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Numerical Investigation of the Low-Frequency Flow Oscillation over NACA-0012 Aerofoil

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Abstract. The present study investigates the low-frequency flow oscillation phenomenon near stall conditions for NACA0012 aerofoil at Reynolds number of 9×10^4 , Mach number of 0.4 and angle of attack of 11.0° . The phenomenon is clearly captured in the time histories of aerodynamic coefficients. Statistical and spectral analysis are carried out for time histories of aerodynamic coefficients. Qualitative study is performed to investigate the unsteady behaviour of laminar separation bubble over one low-frequency cycle.

1. Introduction

At low Reynolds number a laminar flow separation is highly expected near the aerofoil leading edge due to strong adverse pressure gradient. At small angles of attack, the separated shear layer moves toward the aerofoil surface, where the flow is reattached to the surface. The region between the separation and reattachment locations is termed as laminar separation bubble (LSB). This bubble is classified as a short and a long bubble [1]. At higher angles of attack, the separated shear layer moves away from the surface, and the flow becomes fully separated, which is termed as bubble bursting. The leading edge stall occurs as a consequence of bubble bursting. The aerodynamic performance of the aerofoil is markedly affected, since the lift force decreases and the drag force increases. The unsteady behaviour of the LSB leads the flow to switch between stalling and non-stalling conditions, which is found to be in a quasi-periodic manner with a low frequency, and it is known as low frequency flow oscillation (LFO).

Zaman et al. [2] carried out the first study of the LFO, they found that LFO occurs if the Strouhal number (St) is less than 0.2, and when there is a trailing edge or a thin aerofoil stall. In Bragg et al. [3] study they captured the LFO using hot wire measurements in the aerofoil wake, in which they pointed out the relation between shear layer flapping and the flow oscillations. Furthermore, Broeren and Bragg [4] used conditionally averaged laser Doppler velocimetry (LDV) measurements, they showed the periodic turning between stalling and non-stalling conditions with an unsteady LSB, and the mechanism of the LSB interaction with the trailing edge separation. Rinoie and Takemura [5] studied an experiment of flow-field around a NACA-0012 aerofoil at $Re = 1.3 \times 10^5$. They captured the LFO phenomenon at $\alpha = 11.5^\circ$, where the frequency of oscillation was 2 Hz. Tanaka [6] carried out a similar experiment of Rinoie and Takemura [5]. He used Particle Image Velocimetry (PIV) measurements, and he revealed that the amplitude of oscillations is greatest at $\alpha = 11.5^\circ$, and the oscillation is quasi-periodic. Sandham [7] used a time accurate viscous-inviscid interaction method (VII) to study LFO phenomenon, he noticed that the dominant St of the oscillations is dependent on

the aerofoil shape. Also he mentioned that the bubble bursting occurred as a consequence of potential flow/boundary-layer interactions, therefore, a simple model of boundary layer transition and turbulence could be used.

In addition, several numerical simulations were carried out to investigate the unsteadiness of LSB and the mechanism of LFO phenomenon. Almutairi and AlQadi [8] investigated the phenomenon of natural LFO using the same LES method used in [9]. They studied numerical simulations of flow around NACA-0012 aerofoil at $Re = 5 \times 10^4$, angles of attack around $\alpha = 9.30^\circ$, and Mach number of $M_\infty = 0.4$. They found that the time history of lift coefficient exhibits a self-sustained natural LFO at $\alpha = 9.25^\circ$ and 9.40° in a quasi-periodic manner. Almutairi et al. [10] performed LES for the flow over NACA-0012 aerofoil at $Re = 1.3 \times 10^5$ and $\alpha = 11.5^\circ$, which is similar to the experiments in [5] and [6]. They showed the time histories of the aerodynamic coefficients in which the LFO phenomenon was featured in a quasi-periodic manner. They found that the dominant Strouhal number was 0.00826 which is comparable to that of the experiment [5].

2. Mathematical Model and Computational Setup

In the present study, LES is carried out to simulate the flow field around NACA-0012 aerofoil. The LES requires decomposition of the flow field in which the large scales are resolved and the small scales are modelled using sub-grid scale model (SGS). The mixed-time-scale (MTS) model is used as SGS model, this model was developed by Inagaki et al. [11]. The model is constructed without using any explicit wall-damping function to overcome the drawbacks of other SGS models. A fourth-order accurate central difference scheme is used for the spatial discretization of the internal points and a Carpenter fourth order accurate scheme, Carpenter et al. [12], is applied to treat points near the boundary Jones [13] and Jaber [14]. A fourth-order Runge-Kutta explicit scheme is used for the temporal discretization.

