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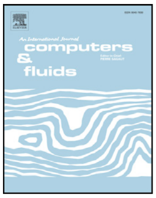

Large eddy simulations of unsteady flows over a stationary airfoil

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ABSTRACT

Two groups of unsteady flows over a stationary SD7003 airfoil are studied with the large eddy simulation method. In the first group, the angle of attack (AoA) is fixed, while the freestream velocity magnitude varies harmonically with various frequencies and amplitudes. In the second group, the freestream velocity magnitude is fixed but its direction, therefore the AoA varies harmonically. Over the range of parameters considered in this study the mean lift and drag coefficients of the unsteady flows with oscillating freestream velocity magnitude are found to be nearly the same as those calculated for steady flows. However, there are significant phase shifts between the aerodynamic forces and the unsteady freestream velocity. The phase shift for drag force is larger than that for lift force, even though both increase as the frequency of freestream velocity oscillations increases. Furthermore, the computed lift amplitudes are found to be noticeably higher than those predicted by Greenberg's inviscid theory, while the lift phase shifts are in better agreement with the theory. For flows with oscillating freestream AoA, there is little change in the mean lift, while the mean drag is reduced by oscillations in AoA due to Katzmayr effect. As the frequency of oscillations in AoA increases, the phase shift for lift increases while that for drag decreases. Our results also indicate that the mean separation point moves downstream and the mean reattachment point moves upstream when the freestream velocity magnitude or the freestream flow direction oscillates with respect to the airfoil.

1. Introduction

There has been a growing interest in Micro Air Vehicles (MAVs) in recent years [1]. These vehicles typically operate at low to moderate Reynolds numbers in the order of 10^4 to 10^5 due to low speed and small size. At this range of Reynolds numbers and modest angle of attack (AoA), the laminar flow at upper surface of the vehicle wing normally separates due to substantial adverse pressure gradient. At moderate Reynolds number and AoA, the flow can reattach to the airfoil and form a laminar separation bubble (LSB) [2–4] between the separation and reattachment points. A large separation bubble decreases the lift and increases the drag, and consequently reduces the efficiency of the airfoil.

Many studies have been conducted on the characterization and control of flow and LSB over various airfoils. A commonly studied asymmetric airfoil for low-moderate Reynolds number flows is the SD7003 airfoil. Experimental studies of flows around the SD7003 airfoil have been reported by a number of researchers using different facilities and methods. Radespiel et al [5] conducted experiments in a water channel and a low-noise wind tunnel at Technical University of Braunschweig (TU-BS) and obtained high resolution velocity and Reynolds stress data. Particle Image Velocimetry (PIV) measurements were conducted by Ol et al. [6]at the Air Force Research Laboratory (AFRL) water channel. Measurements in a water channel using Molecular Tagging Velocimetry (MTV) were conducted by Olson et al. [7–10] at Turbulent Mixing and Unsteady Aerodynamics Laboratory (TMUAL) at Michigan State University. RANS [11–14] and LES [15–19] models were also employed for studying the flow dynamics over SD7003 airfoil.

Generally, two different types of unsteady flows around airfoils are studied: (i) unsteady flows generated by accelerating/maneuvering airfoils in a steady freestream, and (ii) unsteady flows due to unsteadiness in freestream. These are fundamentally different flows but they do have some similarities. Unsteady aerodynamics of maneuvering airfoils has been studied by analytical, experimental and numerical methods [20–24]. The airfoil motions studied include pitching, plunging, and a combination of the two. Classical inviscid models such as that developed by Theodorsen [25] have been used for computing the lift and pitching moments of a two-dimensional, flat-plate airfoil under harmonic pitching and plunging motions. Experimental study performed by Bohl and Koochesfahani [20] provides more detailed information on the fluid velocity in the wake of a pitching airfoil. LES study of flows past a plunging airfoil, reported by Visbal [21], also provides more detailed data on the velocity and pressure distribution around

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Nomenclature

C	Chord length
C_D	Drag coefficient
C_F	Skin friction coefficient
C_L	Lift coefficient
C_P	pressure coefficient
C_w	WALE model constant
D	Drag force per unit span of the airfoil
L	Lift force per unit span of the airfoil
R_e	Reynolds number
$\bar{S}_{ij}$	Filtered rate-of-strain tensor
S_{ij}^{d}	Tensor in WALE LES model
T	Period
U	Freestream velocity in x direction
V	Freestream velocity in y direction
W	Freestream velocity in z direction
X_s	Flow separation point
X_r	Flow reattachment point
X_t	Flow transition point
$\bar{g}_{ij}$	Filtered velocity gradient
i	Imaginary unit
k	Reduced frequency
$\mathbf{n}$	Surface normal
p	Static pressure
$\mathbf{s}$	Surface tangent
t	Time
u,v,w	Velocity components in x, y, and z directions
x,y,z	Cartesian coordinates
Δ	Filter width
∞	Infinity

