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SEPARATION CONTROL AND LIFT ENHANCEMENT ON AIRFOIL USING UNSTEADY EXCITATIONS

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Abstract

External unsteady excitations imposed on the flow field around an airfoil can greatly change its aerodynamic properties. It may be beneficial to prevent flow separation, delay stall and enhance the lift.

In this paper, the techniques used to control flow separation and the possible ways for enhancing the aerodynamic efficiency of the airfoils are investigated, by use of the wind tunnel model test and water channel flow visualization techniques. The excitation procedures considered in the experiments are: (1) Pitch oscillation of the airfoil, (2) The moving surface effects produced by the rotating leading edge. and (3) The oscillating flap at the leading edge of the airfoil.

It is found from the experimental results obtained that the beneficial aerodynamic effects can be reached in varying degrees at high angle attack conditions, as long as the excitation means and its frequency and amplitude are properly selected.

I. Introduction

It is known that the unsteady excitations imposed on the flow field by the time-varying motion of the body itself or by the disturbance of the external excitation devices can be greatly change the aerodynamic properties of the airfoils, such as surface pressure distribution, lift, drag , and pitching moment etc.

The flow field phenomena and mechanism of lifting force produced by unsteady excitations may be much different from the corresponding ones without excitations. It is found that these phenomena are closely relevant to the situation of the boundary layer, the flow separation and reattachment, the vortex formation, as well as the interaction among them.

It is an important topic and becomes a subject of intensive researches due to the urgent needs in developing of the flying vehicles with high maneuverability, and in design of high performance helicopter blades, turbomachines, diffusers an in a variety of other engineering applications.

In recent years, many unsteady excitation techniques for flow control and lift enhancement have been studied by numerous investigators extensively [1-4]. Such as, the use of internal or external acoustic excitations [5,6], pitching oscillations of the airfoil at high angle of attack [3,7,8], small oscillating flapperon, spoiler, fences or ribbons [3,10,11] pulsed or period air injection or suction [12] moving surface effects [9,13,14] as well as the local heating on the body surface [15] etc. Most of the above mentioned techniques promise to be possible means for flow control and can yield good results. But, because of the serious problems associated with the system weight, parasitic drag and energy consumption, especially, the reliability and the sensitivity of the flow structure to the parameters of the excitation system. up to date, most of the unsteady excitation techniques have not been explored in engineering practices, so, further researches on the mechanism about these phenomena are obviously needed.

In this paper, a variety of unsteady excitation techniques for flow control and lift enhancement on the airfoils are considered with an emphasis upon the fundamental understanding of the flow structure and the mechanism of the various fluid mechanical processes that can produce the dynamic lift enhancement effects.

Both the aerodynamic forces measurements and the flow visualizations under different excitation conditions were performed in wind tunnel and water channel respectively. The experimental results indicated that the favorable effects of postponing the separation, delaying the stall and enhancing the section lift, can be reached to a certain extent, as long as the excitation means and its frequency and amplitude are appropriately imposed at the suitable positions.

II. Experimental Set up

The experiments are performed in three low speed wind tunnels: one is an open-type tunnel with $0.6M \times 0.6M$ cross section, its maximum velocity is about 50 m/s, Another is a return-circuit type, the diameter of its open circular test section is 1.5M, the maximum velocity is about 40m/s. The third one is a closed return wind tunnel of $1.4M \times 2.0M$ cross section with free stream turbulence level less than 0.2% at speed of $5.0\sim45 m/s$.

Three models are used in experiments. Model I is a modified NACA 23018 airfoil with chord length of 0.126M. Model II, basically, is a NACA 0024 airfoil with 0.4M chord length but the leading edge portion was substituted by a small rotating cylinder. Model III is a two-dimensional wedge with a oscillating flap at its sharp leading edge. The schematical diagram of Model II and Model III are shown in Figure 1.