The spatial filter is employed to the flow-field for small scales without disturbing large scales in order to overcome grid to grid oscillations. Visbal and Rizzeta [15] found that in order to maintain numerical stability, it is convenient to use compact schemes of order equal or greater than the order of spatial discretization. Therefore, an explicit fourth order tri-diagonal filter is applied and the conservative flow field variables are filtered in x , y and then in z direction.

The domain and curvilinear coordinate system are illustrated in figure 1. A NACA-0012 aerofoil is oriented at an angle of attack of 11.0° . The dimensions $W = 5c$, $L_\eta = 7.3c$ and $L_\zeta = 0.5c$ refer to the wake length, C-grid radius, and the domain length in span-wise direction, respectively. Where c is the aerofoil chord.

Adequate grid resolution is required in order to resolve the large eddies in the flow-field. A C-grid of $832 \times 351 \times 167$ is constructed around the aerofoil in curvilinear coordinates ξ , η , and ζ , respectively. The wall viscous units (y^+ , Δx^+ and Δz^+) are usually used to examine the grid resolution. The first grid point was allocated at $y_1^+ < 0.7$ in the wall-normal direction. The grid resolution in the stream-wise and span-wise directions are $\Delta x^+ < 13$ and $\Delta z^+ < 11$, respectively.

At the free-stream and far-field boundaries, the integral characteristic boundary condition [16] is applied, while at the downstream exit zonal characteristic boundary condition [17] is applied. An adiabatic, no slip condition is applied at the aerofoil surface. A periodic boundary condition is applied in the span-wise direction for each sub-step of the Runge-Kutta time steps.

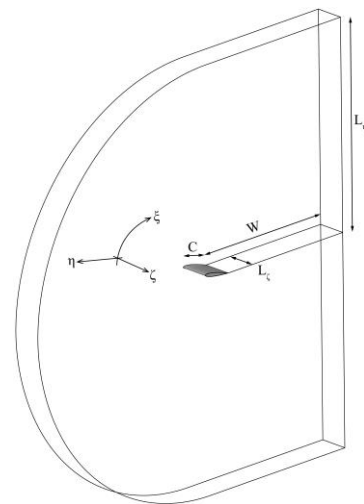


Figure 1. Domain

3. Results and Discussion

In this study, LES is carried out for the flow-field over NACA-0012 aerofoil at Reynolds number of 9×10^4 , Mach number of 0.4, and angle of attack of 11.0° . The free-stream was set parallel to the horizontal axis. The time-step is set to 10^{-4} non-dimensional time units. No artificial forcing is applied, whilst a clean free-stream conditions are used. The LFO phenomenon is captured in the time history of lift coefficient as shown in figure 2. A natural self-sustained oscillation is exhibited at $\alpha = 11.0^\circ$ in a quasi-periodic manner. The flow is oscillating around a mean of 0.7104 between the stalled and non-stalled conditions with a low frequency of 0.0394 and Strouhal number of 0.0075. The observed randomness and irregularity in the cycle are due to the unsteady nature of the transition process and the subsequent turbulent flow.

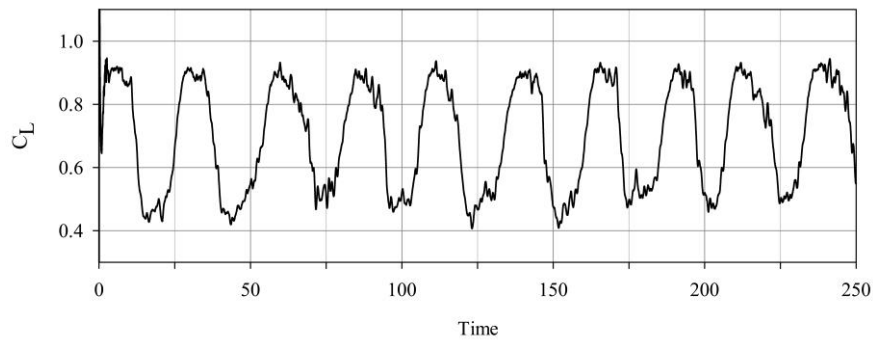


Figure 2. Time history of the lift coefficient (C_L).

