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Unsteady high-lift mechanisms from heaving flat plate simulations

Jennifer A. Franck*, Kenneth S. Breuer

School of Engineering, Brown University, Providence, RI, USA

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ABSTRACT

Flapping animal flight is often modeled as a combined pitching and heaving motion in order to investigate the unsteady flow structures and resulting forces that could augment the animal's lift and propulsive capabilities. This work isolates the heaving motion of flapping flight in order to numerically investigate the flow physics at a Reynolds number of 40,000, a regime typical for large birds and bats and challenging to simulate due to the added complexity of laminar to turbulent transition in which boundary layer separation and reattachment are traditionally more difficult to predict. Periodic heaving of a thin flat plate at fixed angles of attacks of 1°, 5°, 9°, 13°, and 18° are simulated using a large-eddy simulation (LES). The heaving motion significantly increases the average lift compared with the steady flow, and also surpasses the quasi-steady predictions due to the formation of a leading edge vortex (LEV) that persists well into the static stall region. The progression of the high-lift mechanisms throughout the heaving cycle is presented over the range of angles of attack. Lift enhancement compared with the equivalent steady state flow was found to be up to 17% greater, and up to 24% greater than that predicted by a quasi-steady analysis. For the range of kinematics explored it is found that maximum lift enhancement occurs at an angle of attack of 13°, with a maximum lift coefficient of 2.1, a mean lift coefficient of 1.04.

1. Introduction

There has been much interest in the aerodynamics community surrounding the flapping flight of insects, birds, and bats, due to the high-lift mechanisms they exploit during a typical wing-beat such as delayed stall, vortex/wake recapture, or clap and fling. Naturally, the question arises if these same mechanisms can be duplicated in man-made aircraft such as micro-air vehicles (MAV), which requires detailed investigations of the kinematics, mechanics, and control surrounding a flapping wing. The engineering community has traditionally been interested in the rigid motion of airfoils and the unsteady effects of dynamic stall for rotary-wing aircraft (McCroskey, 1982) applications, and more recently, wind turbines (Leishman, 2002), both of which are within a Reynolds number regime of 10^6. However, much of the recent computational and experimental work has been focused on the unsteady flapping motion of insect flight, who typically fly at Reynolds numbers of $O(10^2 - 10^3)$. This work is focused in the intermediate Reynolds number regime of $O(10^3 - 10^5)$, of which there have been fewer publications on flapping flight and the aerodynamics of larger vertebrates, including bats and birds. Using a flat plate computational model, and a time-resolved large-eddy simulation (LES), this work provides insight into the unsteady high-lift mechanisms of flapping flight at an intermediate Reynolds number of 50,000.

The kinematics and mechanics of flapping flight for insects such as clap and fling, wake capture, and delayed stall have been thoroughly investigated and reported, as summarized by Shyy et al. (2010) and more recently by Chin and Lentink (2016). Of particular interest is the delayed stall phenomena, in which a leading edge vortex (LEV) on the upper edge of the wing enhances lift throughout the downstroke, which has been shown experimentally (Ellington et al., 1996; Birch et al., 2004) and computationally (Liu et al., 1998; Wang, 2000). The presence of LEVs and other large flow structures indicates that traditional quasi-steady flow analysis that relies on inviscid flow theory is not capturing the correct physics. One such inviscid model is that of Theodorsen (1934), who developed a unsteady lift prediction in 1935 composed of quasi-steady, added mass, and circulatory parts. However despite is wide use, the Theodorsen model neglects any type of boundary layer separation such as the formation of LEVs or other large-scale structures.

Evidence of unsteady vortex structures at intermediate Reynolds numbers has also been shown in animal flight, such as the wind tunnel testing of bats (Muijres et al., 2008). A common experimental and computational model of flapping flight is the sinusoidal pitching and/or heaving motion of an airfoil geometry in which an LEV is generated, and the effects of lift and drag can be carefully documented. Many experiments have

* Corresponding author.
E-mail address: jennifer_franck@brown.edu (J.A. Franck).

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looked at symmetric airfoils in sinusoidal heaving motion (Lee and Gerontakos, 2004; Young and Lai, 2004), or pitching motion (Rival et al., 2008), finding the boundary layer separation and formation of a LEV can greatly impact the lift generation. Experiments by Cleaver et al. (2011) have looked at small amplitude heaving of a NACA0012 airfoil at post-stall angles of attack at $Re = 10,000$ and also found an enhancement in lift due to the formation and convection of LEVs. They further deduced that lift increased with increasing heaving frequency and plunge velocity. Direct numerical simulations (DNS) were performed to capture the transitional nature of the flow at this Reynolds number, and provide detailed dynamics of the LEV. For a controlled growth of a LEV, Ford and Babinsky (2013) investigated the unsteady vortex formation on an accelerating flat plate, finding that most of the bound circulation remained in the LEV. Also interested in vorticity transport, Eslam Panah et al. (2015) calculated the circulation during the LEV development on a plunging foil at a modest Reyolds number of 10,000.