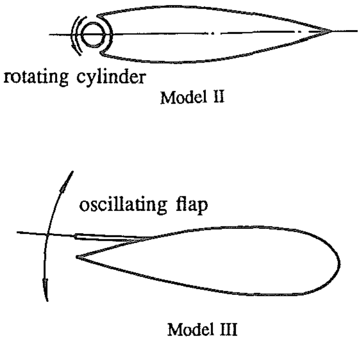


Figure 1. Sketch of test Model II and Model III

The aerodynamic lift and drag acting on the airfoils and the velocity profiles in the wake behind it are measured by aerodynamic balance and Hot-Wire anemometer respectively. The flow visualizations are performed by Tuft method in wind tunnel test and hydrogen bubble method in water channel. All the measured data are fed into a microcomputer for processing, Finally, the experimental results can be obtained from the output of the printer and displayed on the screen of the monitor.

III. Results and Discussion

1. Airfoil oscillating in Pitch

The typical test results on airfoil oscillating in pitch are shown in Figure 2.

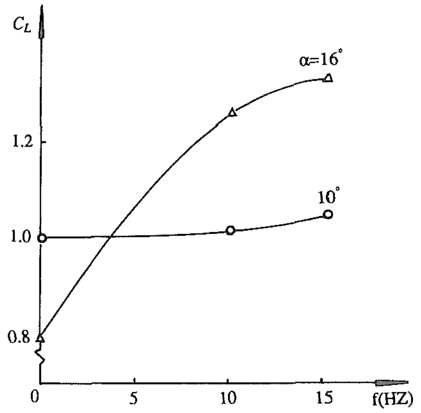


Figure 2. Lift Coefficient vs. oscillation frequency

It is observed that the frequency of the pitch oscillation has very small influence on the lift at the angle below the static stall angle (for example, $\alpha=10^\circ$) but at high angle of attack ($\alpha=16^\circ$) near the onset of the separation on the upper surface, the pitch oscillation effects become noticeable and increase greatly with the excitation frequency.

The tendency of the variation in lift is due to the effects of the time-dependent movement of the separation point and the situation of the boundary layer on the airfoil. It can be seen from the flow visualization pictures that as the leading edge of the airfoil moves upward, the velocity profile of the boundary layer becomes fuller compared with the steady case, but, on the downstroke, the situation is the opposite, so separation is easyly to occur and a flow reversal region appears firstly near the trailing edge. At high angle of attack a separation vortex is formed at the leading edge and then convected downstream along the airfoil surface. The vortex will stay for longer time under the excited conditions, and the strength of the vortex depends on the pitch rate obviously. The change in lift is closely related to this vortex.

Ref[8] has pointed out that under the condition of moderately low reduced frequency $\bar{\omega}=0.2$ (here $\bar{\omega}=\omega c/U_\infty$ is the oscillating frequency, c is the chord length and U_∞ is the free stream velocity) only one separation vortex exist, but at higher values of $\bar{\omega}$, multiple vortex may appear simultaneously on upper surface of the airfoil. The flow field structure becomes more complex. In this experiment, $\bar{\omega}=0.2$ corresponds to the frequency of $5\sim6HZ$. In that case the lift curve shown in Figure 2 appears more serious nonlinearity, which may be produced by this complex vortex interactions.

In order to reveal the essence of the lift increasing mechanism caused by pitch oscillations, the measurements of the velocity profile in the wake behind the oscillating airfoils were performed.

Because of the complexity of the wake flow structure under high angle of attack and pitch oscillations, it is not easy to find out the varying law of the wake velocity components u (stream wise) and v (vertical) with pitch rate by ordinary time-average method. Reference [15] pointed out that with the help of phase average method the situation may be obviously improved.

Taking the data of instantaneous velocities at the same phase for different period of the pitch oscillations, one can get the phase average data. The velocity component u obtained at $\alpha=25^\circ$ and down stream position measured from the trailing edge equals to 1.5 c is shown in Figure 3, here c is the chord length of the airfoil. and y=0 corresponds to the trailing edge position at $\alpha=25^\circ$

The variation of the velocity component v with time t at $\alpha=0^\circ$ is shown in Figure 4. The dotted line in the figure represents the result given by phase average method for pitch oscillation frequency f=20Hz and amplitude $A=\pm4^\circ$ respectively.

It is evident that the velocity component u for oscillating case is quite different from the static one and the vertical velocity component v becomes unsymmetric about time t axis in one cycle, so, the down wash effects generated due to the pitch oscillation. It can be deduced that the extra dynamic lift will exist.

