Large Eddy Simulation of the Low Frequency Flow Oscillation over NACA0012 Aerofoil

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Abstract
This study examines the effect of angle of attack of an aerofoil on the low-frequency flow oscillation near stall conditions. Large eddy simulations are performed for a NACA0012 aerofoil at Reynolds number of 5 \times 10^{6} and Mach number of 0.4. The simulations are carried out at angles of attack ranging from 9.0° to 10.1° with increment of 0.1°, in addition to the angles of attack 8.5°, 8.8°, 9.25°, and 10.5°. Time histories of aerodynamic coefficients show large oscillations due to a switching between attached and separated flow around the aerofoil. This is indicative that the low-frequency oscillation phenomenon is captured. Low frequency flow oscillation is sustained and more pronounced at the angles of attack of 9.8°, 9.9°, and 10.0°.

Introduction
In the presence of strong adverse pressure gradient, a laminar boundary layer detaches and travels away from the surface creating a region of separated flow near the surface. The shear layer is highly susceptible to flow disturbances. The development of a Kelvin-Helmholtz instability breaks down the separated shear layer and initiate transition to turbulence. The energized turbulent flow reattaches to the aerofoil surface forming a separation bubble. Laminar separation bubble (LSB) forms on aerofoils flying at moderate angles of attack and low Reynolds number conditions. Such conditions are present in several applications such as unmanned air vehicles (UAVs), micro air vehicles (MAVs), low-pressure turbines, and small wind turbines. The presence of the bubble leads to considerable degradation of the aerodynamic performance with increase in drag and loss of lift. The complex dynamics of the laminar separation bubble leads to undesirable effects such as flow oscillations due to bubble flapping and abrupt aerofoil stall due to bubble bursting. The lack of understanding of the physics of laminar separation bubble also hinders control of their undesirable effect.

As an aerofoil approaches stall angle, the laminar separation bubble exhibits a quasi-periodic switching between a long bubble and a short bubble resulting in a global low-frequency flow oscillation (LFO). Although LFO has been extensively studied, the underlying mechanism is not well understood. Several experimental studies were performed to investigate LFO [7, 6, 4, 5, 14, 16]. The phenomenon was initially reported by Zaman et al.\cite{17}. Low-frequency flow oscillation was observed in which the laminar separation bubble grows and shrinks between a short bubble near the leading edge and a long bubble resulting in fully separated flow. The phenomenon can cause up to 50% fluctuations in lift with a Strouhal number in the range of 0.017 to 0.03 [7, 6]. The oscillation Strouhal number was observed to increase with Reynolds number as well as with angle of attack. Rinoie and Takemura [14] also detected the low-frequency flow oscillation phenomenon in LDV measurements of a flow field around a NACA-0012 aerofoil at a Reynolds number of 1.3 \times 10^{6} and α = 11.5°. They showed, via phase-averaged measurements, that the flow switches in a quasi-periodic manner between a short laminar separation bubble and a fully separated flow resulting from bubble bursting. Tanaka [16] used PIV measurements to show that LFO is present over a range of angles of attack near stall rather than a specific angle of attack.

LFO has also been studied using numerical simulation. Sandham [15] used an unsteady viscous-inviscid interaction model to simulate LFO and concluded that LFO in the lift coefficient can be related to the unsteady behavior of the laminar separation bubble near the aerofoil leading edge. Marzan and Henningson [10] studied bubble bursting and its relation to aerofoil stall. They argued that changes in the transition process play a major role in bubble bursting along with the viscous-inviscid interaction. Their hypothesis is that bursting takes place when saturated disturbances can not reattach the flow right after transition. Mary and Sagaut [11] carried out the first large eddy simulation of a laminar separation bubble around an aerofoil near stall conditions. However, LFO was not observed. One of the first attempts to capture the low frequency flow oscillation phenomenon by large eddy simulation was by Mukai [12] who observed several aspects of the unsteady phenomenon despite the use of a relatively coarse grid. Almutairi et al.\cite{3} investigated the LFO for a higher Reynolds number of 1.3 \times 10^{6} at an angle of attack α = 11.5°. They observed more regular oscillations in aerodynamic characteristics compared to that observed in the study of Almutairi and AlQadi [2].

Mathematical Model and Computational Setup
The code used in this simulation is a modified version of the DNS code that was written and validated by Jones et al. [9]. Almutairi [1] extended the code to solve the non-dimensional Favre-filtered Navier-Stokes equations in three-dimensional curvilinear coordinates. The code is fourth-order in time and space and it uses advanced physical and numerical boundary conditions along with a solution-stabilizing scheme. Full details of the numerical approach are provided in Almutairi [1].

