THE EFFECT OF JET FREQUENCY EXCITATION ON SEPARATION CONTROL OVER NACA0012 VIA SYNTHETIC JETS

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The effect of jet frequency excitation with different relative velocity over NACA0012 airfoil is investigated numerically. The jet is placed on the upper surface located at 15% of the chord length from leading edge simulating the periodic excitation under Reynolds number $Re_\infty=2,88.10^6$ condition. The calculations are carried out using an Unsteady Reynolds averaged Navier-Stokes (URANS) Flow solver with incompressible fully turbulent and (k-ε) RNG model. The results show that using active flow control via synthetic jet a remarkable improvement in critical stall angle is obtained which can be delayed by 2^0 (from 16^0 to 18^0) and the maximum lift can be increased by 24.35% (from 1.15 to 1.43) with jet slope angle $\beta=45^0$. The effects of jet frequency excitation indicate a reasonable improvement in aerodynamic performances with an increase in maximum lift at optimum non-dimensional frequency $F^+=2.5$ compared with uncontrolled flow.

Keywords: Control, Synthetic jet, Jet frequency, NACA0012 airfoil, Lift.

1. Introduction

In the past decade, aerodynamic flow control has received an important attention by the scientific community [1]. Many control techniques have been developed, which may be classified in two categories, passive and active flow controls, in order to prevent flow separation and to improve the aerodynamic performances [2]. The active control via synthetic jet takes great importance [3-5]. The synthetic jet actuators have been employed in boundary layer stability and in delaying the flow separation, leading to include delay aerodynamic stalling, drag reduction and lift enhancements [6]. In most publications, synthetic jets or zero-net mass-flux jets have been used as an active flow control technique. Tuck and Soria [7] conducted an experimental study over NACA0015 using synthetic jet. Measurements indicated when a non-dimensional frequency is 1.3 and excitation momentum coefficient is 0.14%, the lift coefficient increases. In another experimental work, Seifert et al [8] investigated unsteady suction /blowing over NACA0015 airfoil near the leading edge tangentially to the surface. The result

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showed a significant increase in lift with relatively momentum input and they also observed re-attachment of the flow. In their review, Amitay et al. [9] found that, when actuators located at the most upstream position with excitation frequency applied at f_e=246Hz and f_e=740Hz, no effect on the pressure distribution over airfoil. In contrast, actuator at the same position and excitation at f_e=71Hz, resulted in flow re-attachment and the formation of a separation bubble. Hassan et al. [10] show in their numerical work zero-mass synthetic jets placed at 13% of chord length over NACA0012 airfoil for certain oscillation frequency and peak amplitude, the lift can be increased with high momentum jets. In another trend Wu et al [11] used the periodic excitation at 2.5% chord from the leading edge with suction normal to surface on NACA0012 airfoil. The results showed that the lift was increased for angles between 18^0 to 35^0. Another work was presented by McCormick [12] showed that a tangential synthetic jet placed at 4% chord from the leading edge over profile with oscillatory frequency (F^+=1.3) and jet momentum coefficient ($C\mu$=0.5%) can improve the aerodynamic performance Results indicated that the stall angle is pushed to 6^0 and the maximum lift coefficient increased by 25%.

In recent years, numerical [13, 14, 15] investigations showed that using flow separation control, such as suction, blowing and synthetic jet (ZNMF) causes an improvement in lift for different NACA airfoils. Esmaeili et al. [16] showed that a tangential synthetic jet over NACA23012 airfoil, with dimensionless frequency jet (F^+= 0.159 and F^+= 1) and blowing ratio U_j/U_∞ between 0 to 5, synthetic jet slope angles between 0^0 to 83^0. It was concluded that an increasing blowing ratio resulted in increasing lift to drag ratio. Donovan et al. [17] investigated flow reattachment over NACA0012 airfoil using ZNMF, their results indicated a 20% post-stall increase in lift at α=22^0.