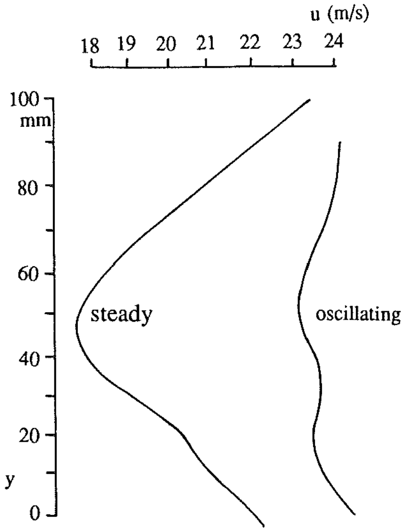


Figure 3. Velocity component u for steady and oscillation conditions

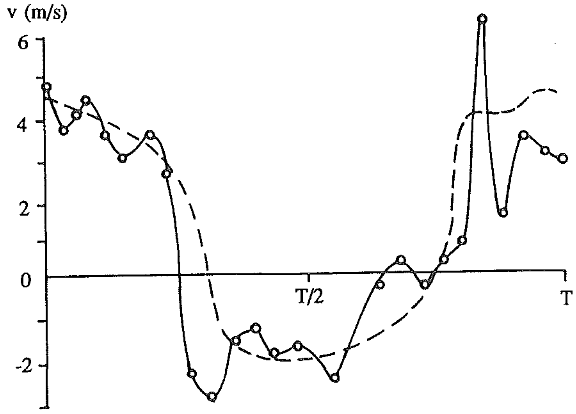


Figure 4. Variation of velocity component v

2. Moving surface effects of rotating leading edge

The typical experimental results obtained on model II is shown in Figure 5 for different angle of attacks and nondimensional rotating velocity $\bar{u}$, here $\bar{u}=u/U_\infty$, u is the tangential velocity of the rotating cylinder and U_∞ is the free stream velocity.

cylinder at leading edge

The test results shown that the lift grows with the increase of the angle of attack and moreover, the rotating velocity is an important parameter which has remarkable influence on the lift augmentation.

It may be imagined that the main effects of the moving surface on the flow around the airfoil are caused by many factors such as the change in external stream velocity relative to the airfoil surface and the momentum injection into the surface boundary lager. All of these play an important roles on retarding boundary layer growth and preventing flow separation. The flow visualization pictures (Figure 6) obtained at higher rotating velocity clearly show the influence of the rotation at the leading edge on lightenning the flow separation.

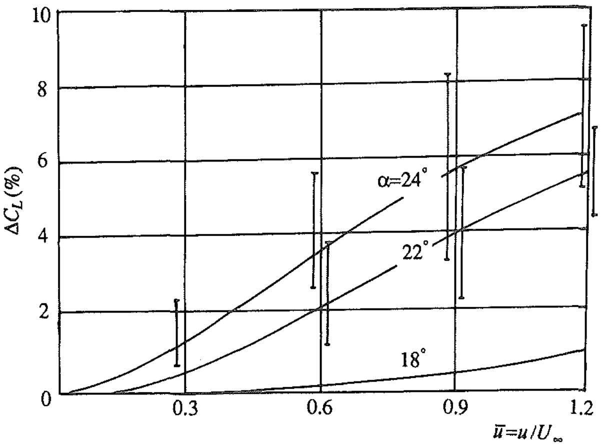


Figure 5. Lift increments caused by rotating

It follows that the influence become more and more prominent as the rotating velocity increases. The numerical simulation results given in Reference [9] indicate the variation of lift with angle of attack at higher rotating velocity (Figure 7).

The calculated pressure distribution and stream line contours shown in Figure 8 reveal very well that the main factor governing lift increase is the large peak of negative pressure at the front part of the airfoil causing by the moving surface effects of the rotating cylinder.

