International Journal of Heat and Fluid Flow 000 (2016) 1–12

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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

Three-dimensional instabilities in the wake of a flapping wing at low Reynolds number

M. Moriche*, O. Flores, M. García-Villalba

Bioing. e Ing. Aeroespacial, Universidad Carlos III de Madrid, Leganés, Spain

ARTICLE INFO

Article history:
Available online xxx

Keywords:
Direct numerical simulation
Flapping wing
Floquet stability analysis
Unsteady aerodynamics
Leading edge vortex
Trailing edge vortex

ABSTRACT

We present a stability analysis of a plunging and pitching wing of infinite aspect ratio at low Reynolds number. Four cases are considered by varying the mean pitch angle and the phase shift between pitching and plunging. Each case is studied by performing two dimensional DNS and Floquet stability analysis. The four cases considered display different wake structures resulting in different mean aerodynamic forces. Two cases produce thrust and lift, one case only thrust (with symmetric plunging and pitching) and the remaining case mainly lift (with the highest mean pitch angle). In addition, the latter case displays a period doubling phenomenon, and it is found to be linearly unstable for long wavelengths, with an instability mode that resembles that of mode A found in the wake of cylinders. Other cases, although being linearly stable, present a convective instability at smaller wavelengths. Finally, the unstable case has been studied with a fully 3D DNS to evaluate the effect of the three-dimensionality on the forces. The resulting flow structure is consistent with the linear stability analysis in the near wake. Further downstream non-linearities lead to a fully 3D wake. Despite this, the aerodynamic forces on the 3D wing are very similar to those obtained in the 2D simulation.

1. Introduction

In recent years the development of micro air vehicles (MAVs) has led to an increased interest in flapping wing aerodynamics at low Reynolds (*Re*) number (Shyy et al., 2013). The challenge is to develop MAVs which are able to mimic the maneuverability of insects and small birds (Ellington, 1999; Sun, 2014). In order to emulate their performance a prerequisite is to completely understand the unsteady aerodynamic and control mechanisms that they employ in their flight (Sane, 2003; Wang, 2005). This understanding is necessary to be able to predict the aerodynamic forces and moments as a function of the wing motions by means of simplified models (Ansari et al., 2006). There is a broad literature on the aerodynamics of flapping wings as recently reviewed by several authors (von Ellenrieder et al., 2008; Platzer et al., 2008; Rozhdestvensky and Ryzhov, 2003; Shyy et al., 2010; 2013).

Insects and birds flap their wings in a so-called stroke plane employing a combination of wing rotation with respect to the wing-body junction and wing pitching with respect to a spanwise axis. In addition, the stroke plane is not fixed and might be tilted by the animal when performing maneuvers (Ellington, 1984). This 3D motion is rather complex and many studies have employed various simplifications in order to clarify the main mechanisms at play. Assuming that the aspect ratio of the wing is large (in the limit of infinite aspect ratio, AR) and that the Reynolds number is low, it is possible to restrict the attention to 2D airfoil configurations. Then, the complex 3D motion of the wing is simplified in 2D to be the combination of a vertical oscillation of the airfoil, so called heaving or plunging, and a rotation of the airfoil with respect to a pivoting point, so called pitching. This still leaves us with a large number of parameters to specify: the Reynolds number of the flow, the airfoil geometry, the position of the pivoting point, the frequency of oscillation and the temporal laws of evolution of both plunging amplitude and pitching angle over a period of oscillation. Even when using sinusoidal laws for the plunging amplitude and pitching angle, the parametric space to be covered is huge. Thus, although the problem is considerably simpler in 2D, the task of generalizing the acquired knowledge is still intimidating.

The problem can be further simplified by considering only the plunging motion of the airfoil (Choi et al., 2015; Jones et al., 1998; Lewin and Haj-Hariri, 2003; Lua et al., 2007; Martín-Alcántara et al., 2015; Wang, 2000; Wei and Zheng, 2014; Young and Lai, 2004). This model has been often used to understand the flow mechanisms which are responsible for thrust generation. It has been observed that the vortical structures around the airfoil play

* Corresponding author. Tel.: +34916248220.
E-mail address: mmoriche@ing.uc3m.es (M. Moriche).

http://dx.doi.org/10.1016/j.ijheatfluidflow.2016.06.015
0142-727X/

a major role in the process of thrust generation (Anderson et al., 1998). Of these vortical structures formed during the oscillating cycle, the most important ones are the leading-edge vortex (LEV) and the trailing-edge vortex (TEV). In a comprehensive numerical study, Lewin and Haj-Hariri (2003) found that the wake patterns behind a plunging airfoil mainly depend on the fate of the LEV, and in particular, on its interaction with the TEV. They found that high propulsive efficiencies were obtained when TEV and LEV interacted constructively. Recently, Martín-Alcántara et al. (2015) were able to provide a quantitative description of some of these interactions using a vortex force decomposition. In some of the cases studied by Lewin and Haj-Hariri (2003), loss of periodicity was observed and also wake deflection even in a purely symmetrical airfoil motion. The wake deflection phenomenon has been recently studied experimentally (Godoy-Diana et al., 2008; Heathcote and Gursul, 2007; Lua et al., 2007), numerically (Wei and Zheng, 2014; Zheng and Wei, 2012) and combining both approaches (Jones et al., 1998; Yu et al., 2012).