This article focuses on the effect of frequency excitation jet and jet amplitude on separation control of the flow over NACA0012 airfoil. The results show significant improvement in lift and drag and aerodynamic stall delay compared with clean airfoil.

2. Computational methodology

2.1. Numerical model

The flow around the airfoil is simulated using the unsteady, Reynolds-averaged Navier-Stokes (URANS) equations, which in the incompressible form can write as follow:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_i \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i}\left[v\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + \overline{u_i' u_j'} \right] \tag{2}$$

Where t and x_i denote the time and space in Cartesian coordinates, u_i and u_i' respectively, the time-averaged and fluctuating flow velocity components, p the time-averaged pressure, v and ρ the kinetic viscosity and the fluid density. The two-dimensional simulation over NACA0012 is solved using the finite volumes method in URANS approach. The solution of the flow field is achieved using the commercial CFD code " AnsysFluent ". Pressure-velocity coupling is achieved using the SIMPLE method. The terms of the convection velocity field and turbulent quantities are discretized by a second order "UPWIND scheme ". The time advancement is determined by the fixed time step Δt for controlled cases with 100 time-steps in one oscillation period. The model k-ε RNG is used in the present computation for its relatively accurate and economic benefit in term of time. Velocity inlet boundary conditions are specified at the front, upper and lower boundaries of the control region. The outflow boundary condition is used at the outlet and no-slip boundary conditions were used on all solid surfaces. Concerning the slot jet of control, a user defined function (UDF) is developed to represent an oscillate diaphragm (SJ) (see fig.1) [18-19-20].
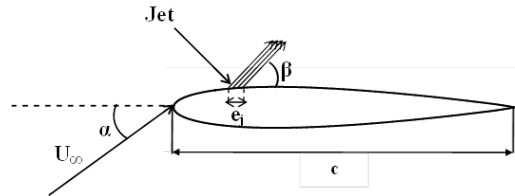

Fig.1. Profile geometry with unsteady blowing/suction

The synthetic jet is defined as the following time function

$$U_j = U_0 \operatorname{Sin}\left(2\pi \frac{F^+ U_\infty}{c} t \right) \tag{3}$$

The parameters of the jet that affect the external fluid are in the reference [21]. The non-dimensional frequency of a synthetic jet is defined as:

$$F^+ = \frac{fc}{U_\infty} \tag{4}$$

To describe the energy of a synthetic jet used for control, the momentum coefficient defined as:

$$C_\mu = \frac{\rho_j e_j U_0^2}{\frac{1}{2}\rho_\infty U_\infty^2}$$ (5)

The ratio between the jet velocity and upstream velocity is

$$V_r = \frac{U_0}{U_\infty}$$ (6)

Where U_j is jet velocity and U_0 is jet velocity amplitude, U_∞ is upstream velocity. Notes that F^+ represents non-dimensional jet frequency, f is jet frequency, Vr is relative velocity and c is chord length, ρ_j and ρ_∞ are, respectively, jet density and freestream density, e_j is the relative jet width.

2.2 Grid generation and Grid independence check

In this investigation, the flow model considered unsteady, incompressible regime and fully turbulent. The selected Reynolds number and Mach number for both clean airfoil and controlled configurations via synthetic jet are, respectively, $Re_\infty=2.88 \times 10^6$ and $M_\infty=0.13$ with upstream velocity $U_\infty=40$m/s [22] with a chord length of airfoil c=1m. The validation is carried out with the aerodynamic coefficients of clean airfoil at a Reynolds number of $Re_\infty=5.0 \times 10^5$ ($U_\infty=7.3$m/s) [23] whereas the pressure distribution of clean airfoil is validated at a Reynolds number of $Re_\infty=2.88 \times 10^6$.

The C-H type structured grid is generated using pre-processor Gambit over the clean airfoil, which is shown in (fig.4 (a)). The computational area was large enough to prevent the outer limit from affecting the near flow field around the airfoil. Several meshes in independence study using a coarse and fine mesh were carried out, with the calculated results through the study of lift and drag coefficients at angles of attack of 10^0 and 14^0 (fig.2 and 3) whereas other grid is generated when jet is placed on the upper surface at 15% chord from the leading edge and with a slot jet width of 2% of chord length (fig.4 (b)).