The spectrum of the lift coefficient features the dominant frequency modes on the flow-field. The spectrum is estimated using the fast Fourier transform (FFT) algorithm. The lift spectrum is presented in figure 3. The lift spectrum features a low frequency mode, $St = 0.0075$, which is in the same order of magnitude as that of the experimental measurements [5].

The instantaneous iso-surface of Q -criterion ($Q = 200$) coloured by the total energy per unit mass (E) is illustrated in figure 4 for both attached and separated flow phases. Figure 4a shows the early transition process where the shear layer is attached. The shear layer is a little bit distorted and a two dimensional scales convert to a large three dimensional structures followed by a breakdown and consequently the flow becomes turbulent. The separated flow phase, figure 4b, shows a late transition process. The shear layer is detached from the surface towards the free-stream and the breakdown process of the two dimensional scales moves downstream.

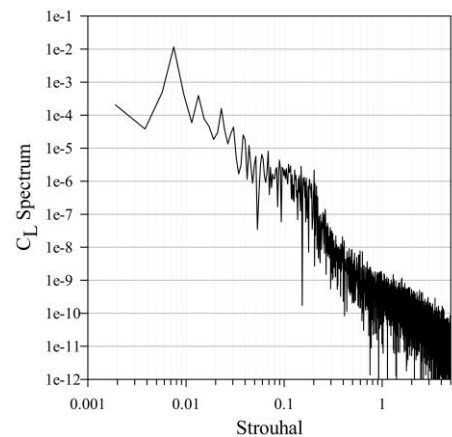


Figure 3. Lift coefficient spectrum.

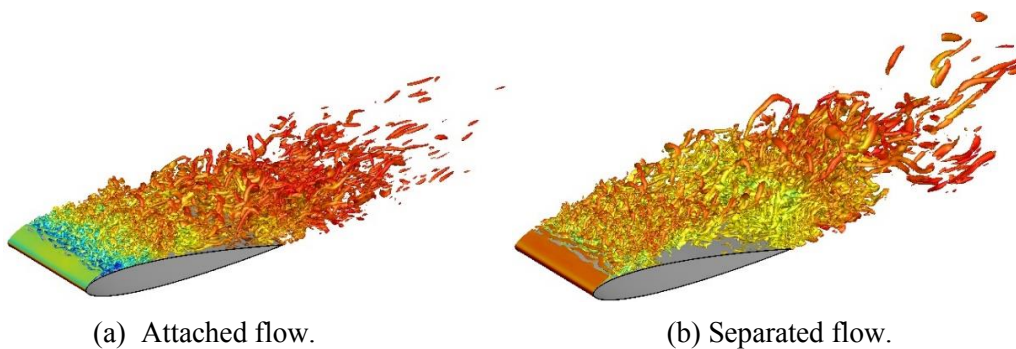


Figure 4. Iso-surface of Q -criterion.

2D $x - y$ planes of data are sampled every 50 time-steps, non-dimensional sampling frequency of 204. The sampled data contains time and span-wise ensemble averaged velocity components, pressure, Reynolds stresses and density. The sampling started after the flow was fully developed and the flow became stationary in time. The starting sampling time was $t = 210$ non-dimensional time units and it ended at $t = 240$, covering one LFO cycle. The data was locally averaged over sixty subintervals and each subinterval consist of 5,000 time steps (0.5 non-dimensional time units).

Figure 5 shows streamlines for the complete LFO cycle. At the beginning of the cycle, $\phi = 18^\circ$, a short bubble forms near the aerofoil leading-edge on the suction side. The short bubble grows in length and height in time as shown in figure 5b. The bubble continue to grow in size until it eventually burst and a fully separated flow is observed at $\phi = 138^\circ$. The flow remains separated for $\phi = 198^\circ$ and 258° and the bubble size varies with time. The flow reattaches to the aerofoil surface at $\phi = 318^\circ$ and the bubble becomes identical to that observed at $\phi = 18^\circ$. The cycle continue in a quasi-periodic manner. This behaviour is in agreement with Rinoie and Takemura [5] and Tanaka [6] observations in which they showed flow visualization. The behaviour also agrees very well with Almutairi et al. [10].