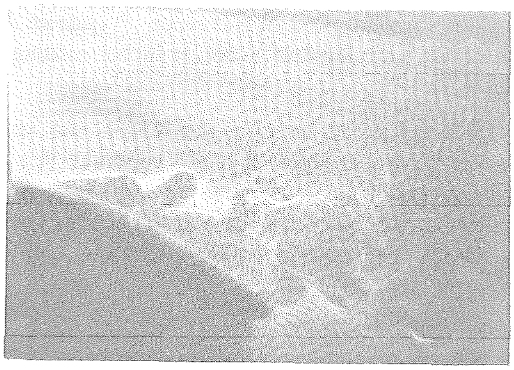
3. Oscillating flap at the leading edge

The model is set at the angle of attack α=27.5°. In that case, the flow over the model without excitation of oscillating flap is fully separated. It is found that the excitation at proper frequency (f=20HZ) makes the flow reattached and a closed separation bubble forms on the surface of the model Figure 9 demonstrates the skin friction C_f distributions along the centre line of the model for the cases with and without excitation. It shows that the separated flow reattached firstly on the rear part of the airfoil, where the C_f equals zero. We can also see that C_f is very small for unexcited case but for the excited case the magnitude of C_f in separated bubble is as large as that in attached flow.

Figure 10 presents the pressure distribution along the centreline of the model. It is clear that static pressure coefficient is nearly constant for the fully separated flow without excitations and a suction region is induced as the flow is excited at leading edge. The change of pressure distribution results in a net lift increment.

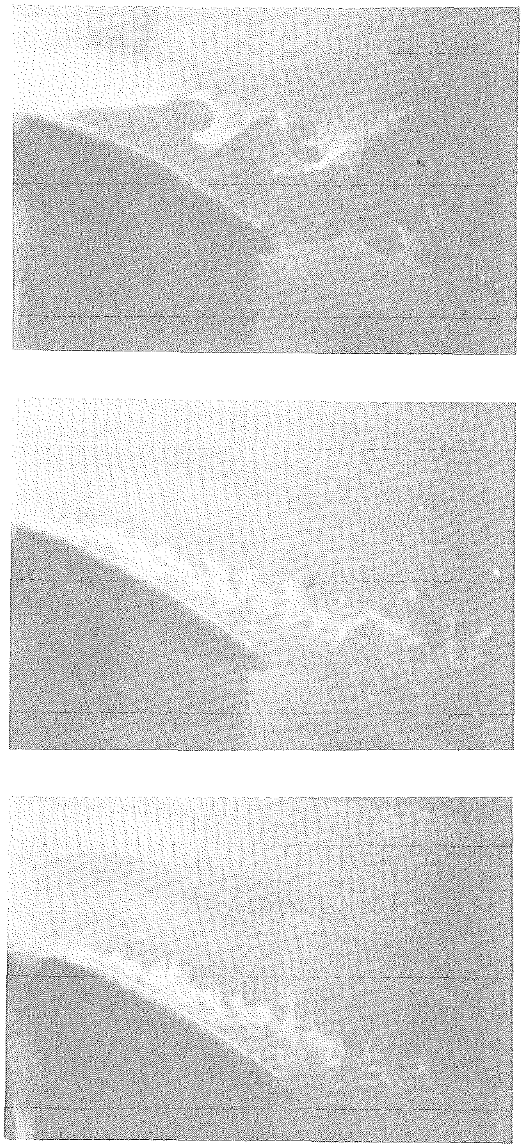
$\alpha=11^\circ$ f=0HZ

$\alpha=11^\circ$ f=11HZ



$\alpha=20^\circ$ f=0HZ

$\alpha=20^\circ$ f=12HZ



$\alpha=24^\circ$ f=0HZ (upper) f=12HZ (middle) f=18HZ (lower)