The grid independence test was conducted on four meshes under a Reynolds number $Re_\infty=5.10^5$. Figure 2 and 3 shows the lift and drag coefficients of each mesh. The numerical results are compared with experimental lift coefficient ($C_L=0.9542$) value of Critzos et al. [23] at an angle of attack of 10°, where they show a good agreement for most of the mesh.
According to figures 2 and 3, the grid size, giving a grid independent result with reasonable accuracy was selected to have 48400 cells.
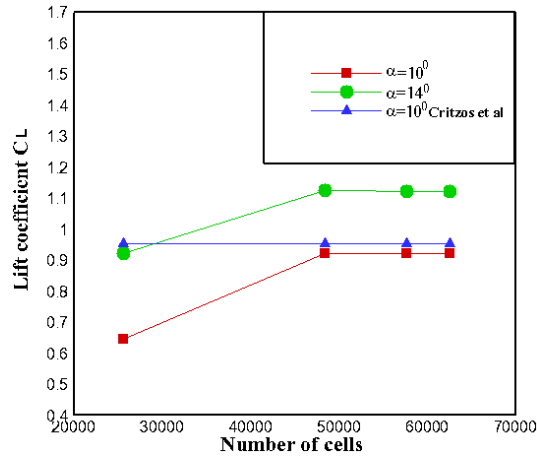
Fig.2. Mesh independency for lift coefficient at a Reynolds number of $5.10^5(Y^+<1)$

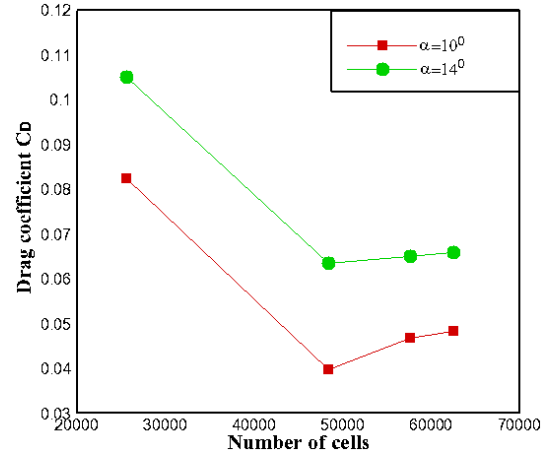Fig.3. Mesh independency for drag coefficient at a Reynolds number of $5.10^5(Y^+<1)$

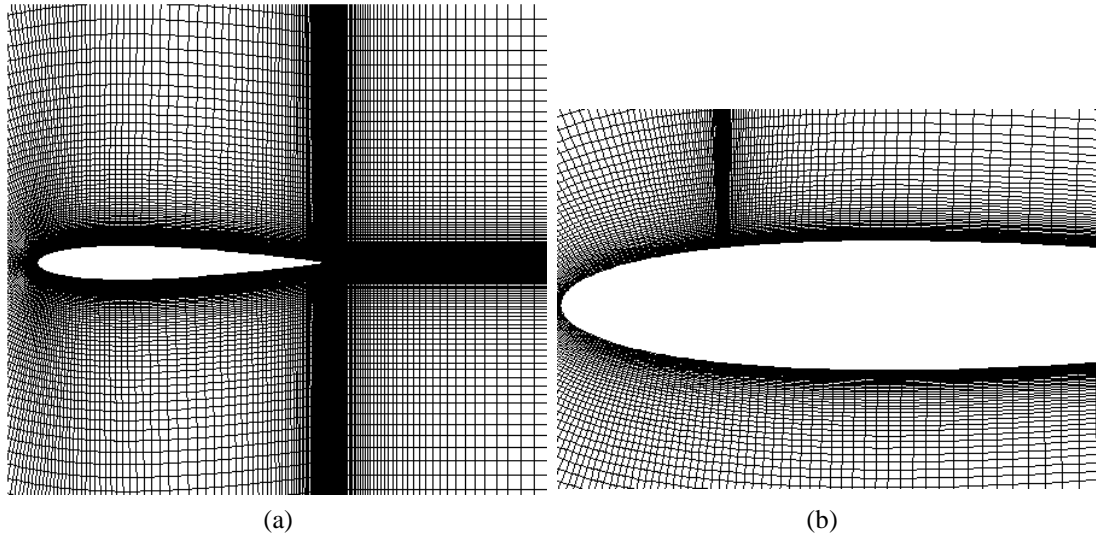(a)   (b)