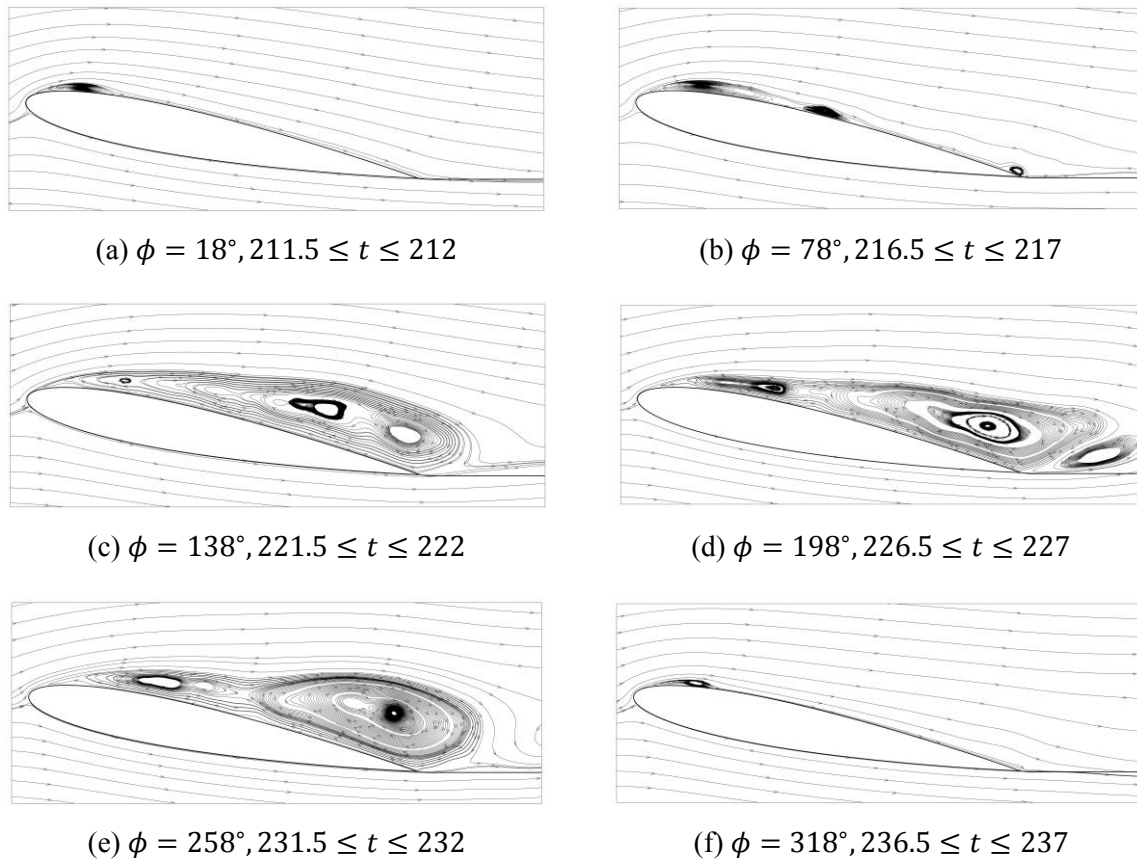


Figure 5. Streamlines of the flow field over one LFO

The averaged pressure coefficient (C_p) over the previously selected subintervals is plotted in figure 6. The pressure decreases drastically at the aerofoil leading-edge due to the curvature shape as the velocity tends to increase. A strong adverse pressure gradient is present near the aerofoil leading edge at the beginning of the cycle ($\phi = 18^\circ$) which causes the flow separation, followed by a small declining and increment in the pressure for a small distance where the flow is reattached and the bubble is formed. Downstream the bubble there is a rapid increase in the pressure due to the turbulent flow. Further downstream C_p remains almost constant. A slight reduction of C_p with time is observed

when the bubble burst (from $\phi = 48^\circ$ to $\phi = 238^\circ$). During the fully separated flow phase the C_p distribution is almost flat along the aerofoil suction side ($\phi = 258^\circ$). The C_p increases at $\phi = 288^\circ$ which is indicative that the flow has reattached. The C_p continue to increase until the short bubble is formed near the leading edge at $\phi = 348^\circ$. The C_p behaviour is in agreement with the experimental work of [5] and [6] and the numerical work of [10].