Figure 6. Flow visualization of airfoil with rotating leading edge

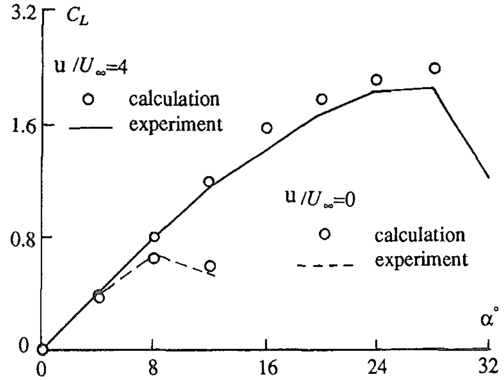


Figure 7. Variation of lift vs. α

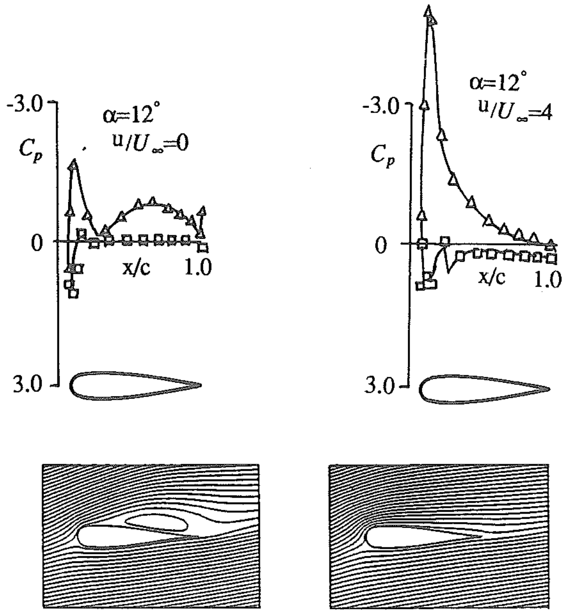


Figure 8. Pressure distribution and stream line contours

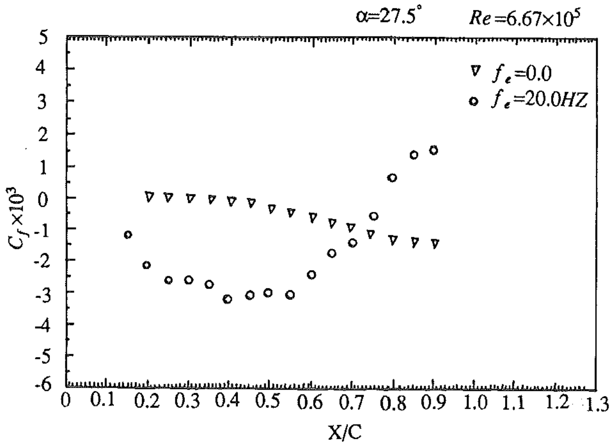


Figure 9. Skin friction C_f distribution along centre line of the model

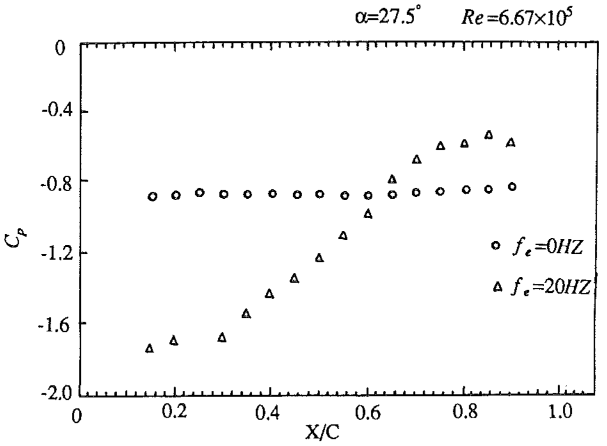


Figure 10. Pressure distribution along cetre line

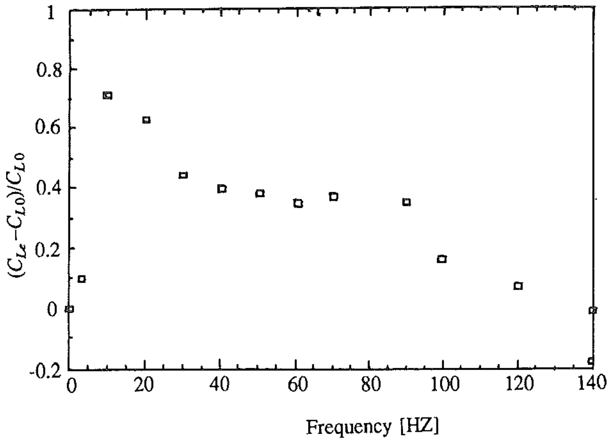


Figure 11. Variation of lift increment

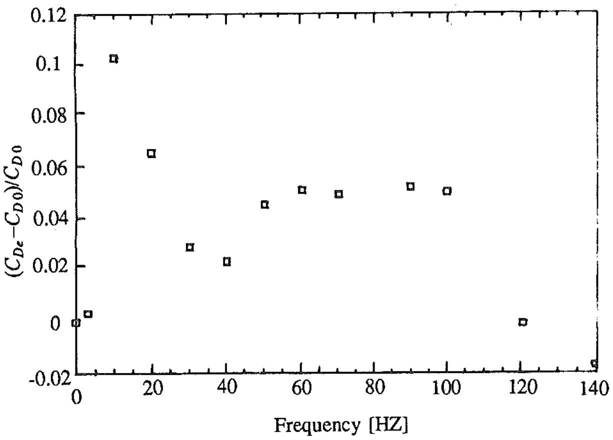


Figure 12. Variation of Drag increment

Figure 11 and Figure 12 show the variation of lift and drag increment at α=27.5° and U_∞=10m/s, respectively.

The results obtained indicate that the increment of lift is dependent on the frequency. The lift increment as high as 70% has been obtained at f=10HZ and there is a little increase in drag. The reattachment length normalized in the form X_r/c is plotted is Figure 13. It is also sensitive to

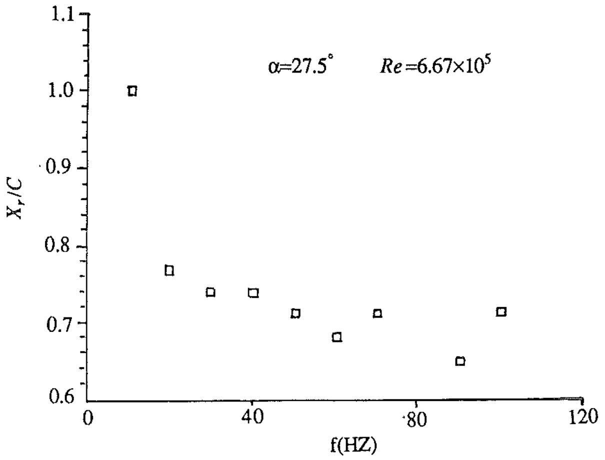


Figure 13. Rettachment length vs. frequency of excitation

the frequency of the excitations. It is found from these figures that the high lift is accompanied with big separation bubble and corresponds to high drag. These imply that the vorticity in separation bubble is important to the lift augmentation.