Fig.4. Computational grids used for the clean airfoil validation (a) and for controlled study (b)

2.3. Validating Results

Computational model is tested for uncontrolled (Clean profile) airfoil configuration with angle of attack equal 10°, a comparison between numerical study and experimental results given by N. Gregory and al. (1973) [22] is shown in fig.5, for pressure coefficient evolution. This comparison gives a good agreement between the two results only on the upper surface.
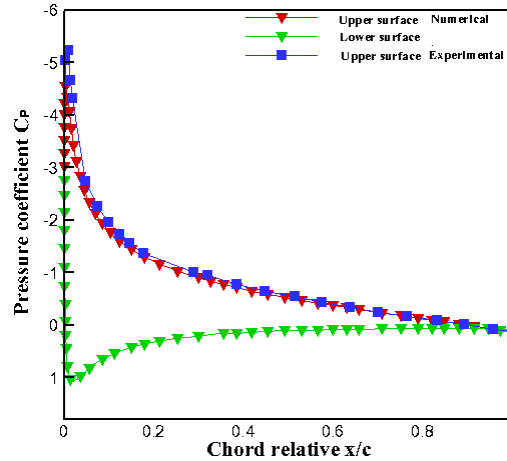
Fig.5. Comparison between experimental and numerical results for NACA0012 profile
upper surface pressure distributions without control ($\alpha= 10^0$, $M_\infty=0.13$ and $Re_\infty=2.88.10^6$)

3. Results and discussion

The simulations were performed with synthetic jet located at 15% from the leading edge of the airfoil and slot jet width 2% of chord length for a jet angle of 45^0. The effects of non-dimensional frequency for various relative velocities are successively examined.

3.1 Effect of synthetic jet

At first, part the lift and drag coefficients for one period are obtained for different angles of attack with non-dimensional frequency $F^+=2.5$ and relative velocity $V_r=1.5$ were shown in figures 6 and 7. The computational results with synthetic jet control were compared with the uncontrolled flow (Clean profile). This comparison showed in figure 6, that the synthetic jet can significantly increase the maximum lift by 24.35% (1.15 to 1.43) and the critical stall angle of attack was delayed by 2^0 (from 16^0 to18^0) which indicate an improvement of stall performance. Whereas, in figure 7 a slight improvement was obtained for the drag coefficient for angles of attack lower than 10^0 and beyond the angle of attack 22^0, but for angles of attack between 10^0 and 22^0 no improvement can be seen.
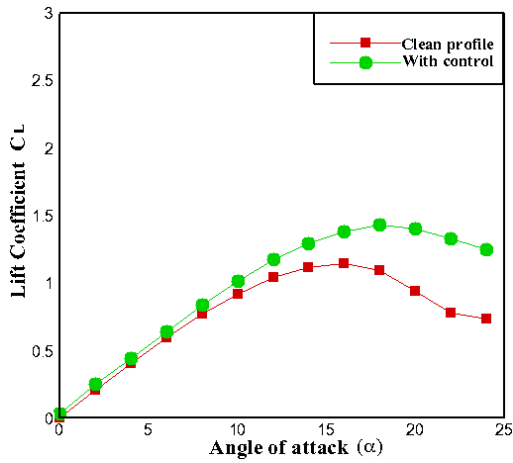
Fig.6. Evolution of lift coefficient on NACA0012 profile, $M_\infty=0.13$ with and without control for different angle attack
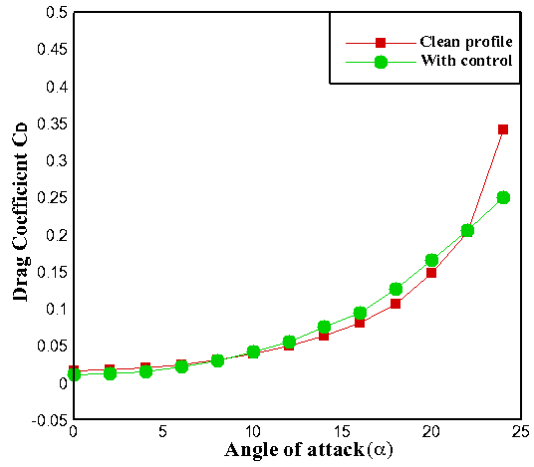
Fig.7. Evolution of drag coefficient on NACA0012 profile, $M_\infty=0.13$ with and without control for different angle attack