Greek symbols

α	Angle of attack
δ_{ij}	Kronecker symbol
μ	Dynamic viscosity
γ_t	Turbulent viscosity
ρ	Density
ω	Angular frequency
ω_x, w_y, w_z	Streamwise and spanwise vorticity components
$\lvert\Omega\rvert$	Vorticity Magnitude
σ	Normalized amplitude of oscillations

Subscripts

f	Fluctuation quantities
i, j, k	Coordinate index
m	Mean quantities

Superscripts

$-$	Filtered quantities
$'$	Disturbance quantities

maneuvering airfoils. A comparison between experimental and computational results for an airfoil in pitching and plunging motions was given by McGowan et al. [22]. An overview of a broad range of studies on maneuvering airfoils is given in reference [26].

The second type of unsteady aerodynamics involves those created by some form of unsteady freestream flow over non-accelerating airfoils [27]. For low speed and small size MAVs, the unsteadiness in freestream flow may cause significant changes in aerodynamic forces and thus possible flight instability. The inviscid theory of Von Kármán and Sears [28] provides valuable insight on unsteady aerodynamics of non-uniform flows over two-dimensional (2D) airfoils. Other analytical methods based on inviscid theory, developed by Isaacs [29] and Greenberg [30] for example, have also been used for analyzing unsteady freestream flows over different types of airfoils. However, there are only a few experimental and studies on fixed airfoils operating in an unsteady freestream [e.g. [31]]. This is partly due to difficulty in changing and controlling the freestream flow unsteadiness in experiments. For example, the frequency of freestream flow oscillations is often limited by the test section geometry [32]. To verify the Katzmayr effect [33], Toussaint et al. [34] used an array of pitching blades in front of an airfoil to create a freestream flow with oscillating flow direction. In this experiment, the maximum reduced frequency was less than 0.5, and freestream flow properties (e.g. turbulence level) behind the oscillating blades were not given. Williams et al. [35] measured flows over a semi-circular wing in a wind tunnel that generates sinusoidal oscillations in the freestream velocity magnitude with reduced frequencies less than 0.7. They found that the measured lift force noticeably lags the freestream velocity even at low reduced frequencies, and the phase shift does not show a strong dependence on the mean AoA. The amplitude of oscillations in the lift coefficient was shown to be affected by the amplitude and frequency of oscillations in the freestream flow direction with respect to airfoil. However, the measured amplitude and phase shift in the lift coefficient differed significantly from the predictions of Greenberg's model. Using k-ω turbulence model and a 2D mesh, Gharali and Johnson [36] conducted unsteady RANS simulations of flows over a fixed airfoil with oscillating freestream velocity direction. In these simulations, the reduced frequency ranged from 0.026 to 18. The results for very low reduced frequency of 0.026 were shown to be in general agreement with the experimental results of a pitching airfoil.

To understand and to characterize the effects of freestream flow unsteadiness on aerodynamic surfaces, this paper considers the numerical study of harmonically oscillatory flow over a fixed SD7003 airfoil with the LES method. The effects of freestream turbulence on SD7003 airfoil flow separation and reattachment was extensively investigated in previous experimental studies [5–10]. This paper looks into how the airfoil aerodynamics is affected by a better characterized, large-scale freestream flow unsteadiness for conditions (e.g. frequencies) not easily achievable in experiments. The main objective is to systematically study the effects of well-characterized harmonic oscillations in the freestream flow on the global aerodynamic forces and detailed distribution of velocity, vorticity as well as flow separation and reattachment for a well-studied stationary airfoil. Two types of unsteady freestream conditions are considered. In the first type, the freestream velocity direction is fixed, but the freestream velocity magnitude is forced to oscillate harmonically with different reduced frequencies, ranging between $\pi/8$ and 2π,and normalized amplitudes of 0.183 and 0.366. In the second type of unsteady flow, the freestream velocity magnitude is fixed but the freestream velocity direction or AoA is changed harmonically in time, over a range of ($\pi/8$–2π)reduced frequencies and amplitudes of 4° and 8°. The oscillation frequencies in the freestream flow extend from a relatively low value ($\pi/8$) to a high value (2π), well beyond the highest found in experiments conducted with freestream flow oscillations. The amplitude of oscillations is also very significant. However, to the make sure that the numerical results remain accurate, "extreme" freestream oscillations with very low or very high frequencies and very large amplitudes beyond those listed above were not considered. Effects of these two types of freestream flow oscillations on the lift and drag forces, vorticity, root mean square (RMS) of velocity fluctuations, flow separation and reattachment are discussed below.

2. Computational method

Steady and unsteady flows over SD7003 airfoil (Fig. 1) are simulated in this study with the LES method using the Fluent par-