The combination of plunging and pitching motion has been considered in many studies (Anderson et al., 1998; Ashraf et al., 2011; Baik et al., 2012; Fenercioglu and Cetiner, 2012; Kang et al., 2012; Liang et al., 2011; Moriche et al., 2015; Ramamurti and Sandberg, 2001; Read et al., 2003; Widmann and Tropea, 2015). Often the quest of these studies is to determine the optimum parameter range for a given application, either in terms of thrust or lift. For example, when the flapping device is intended for propulsion only, then the driving quantity is the thrust or the propulsive efficiency. In other cases, like for MAV flight, both thrust and lift need to be considered, and the parametric range of interest will be a different one. Nevertheless, as in the case of pure plunging motion, the relation between the vortical structures (and their interaction) and the resulting aerodynamic forces is of major interest. For lift production, the important role played by the LEV has long been recognized (Ellington et al., 1996). The need of a stable and persistent LEV in order to have a positive influence on the lift is the subject of current debate (Pitt Ford and Babinsky, 2013; Widmann and Tropea, 2015).

The assumption of two-dimensionality is invalid when the aspect ratio of the wing is small. Thus, there are many studies that investigate three-dimensional effects in the wake of low-aspect-ratio flapping wings (Dong et al., 2006; von Ellenrieder et al., 2003; Visbal et al., 2013). However, even in the limit of infinite AR, 3D instabilities might develop and lead to modifications of the flow around the airfoil, and consequently, to modifications of the aerodynamic forces. Visbal (2011) performed 3D large eddy simulations of a plunging wing of infinite AR in a broad range of Reynolds number ($10^3 \leq Re \leq 1.2 \cdot 10^5$). Three-dimensional effects were absent at $Re = 1000$, but clearly present at $Re = 5000$ and beyond (see his figure 22). Generally, it is therefore assumed that at low Re, (say $Re < 2000$), the flow is going to remain 2D. Note that in simpler flows the onset of three-dimensionality occurs at a lower Reynolds number. For example, for the flow over a fixed circular cylinder three-dimensional effects occur already in the range $Re \sim 200{-}300$ (Williamson, 1996). Hoarau et al. (2003) studied the incompressible flow over a fixed NACA0012 wing at a relatively large angle of attack of 20° and observed three dimensional effects at $Re = 800$. Considering that in plunging and pitching airfoils the parametric space is very large, it is unclear in which parameter regime the flow actually remains two-dimensional.

A suitable tool to predict the onset of 3D instabilities in time-periodic flows is Floquet stability analysis. This method has been used to predict the onset of 3D effects in the flow over a fixed circular cylinder by Barkley and Henderson (1996) and in the flow over a fixed square cylinder by Robichaux et al. (1999). It has also been employed for the case of flow over oscillating cylinders by Leontini et al. (2007). Recently, Deng and Caulfield (2015) and Deng et al. (2015) used Floquet stability analysis to study the three-dimensional transition in the wake of a pitching airfoil. In the present study, this method is employed for the case of plunging and pitching airfoils. We do not intend to be comprehensive here, since the parametric space is very large. Instead, we have selected a few cases from a larger database (Moriche et al., 2015) with different wake structures and resulting aerodynamic forces with the intention of determining if 3D effects might occur for those cases. More systematic studies in order to determine the parametric range for the onset of 3D effects are left for future studies. The present study also includes a 3D DNS in order to evaluate the effect of the three-dimensionality of the flow on the aerodynamic forces on the wing.

The paper is organized as follows. In Section 2 the details of the numerical method and computational setup are presented. In Section 3 the results are presented. First, 2D computations are analyzed in terms of wake structure and aerodynamic forces. This is followed by a Floquet stability analysis to determine whether three-dimensional instabilities might develop in some of the cases. Then, a full 3D calculation is presented for the unstable case. The results of the 3D calculations are compared to the corresponding results of the 2D calculations. Finally, some conclusions are provided in Section 4.

2. Numerical method

The configuration under study is a plunging and pitching wing of infinite aspect ratio, made of NACA0012 airfoils. The Reynolds number of the flow is $Re = U_\infty c/\nu = 1000$, where U_∞ is the free stream velocity, c is the chord of the wing and ν is the kinematic viscosity. The kinematics of the wing is sketched in Fig. 1, where x and z are the streamwise and vertical coordinates, respectively. The prescribed plunging and pitching motion is given by

$$h(t) = h_0 \cos(2\pi f t), \qquad \theta(t) = \theta_m + \theta_0 \cos(2\pi f t + \phi), \qquad (1)$$

where $h(t)$ is the vertical displacement of the pivoting point of the wing and $\theta(t)$ is the angle formed between the chord of the wing and the free stream. Most parameters in Eq. (1) are kept fixed in the simulations developed for this work. In particular, the plunging amplitude is $h_0/c = 1$, the pitching amplitude is $\theta_0 = 30^\circ$, the distance from the leading edge to the pivoting point is $x_p/c = 0.25$ and the reduced frequency is $k = 2\pi f c/U_\infty = 1.41$. This results in a period of oscillation $T = 4.44c/U_\infty$. The other parameters, namely the mean pitch angle θ_m and the phase shift between pitching and plunging ϕ, have been varied to configure the four cases described in Section 3.

2.1. Direct numerical simulations

Two- and three-dimensional Direct Numerical Simulations (DNS) are carried out with TUCAN, an in-house code that solves the Navier Stokes equations for an incompressible flow

$$\frac{\partial u_i}{\partial x_i} = 0, \qquad (2a)$$

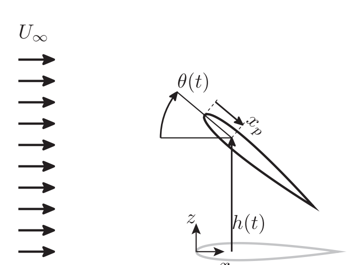

Fig. 1. Sketch of the plunging and pitching motion of the wing.