The following figure 8 indicates the time averaged flow field in one period for angle of attack of 22^0, the detail of flow fields is illustrated by the streamline pattern.
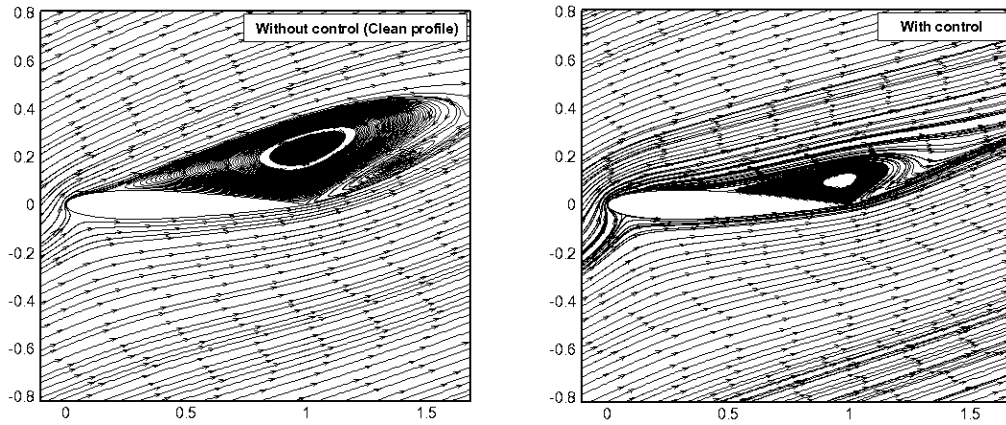

Fig.8. Streamlines pattern in flow field over NACA0012 profile, $M_\infty=0.13$ and for angle of attack $\alpha=22°$ with and without control

The flow field controlled by slope slot synthetic jet angles with the value $45°$ where compare with the uncontrolled flow. We observe the separation zone is reduced, resulting an improvement in performance aerodynamic.