The size of the computational domain in terms of aerofoil chord c, figure 1, is L_{x} = 5.0c, L_{y} = 7.3c, L_{z} = 0.5c. An investigation was performed to assess the effect of the domain span-wise width on LFO. Five span-wise widths L_{c} = 0.2c, 0.25c, 0.5c, 0.75c, and 1.0c were considered. C_{p} signals showed that LFO is captured for L_{c} \geq 0.25c. Therefore, a domain width of L_{c} = 0.5c is considered sufficient for the current Reynolds number.

At the far-field and downstream boundaries, the code implements a characteristic type boundary condition. The aerofoil...
surface is insulated and no-slip wall condition is applied. The internal branch-cut boundary is updated at each step of the temporal scheme.

A computational grid of size \( N_x \times N_y \times N_z = 780 \times 320 \times 101 \) was generated around NACA-0012 aerofoil for each of the sixteen angles of attack in which the aerofoil is oriented such that the incoming freestream is always at zero angle. The current computational domain is similar to the configuration of Almutairi [1]. However, the current grid is refined and optimized by redistributing grid points in \( \eta \) direction such that around 60% of the total grid points are within one chord from the aerofoil surface. The grids were generated using hyperbolic grid generator to improve grid orthogonality and minimize grid skewness. Furthermore, the wall-normal grid spacing was reduced to ensure a wall-normal spacing of \( y^+ \leq 1 \). Figures 2 and 3 show grid resolution, at the aerofoil surface, for the attached and separated phases of the LFO cycle at \( \alpha = 9.8^\circ \). The figures illustrate the variation of \( y^+ \) in \( \eta \) direction, \( \Delta x^+ \) in \( \xi \) direction, and \( \Delta z^+ \) in \( \zeta \) direction on the aerofoil suction side. The maximum grid spacing values in wall-normal units, at the attached phase, are \( y^+ = 0.5 \), \( \Delta x^+ = 12 \), and \( \Delta z^+ = 14 \) with 20 grid points within \( y^+ \leq 10 \). It is noted that \( y^+ \) has relatively higher values in the range \( 0.2 \leq x/c \leq 0.4 \), this is the region where transition to turbulence takes place. Having inadequate spacing in \( \zeta \) direction could affect the development of the evolving Kelvin-Helmholtz instability and consequently the transition process. Equidistant grid spacing with relatively smaller \( \Delta x \) is adopted in the range \( 0 \leq x/c \leq 0.5 \). The minimum grid spacing is smaller for the separated phase as the velocity gradient is much smaller in this case.

