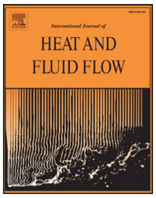
International Journal of Heat and Fluid Flow 000 (2017) 1–14

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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



Computational study of a pitching bio-inspired corrugated airfoil

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ARTICLE INFO

Article history:
Received 21 February 2016
Revised 22 November 2016
Accepted 28 December 2016
Available online xxx

Keywords:
CFD
PIV
Oscillating airfoil
Pitching airfoil
Bio-inspired airfoil
Biomimicry

ABSTRACT

The phenomenon of insect flight has been of scientific interest for many years and is more recently inspiring modern engineering devices such as Micro Aerial Vehicles (MAVs). Insect flight is characterized by unsteady fluid dynamics at low Reynolds numbers. The importance of viscous effects to the successful flapping flight of insects has been identified and with the current state of computing and Computational Fluid Dynamics (CFD) these effects can now be studied in detail. The present work attempts to simplify this complex phenomenon by considering symmetric oscillating rotational motion of a wing (pitching). What is of interest in this study is how the shape of a corrugated idealized insect wing affects the performance and flow characteristics around the pitching wing. Two dimensional CFD on an oscillating wing has been performed and reported. Measurements were taken to ensure the accuracy of the computational solution and the results validated against experimental PIV results. A range of frequencies and rotational amplitudes have been investigated. Lift and drag coefficients have been analyzed for all cases to quantify the effects of unsteady flow features on the performance of the oscillating wing. It was found that the wing shape used in this study resulted in the viscous features formed on the top of the wing exhibiting high sensitivity to the oscillating conditions and these influenced the performance of the wing. The flow features formed on the bottom of the wing remained similar throughout the cases tested. In the pitching regime this wing profile did not perform as well as published results for smooth airfoils in terms of thrust and propulsion efficiency. However this may be due to reduced frequency effects becoming important at our high pitching amplitude which need to be investigated further. There may be other oscillatory regimes that more accurately represent flapping flight in which the corrugated foil outperforms a smooth counterpart but these are yet to be investigated. Further research in this area may help answer the question as to how evolutionarily significant other benefits of a corrugated wing, such as being light and strong, are compared to its aerodynamic properties, the present results seem to favor the former.

1. Introduction

Adapting solutions engineered by nature to improve technologically advanced products is a familiar and increasingly popular practice by engineers and researchers to come up with implementations that are simple and robust (Nawroth et al., 2012). Dragonflies are incredibly agile fliers, able to dip and dart in all directions. It was shown that the lift coefficients required for the flapping flight of dragonflies far exceeded the steady state values measured from non-flapping dragonfly wings (Norberg 1975; Wakeling and Ellington 1997a,c). This suggested that unsteady aerodynamic effects, among others, were significant to the generation of lift. Dragonfly wings operate at Reynolds numbers ranging from about 10^2 to 10^4 (Kesel, 2000; Rüppell, 1989) meaning that viscous effects such as the formation and subsequent shedding of vortices become important to the flow structures and forces acting on the wings. Low Reynolds number flows are often complicated since separation, transition and subsequent reattachment occur within a short distance and are dominated by large scale vortex motions (Lin and Pauley, 1996).

Unlike smooth airfoils seen on aeroplanes and birds, dragonflies (and most flying insects) have corrugated wings (Kesel, 2000; Newman, et al., 1977; Rees, 1975). The corrugations of the wings provide strength benefits with minimal weight penalties (Rees, 1975; Lian et al., 2014). Aerodynamic and biological studies have demonstrated that such superior flight may be due not only to the flapping motion but the cross-sectional profiles of the wings also. The latter being supported by recent experimental and numerical studies of corrugated bio-inspired wing sections in steady flow

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http://dx.doi.org/10.1016/j.ijheatfluidflow.2016.12.009
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Please cite this article as: T.J. Flint et al., Computational study of a pitching bio-inspired corrugated airfoil, International Journal of Heat and Fluid Flow (2017), http://dx.doi.org/10.1016/j.ijheatfluidflow.2016.12.009

Notation

A	amplitude of oscillation [°]
C	courant number [dimensionless] (defined in Eq. (3))
C_d	sectional drag coefficient [dimensionless] (defined in Eq. (7))
C_{ip}	power coefficient [dimensionless] (defined in Eq. (9))
C_l	sectional lift coefficient [dimensionless] (defined in Eq. (4))
C_p	pressure coefficient [dimensionless] (defined in Eq. (6))
C_T	thrust coefficient [dimensionless] (-1^*C_d)
c	airfoil chord length [m]
ϵ_l	relative difference in lift coefficient [%] (defined in Eq. (5))
$\overline{\epsilon_l}$	mean relative difference in lift coefficient [%]
F_d	drag force per meter span [N/m]
F_l	lift force per meter span [N/m]
f	frequency of oscillation [Hz]
h	wake width [m]
k	reduced frequency [dimensionless] (defined in Eq. (2))
M	pitching moment per unit span [N]
η	propulsion efficiency [dimensionless] (defined in Eq. (10))
P	pressure [Pa]
P_∞	far-field pressure [Pa]
ρ	fluid density [kg/m^3]
Re	Reynolds number [dimensionless] (defined in Eq. (1))
St	Strouhal number [dimensionless] (defined in Eq. (8))
T	period [s]
t	time [s]
Δt	simulation time-step [s]
$\dot{\theta}$	wing rotation rate [rad/s]
U	free stream velocity [m/s]
ν	kinematic viscosity [m^2/s]
x	distance along the chord from the leading edge of the airfoil [m]
Δx_i	height of the first inflation layer on airfoil surface [m]
y^+	distance from the wall normalised by the viscous length scale [dimensionless]