3.2 Effect of jet frequency

In the second part, the study focuses on the effect of the jet frequency at the jet location 15% from the leading edge of the airfoil with jet width 2% of the chord length and jet slope angle $\beta=45^o$, Mach number $M_\infty=0.13$, angle of attack $\alpha=22^0$.
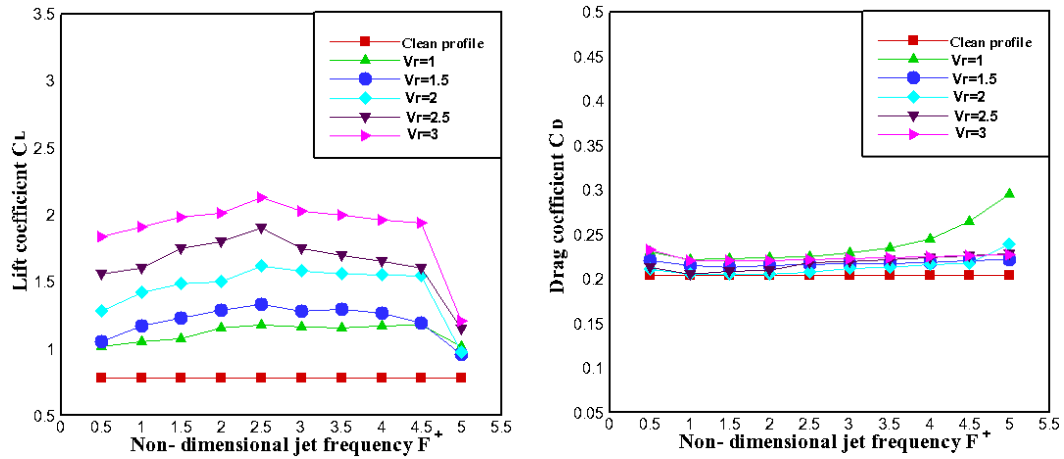

Fig.9. Evolution of (a) lift coefficient and (b) drag coefficient on NACA0012 profile, $M_\infty=0.13$, $\beta=45^0$ and $\alpha=22^0$ for different non-dimensional jet frequency
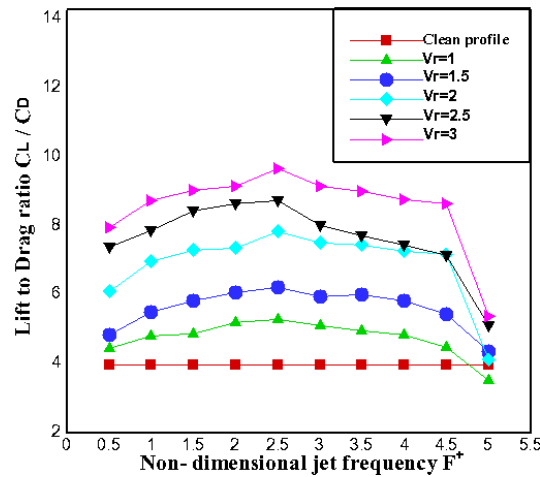