The effects of excitation frequency on the lift and drag of the model for various Reynolds number and angle of attack were also studied. As a example, the results of lift increment are presented in Figure 14. In this figures, the lift increment $R=(C_{Le}-C_{L0})/C_{L0}$ is normalized with the maximum lift increment $R_{\max}$, and the excitation frequency is given is non-dimensional form $\bar{f}=fc/U_\infty$.

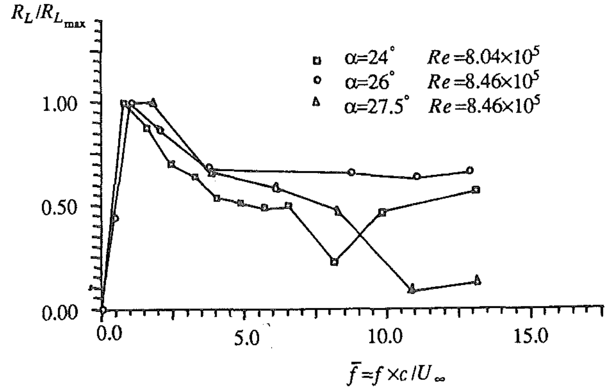


Figure 14. Effects of excitation frequency on lift for various Re.

To document the effects of the unsteady excitation on the time-averaged flow, a detailed survey was conducted by pulsed-wire anemometer at $\alpha=27.5^\circ$ and $Re_c=6.67\times10^5$ for the cases with and without excitation (f=20HZ). The normalized longitudinal mean velocity profile (U/U_∞) at two positions are shown in Figure 15. The mean velocity in the reverse flow region almost equals to zero, but for the excited case, the maximum negative velocity of reverse flow equals to -0.4 U_∞ . It may be seen that the big separation bubble and strong reverse flow over the model produce the high lift increment.