### Results and Discussion

Large eddy simulations were carried out for flow around NACA-0012 aerofoil at sixteen angles of attack (\( \alpha = 9.0^\circ \) to \( 10.1^\circ \) with increment of \( 0.1^\circ \), in addition to the angles of attack \( 8.5^\circ, 8.8^\circ, 9.25^\circ, \) and \( 10.5^\circ \)). The simulation Reynolds number and Mach number are \( \text{Re} = 5 \times 10^5 \) and \( M_{\infty} = 0.4 \), respectively. The free-stream flow direction is set parallel to the horizontal axis for all simulations (\( u_1 = 1, u_2 = 0, \) and \( u_3 = 0 \)). The entire domain was initialized using the free-stream conditions. The simulations were performed with a time step of \( 10^{-4} \) non-dimensional time units. Aerodynamic coefficients; \( C_L, C_D, C_m, \) and \( C_n \), were sampled for each angle of attack at a frequency of 10kHz generating three million samples over a time period of 300 non-dimensional time units. Span-wise ensemble averages of pressure, velocity components, and Reynolds stresses are sampled every 50 time-steps in \( x - y \) plane. A data set of 20,000 \( x - y \) planes is recorded at a frequency of 204Hz for each angle of attack. Span-wise ensemble averages of pressure and skin friction coefficients are sampled around the aerofoil surface every 50 time-steps. In the interest of brevity, only results pertinent to the present discussion are presented. Figures 4 and 5 show isosurfaces of (\( Q \)-criterion \( = 200 \)) for attached and separated phases of the LFO cycle. The isosurfaces are colored by the total energy per unit mass \( \tilde{E} \). A local average of streamlines at both phases is superimposed on the isosurfaces to indicate the average shape and location of the separation bubble. The figures illustrate the initial development of Kelvin-Helmholtz rolls in the separated boundary layer. Then, a secondary spanwise instability develops causing helical pairing between adjacent spanwise vortical structures leading to the formation of A-shaped structures and the subsequent breakdown to turbulence. Figure 5, in comparison to the attached phase illustrated in figure 4, shows the separated shear layer moving away from the aerofoil surface toward the energetic freestream while the location of the breakdown of the 2D structures moves downstream during separated phase. Figure 6 shows the time history of the lift coefficient for angles of attack \( 9.0^\circ, 9.5^\circ, 9.8^\circ, 9.9^\circ, 10.0^\circ, \) and \( 10.5^\circ \). The lift coefficient exhibits large oscillations due to switching between attached and separated flow around the aerofoil. The oscillations in the coefficients develop naturally and are self-sustained. However, the LFO cycles do not repeat uniformly but rather with some degree of randomness. Such stochastic behavior in the LFO is expected taking into consideration the unsteady nature of the transitional flow including random and frequent break-up of the laminar separation bubble with relatively high oscillation amplitude. This behavior is in agreement with the experimental measurements of Rinoie and Takemura.
[14]. Furthermore, Tanaka [16] indicated that there were disturbed cycles that do not resemble other regular cycles in his experimental measurement. As shown in the figure, at the angle of attack $9.0^\circ$ the flow is attached. However, the laminar separation bubble is present and intact since it starts forming at much lower angle of attack. Jones [8]. At angle of attack $\alpha = 9.5^\circ$, the flow field is attached for the first 150 non-dimensional time units after which the flow starts to separate and reattach leading to oscillation in the lift coefficient. This indicates that flow oscillation can evolve naturally in numerical computations from initial uniform free stream conditions with no flow forcing. At higher angles of attack ($\alpha = 9.8^\circ$, $\alpha = 9.9^\circ$, and $10.0^\circ$) the oscillation becomes quasi-periodic and self-sustained with larger amplitude. At an angle of attack $10.5^\circ$ the flow is mostly separated with intermittent reattachment. This is also consistent with the experimental observations by Tanaka [16], who conducted a study of low-frequency flow oscillations using PIV. LFO was observed over a range of angles in which the oscillation starts as intermittent bursts of LSB at lower angles. As the angle of attack increased, LFO became more regular. At the upper limit of the range, the flow was mostly stalled with intermittent reattachment.

Figure 7 shows the pressure coefficient, $C_p$, at $\alpha = 9.8^\circ$ averaged over selected subintervals of 5000 time steps (0.5 non-dimensional time units). It is noted that at $\phi_1$, there is a strong adverse pressure gradient near the leading edge at $x/e \approx 0.025$, which causes flow separation, followed by a pressure plateau extending to $x/e \approx 0.25$ that indicates the separated region of the laminar separation bubble. Transition to turbulence energies the separated shear layer and leads to reattachment. Consequently, the flow reattachment causes the small decrease in the pressure that follows pressure plateau at the end of the bubble. At this phase of the cycle, $\Phi_1$, the flow is attached and the laminar separation bubble is present and intact. In the following phases of the cycle, $\Phi_2$ to $\Phi_6$, the suction pressure is gradually decreasing which indicates bubble bursting. The bubble continues to burst until the pressure coefficient distribution becomes almost flat which is an indication of airfoil stall at phase $\Phi_6$.

Figure 8 (top) shows the averaged values of $C_l$ for all angles of attack. As shown in the figure, $C_l$ has maximum value at $\alpha = 9.0^\circ$ and decreases as the angle of attack increases. However, the $C_l$ profile shows some degree of nonlinearity. This is in agreement with the experimental work of Ohtake et al. [13] at low Reynolds number. Figure 8 (bottom) shows that the mean drag coefficient increases with the angle of attack.

Conclusions
This work investigated the effect of angle of attack on low-frequency flow oscillation near stall conditions. Sixteen large eddy simulations were performed for NACA0012 aerofoil at Reynolds number of $5 \times 10^4$ and Mach number of 0.4. The simulations were carried out at angles of attack from $9.0^\circ$ to $10.1^\circ$ with increment of 0.1°, in addition to the angles of attack $8.5^\circ$, $8.8^\circ$, $9.25^\circ$, and $10.5^\circ$. The time histories of aerodynamic coefficients show that the low-frequency oscillation phenomenon and its associated physics are captured in the simulations. It is noted that the low-frequency oscillation evolves naturally from uniform free stream conditions with no flow forcing. It is also observed that the LFO is present over a range of angles of attack, which is in agreement with the experimental observations of Tanaka [16].
Figure 7: Pressure coefficients around the aerofoil plotted versus the scaled x-axis (x/c).

Figure 8: Mean values of the lift and drag coefficients plotted versus the angle of attack.

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