Fig.10. Evolution of lift to drag ratio on NACA0012 profile, $M_\infty=0.13$, $\beta=45^0$ and $\alpha=22^0$ for different non-dimensional jet frequency
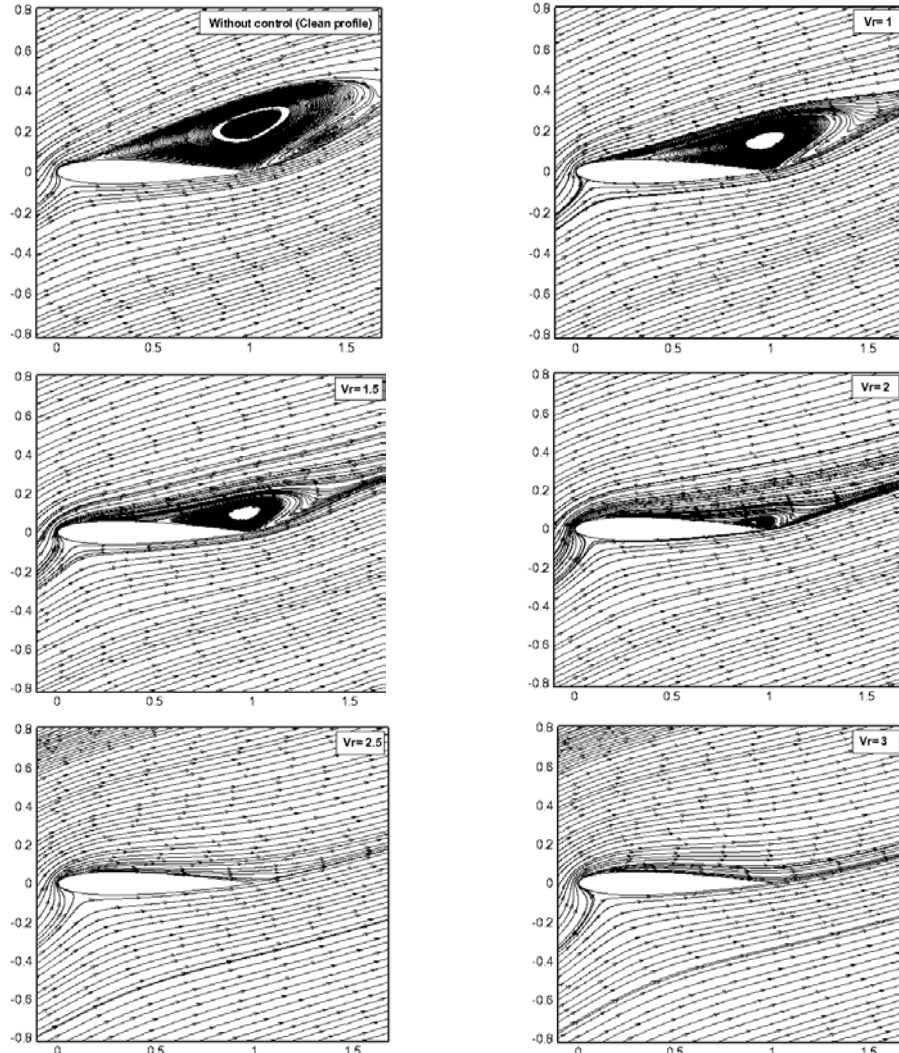
Fig.11. Streamlines pattern in flow field for clean and controlled configurations for different values of relative velocity, angle of attack α=22^0, M$_\infty$= 0.13 and jet slope angle β=45°

The average lift and drag coefficients and lift to drag ratio are calculated of one period of oscillation for different non-dimensional frequency with relative velocity values V_r=1, 1.5, 2, 2.5, 3 of controlled cases is presented in Figs. 9-10, compared with and without control flow results. From Fig. 9.a, we can observe when the non- dimensional frequency was increased, the lift coefficients were increased in different relative velocity respectively, indicate the maximum in lift at F^+= 2.5 beyond this value the lift coefficients decrease, but remains higher

compared to the uncontrolled case (clean profile). Whereas the drag is usually an undesirable effect (fig.9.b). In figure 10, the lift to drag ratio increases until to F^+=2.5 then decreases up this value, indicated an optimum value in F^+=2.5 with maximum lift to drag ratio for various relative velocities.

The Figs. 11 indicate the time averaged flow fields in one period for angle of attack of 22°. The detail of flow fields is illustrated by the streamlines pattern. The controlled flow fields by different relative velocity V_r =1, 1.5, 2, 2.5, 3 for non-dimensional frequency F^+= 2.5 and jet slope angle β=45°, were compared with the uncontrolled flow. We can see that the separation zone is reduced respectively, until V_r =2 beyond this value bubble separation are eliminated, resulting an improvement in aerodynamic performances.

4. Conclusions

In this study the active flow control over a NACA0012 airfoil using synthetic jet is examined. The effects of jet frequency of different relative velocities on the flow field around airfoil are investigated. First, the results confirm a significant improvement in aerodynamic performance which obtained for F^+=2.5 and relative velocity V_r=1.5 with an increment in the lift of almost 24.35% increment in the lift and a delay of the stall angle delayed by 2° compared with uncontrolled flow. Furthermore, the effects of jet frequency with various relative velocity for jet angle β= 45° and angle of attack α= 22°, are studied; the results conduct to an optimal value equal to F^+=2.5 when the slot is positioned at 15 % of chord length from the leading edge which lead to a maximum value in both lift and lift to drag ratio, resulting an improvement in aerodynamic performances. It can be concluded that synthetic jet is a promising approach that is effective in controlling the flow separation over airfoil.

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