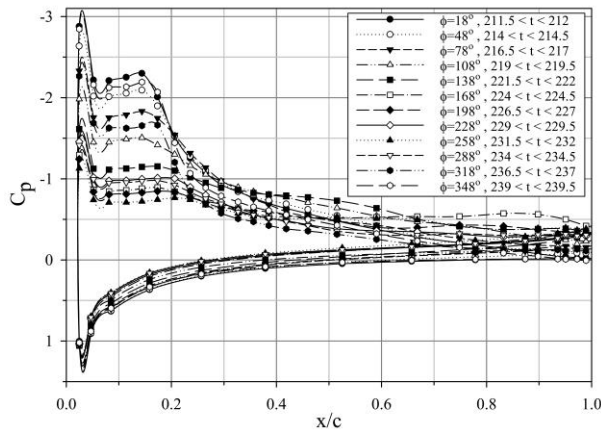


Figure 6. Pressure coefficient.

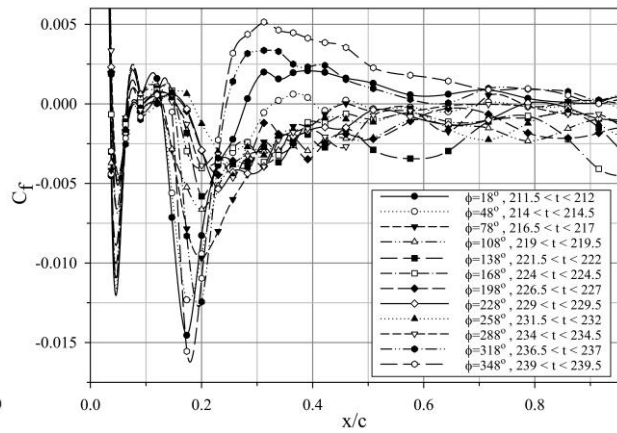


Figure 7. Skin friction coefficient.

The averaged friction coefficient C_F over the selected subintervals is shown in figure 7. Maximum values of C_F are observed at the leading-edge all over the cycle. The C_F is then dropped sharply near the leading-edge where the averaged C_F crossed the $x -$ axis. This is indicative that the C_F has negative values and the flow is reversed, i.e., separated. The C_F continued to decrease until it reached minimum values in the interval $0.04 \leq x/c \leq 0.05$, separation locations over the cycle. After that the C_F switched to positive values indicating flow reattachment locations and recirculation zone. The relatively small recirculation zone features a small counter-clockwise vortex as shown in figure 8. The C_F decreased again and reached a second negative peak in the interval $0.18 \leq x/c \leq 0.285$ followed by a sharp increase forming a larger recirculation zone constituting laminar separation bubble. The second recirculation region has a higher velocity gradient than the first recirculation region. At $\phi = 318^\circ$ and 348° the flow became similar to that at $\phi = 18^\circ$ and 48° where the flow is fully attached except for a short laminar separation bubble near the leading edge.

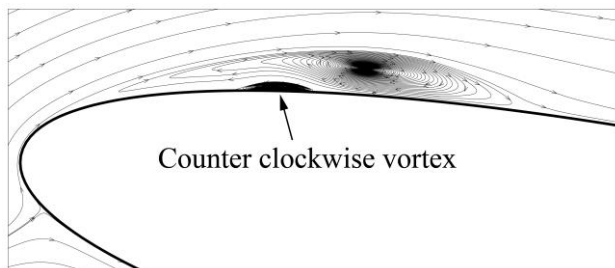


Figure 8. The counter-clockwise vortex.

4. Conclusion

In the current study, the low frequency flow oscillation phenomenon is captured using LES technique for the flow field over NACA-0012 aerofoil at Reynolds number of 9×10^4 , Mach number of 0.4 and angle of attack of 11.0° . The time history of the lift coefficient exhibited the natural self-sustained LFO phenomenon, where the flow is switching between attached flow and separated flow phases. The lift coefficient spectrum showed that the dominant low frequency mode in the flow-field is at Strouhal number of 0.0075, which is in agreement with experimental measurements.

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