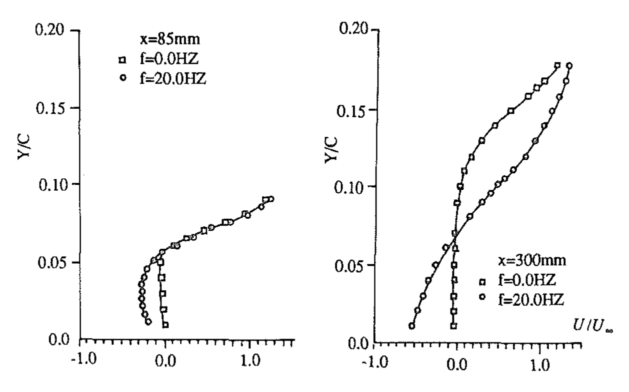


Figure 15. Longitudinal mean velocity profils

The effects of excitation on turbulence intensity level is shown in Figure 16 at the same position as given in Figure 15.

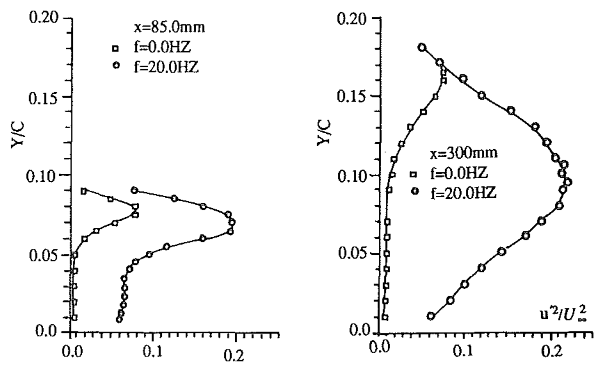


Figure 16. Effects of excitation on turbulence intensity level

In the reverse flow region for the unexcited case $\bar{u}'^2/U_\infty^2$ is equal to zero approximately, but for the excited case (f=20HZ), $\bar{u}'^2/U_\infty^2$ is as large as 15% in this region. So it can be deduced that unsteady excitations intensify the turbulent activities in the reverse flow region and separated shear layer and enhance the entrainment rates of the shear layer. Moreover, another thing to be mentioned is the location $y_{\max}$ of maximum value $(\bar{u}'^2/U_\infty^2)_{\max}$ in y direction (here y is perpendicular to the surface of the airfoil). Figure 16 indicates $y_{\max}/c=0.16$ for unexcited case and $y_{\max}/c=0.09$ for excited case at x=300mm. It shows that the shear layer bounding the reverse flow region bent with the excitation to the surface of the model.

Conclusions

From the results obtained, it is found that the unsteady excitation procedures used in these experiments are quite effective in flow control and enhancement of the lift

1. The emphasis of the unsteady excitation procedures is placed on the control of the overall flow field by means of the weak excitations with very little energy compensation to achieve remarkable aerodynamic efficiency. It is found that, at high angle of attack near or beyond the angle of static stall, appropriately selected unsteady excitations with suitable frequency and amplitude can accomplish this purpose.

2. Airfoil oscillating in pitch at high angle of attack can maintain the flow closely attached to the surface or make the separated flow reattached on the surface and produce high dynamic lift. This lift enhancement effects grow up with the increase of exciting frequency and amplitude. If the initial angle of attack is small enough, no such effects have been detected obviously in these experiments.

3. The moving surface effects of the rotating cylinder at the leading edge on the flow characteristics are caused mainly due to the delay of separation and the reduction of separated region, but, the produce of high lift is dominated by the large peak of negative pressure near the leading edge.

4. Oscillating flap at leading edge has remarkable effects on the flow around the airfoil, sometimes it can force the fully separated flow to reattach on airfoil surface, so a closed separation bubble formed on it, as a result, large lift increment will be generated. With the help of detailed measurements on the mean velocity distribution and turbulence parameters in separated flow, the mechanism of interaction between the external flow field and the separated region was studied, the results obtained are very useful for improving our understanding about the lift enhancement produced by unsteady excitations.

5. There are some problems that still remain to be solved, such as, optimal combination of the excitation parameters, three dimensional effects on flow control and the more effective means for managing and controlling the fully separated or vortex dominated flow etc. so, further research works are needed.

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