Water tunnel experiments by Ol et al. (2009) performed two plunging configurations of an SD7003 airfoil in freestream conditions at $Re = 10,000 - 60,000$. Although unsteady vortices were clearly present, the attached-flow theory still managed to predict proper trends in lift force. Simulations were preformed with a 2D RANS model, and captured the formation of the LEV, but could not accurately capture the reattachment, which has been previously documented in RANS computations of unsteady flows (Rumsey et al., 2006). In a followup paper, a thin flat plate is compared to the SD7003 airfoil, and it is found the geometry can influence the LEV formation and lift forces by promoting earlier separation (Kang et al., 2013), and experimental studies have by Rival et al. (2014) have shown a similar trend in a plunging plate of various leading edge geometries. Visbal performed large-eddy simulations at $Re = 60,000$ of a plunging SD7003 airfoil at an angle of attack of 8°, providing a detailed analysis of the LEV flow structure and 3D effects (Visbal, 2011).

This study was motivated by recent wind tunnel experiments have been performed by Curet et al. on a self-excited flapper in a uniform flow (Curet and Breuer, 2011; Curet et al., 2013) that demonstrate an increase in lift after transitioning from a stationary to flapping mode. The flapper model is composed of two rigid plates, a main body connected to a trailing-edge flap with a sailcloth, and is mounted at a positive angle of attack. The trailing edge flap is free to pitch with respect to the main body, and the main body is mounted on a cantilever beam and free to heave. The experiments show that at low velocities the flapper remains a motionless single flat plate at a fixed angle of attack. However above a critical freestream velocity U^* an instability develops and the flapper begins to passively heave in a sinusoidal heaving motion, driven by the trailing flap motion. Upon its transition to the heaving mode, the flapper displays a large increase in average lift, which is dependent on the angle of attack as well as the ratio of U_∞/U^*.

This research is a followup investigation that provides a more detailed explanation of the lift enhancement documented in the experiments by Curet et al. using a computational model of the flapper. The computations simulate the flow over the main body (flat plate) of the flapper in its stationary position and in its heaving position, and computing the lift and vortex dynamics and comparing it with quasi-steady predictions. Although only the main body of the flapper is modeled in the computations, it is hypothesized that the increase in lift experienced by the flapper is its heaving mode is primarily due to the LEV formation on the main body, and that the trailing flap provides the instability that drives the sinusoidal heaving motion but does not contribute significantly to the lift enhancement.

The Reynolds number matches the experiments at 40,000, and the fixed angle of attack in the computations is varied from 1° to 18°. A large-eddy simulation (LES) in utilized for the computations due to its ability to resolve the time-dependent kinematics and dynamics of unsteady flow structures, such as the LEV, that develops during the heaving motion. Unlike the blunt leading edge airfoil geometries previously computed (Visbal, 2011; Cleaver et al., 2011; Ol et al., 2009), the boundary layer on the thin flat plate model separates at the sharp leading-edge, producing a LEV even at small angles of attack. Using a well-resolved boundary layer, the LES solver is expected to predict both separation and any subsequent reattachment of the separated shear layer, which is usually under predicted or not captured at all with RANS models. With this heaving flat-plate model, we focus our attention on the two-dimensional effects of the flapping motion as opposed to any three-dimensional tip effects that may be present in the experiment. In particular we are interested in the leading edge separation and subsequent formation and convection of a dynamic stall vortex, and the effects on lift force for various plunging configurations.

2. Simulation details

2.1. Governing equations and computational methods

An incompressible LES is used to perform the simulations. The governing equations are the filtered Navier–Stokes equations,

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_j} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} + f_{b_i} - \frac{\partial \tau_{ij}}{\partial x_j} \quad (1)$$

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0, \quad (2)$$

where overbar represents a low-pass spatially filtered quantity, u_i are the three components of velocity, p is pressure, ν is kinematic viscosity, and ρ is density. The sub-grid scale stresses are calculated with a constant Smagorinsky model, where

$$\frac{\partial \tau_{ij}}{\partial x_j} = -2C_s^2 \Delta^2 |\bar{S}| \bar{S}_{ij} \quad (3)$$

and the filtered rate of strain is

$$\bar{S}_{ij} = \frac{1}{2}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right). \quad (4)$$

For all simulations the Smagorinsky constant is $C_s = 0.1$, chosen to be on the lower end of the acceptable range to minimize superfluous dissipation. The effect of changing the Smagorinsky constant is briefly discussed in the context of the mesh resolution in the following section. Rigid body motion is added by prescribing the appropriate body forces, $\mathbf{f_b}$, to the momentum equations creating a non-inertial frame of reference. The governing equations are solved using OpenFOAM libraries (Weller et al., 1998), with a custom-built LES sub-grid scale model and additional of the non-intertial terms for the rigid body motion. The LES solver utilizes a second-order accurate finite-volume scheme using Gaussian integration and linear interpolation from cell centers to cell faces, which is standard in OpenFOAM solvers. A pressure-implicit split-operator method is used to solve for the pressure, a second order backwards time-stepping routine is implemented, and a preconditioned conjugate gradient method solves the matrix equations.

2.2. Flow configuration of heaving plate simulations

The static and heaving flow over a flat plate is modeled by a thin ellipse of aspect ratio 50. For the heaving flat plate model, the