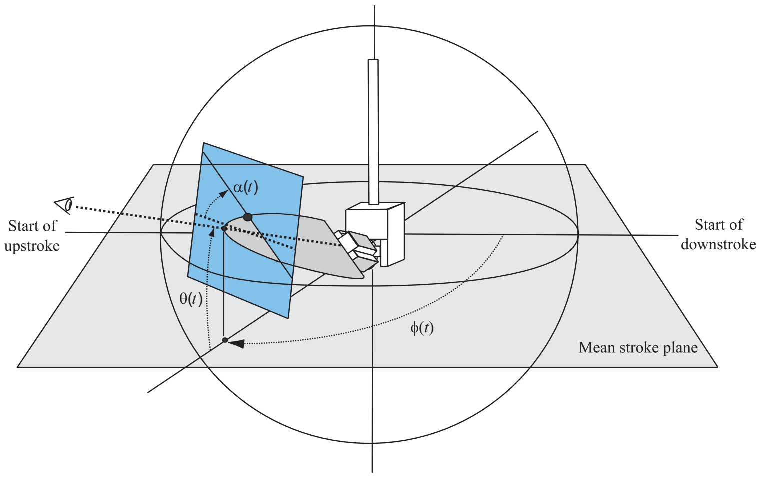

Fig. 1. Illustration of the main motion directions. $\phi(t)$ corresponds to the stroke variation, $\alpha(t)$ to the geometrical angle of attack and $\theta(t)$ to the deviation from the horizontal stroke plane. Source: Sane and Dickinson (2001).