(Hu and Tamai, 2008; Murphy and Hu, 2010; Levy and Seifert, 2009; New et al., 2014). The evidence shows that the corrugated wing sections delay stall and results in smaller separation regions at high angle of attack compared to smooth counterparts resulting in superior lift to drag characteristics in some regimes. It has been suggested that the corrugations provoke an early transition to turbulent flow resulting in the reattachment of flow and thus reduced separation (Newman et al., 1977). Murphy and Hu (2010) conducted PIV experiments and concluded that the corrugations help to overcome adverse pressure gradient and discourage large-scale separation and airfoil stall by first tripping the boundary layer to promote transition from laminar to turbulent and then “trapping” the unsteady vortex structures by pulling high-speed flow into the near wall region. Levy and Seifert (2009) also reached similar conclusions when studying a different profiled corrugated airfoil.

Flapping wing research has focused on furthering understanding of the unsteady aerodynamic mechanisms that result from wing movements (Viieru et al., 2006). In the same paper, the authors list a number of theories that suggest the source of lift generation including the effects of leading-edge vortices (LEV), capturing of wake and pitching-up rotation. Dickson and Gotz (1993) first showed that lift was enhanced by the presence of LEVs. Further studies by Liu and Kawaguchi (1998) and van den Berg and Ellington (1997) confirmed the status of the leading-edge vortex.

Although there has been much previous work detailing the flow field near to oscillating airfoils (Lu et al., 2013; Zhou et al., 2013; Panda and Zaman, 1992; Lee, 2011), these have been confined to smooth conventional NACA type airfoils or flat plates. There are few studies of flow characteristics about oscillating corrugated bio-inspired airfoils (Saharon and Luttges, 1987; Okamoto and Azuma, 2005) and to date the authors are unaware of any other work that makes use of PIV or computational methods (CFD) to visualise the flow. While work has been performed for curved deforming wings (Molki and Sattari, 2013) reviews of Micro Aerial Vehicle (MAV) development have neglected to consider the effect that corrugations have on the flow field (Pines and Bohorquez, 2006). There has been a significant research effort to understand the unsteady effect around moving wings for MAV applications but none including corrugations or bio-inspired cross-sections (Shyy et al., 2008). The present study intends to expand the scope of knowledge in this field by studying the aerodynamics of a pitching corrugated airfoil which is an idealised geometry inspired by dragonfly wings. The prevalence of corrugated wings on dragonflies and other insects indicates some form of evolutionary advantage, it is not certain whether this is solely structural or if unsteady aerodynamics are improved also. Either way, such a wing is well suited for technology such as MAVs (Pines and Bohorquez, 2006) as proven by nature’s own MAVs, insects. Our aim is to provide insight into the characteristics of viscous flows forming around oscillating airfoil and how corrugations similar to those seen on dragonfly wings affect their unsteady aerodynamic properties. The geometry is similar to the one used in previous, steady, investigations (Levy and Seifert, 2009; New et al., 2014).

2. Methodology

2.1. CFD methodology

A rigid two-dimensional airfoil was modeled using ANSYS Fluent version 14.5 to simulate the flow-field and calculate the lift and drag on a bio-inspired corrugated airfoil undergoing two dimensional oscillations subject to a constant horizontal flow at a chord Reynolds number (Re) of 14,000 as defined by:

$$Re = \frac{Uc}{\nu} \tag{1}$$

where U, c, and ν are the free stream velocity, airfoil chord length, and the fluid kinematic viscosity respectively. The range of oscillations used in the calculations had reduced frequencies, k (Eq. (2)), between 1.24 – 4.96 and angular amplitude between 5° - 20°

$$k = \frac{\pi f c}{U} \tag{2}$$

where f is the frequency of oscillation. The center of rotation of the airfoil was located at quarter-chord position in the middle of the plate thickness. The geometry used is shown in Fig. 1(a) and corresponds to the “Corrugated B” section used in the experiments of New et al. (2014). Locations A-F are also defined here to aid discussion of the results. This particular wing geometry is described in detail by Levy and Seifert (2009), where full details of the geometry can be found there. The only modifications made to the geometry is an increased thickness which was a requirement for the experimental portion of the study. This general idealised shape was first used by Newman et al. (1977) for the wings of model gliders that were flown to assess the performance of such a wing.

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