Technical Notes

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Separation Control on an Airfoil by Periodic Forcing

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Introduction

THE effect of acoustic excitation on flow over airfoils at high angles of attack has been studied by several investigators.[1-4] Ahuja and Burrin[2] have shown that acoustic excitation at the "right" frequency and sufficient amplitude can substantially increase lift at chord Reynolds numbers up to 1×10^6. Zaman et al.[3] have found that the most effective separation control is achieved at frequencies in which the acoustic standing waves that form in the test section induce transverse velocity fluctuations (rather than pressure fluctuations) in the vicinity of the airfoil. They have surmised that effective separation control can be obtained by direct introduction of velocity disturbances.

Periodic forcing of the velocity field has been shown to reduce reattachment length in laminar and turbulent flows on a number of basic geometrical configurations.[5-7] Although the mechanisms (one or more) involved are not fully understood, it is generally agreed that the large-scale vortical structures produced by forcing play a major role in enhancing mixing and entrainment, leading to reattachment. The objective of the current experiment is to investigate the effect of locally introduced transverse velocity fluctuations on flow separation over an airfoil at high angles of attack.

Experimental Method

The experiment was conducted in the NASA Langley 30×45 cm Low Speed Wing Tunnel, which is described in detail in Ref. 3. A 15 cm chord, 30 cm span model of the LRN(1)-1010 airfoil[8] was mounted horizontally in the test section at midheight. Static pressures on the airfoil were measured using surface orifices and were integrated to obtain the lift coefficient. Section drag estimates were made based on the pressure distribution acquired across the airfoil wake. A hot-wire probe was used to measure the streamwise mean and fluctuating velocity profiles as well as velocity spectra at selected chord locations.

An "oscillating-wire" technique was used in order to generate transverse velocity fluctuations. A 0.1 mm tungsten wire was located about 1.5 mm upstream and parallel to the airfoil's leading edge and was passed through horseshoe-shaped permanent magnets placed on either side outside the test section. The wire was forced to oscillate by passing an oscillating electrical current through it. The frequency of the electrical current and the tension of the wire were set so that the wire was always oscillating at its fundamental natural frequency. This provided the large amplitude required for effective control and good spanwise uniformity. However, the band of attainable frequencies was limited to the range of 55–275 Hz.

Results and Discussion

The effects of periodic forcing of the separated shear layer on the aerodynamic characteristics of the airfoil have been studied for a range of poststall angles of attack. All results shown are for a Reynolds number based on chord of 150,000. At this Reynolds number, the separating shear layer was laminar. Figure 1 shows the variation of unforced and forced lift coefficients C_l as a function of angle of attack α. The forced case represents, for each α, the best lift achieved at any combination of forcing frequency and amplitude. Increased lift has been achieved at all α shown in Fig. 1. Some improvement was observed even at $\alpha = 14$ deg where unforced separation occurs at 65% chord. Forcing increased $C_{l,\max}$ from 1.43 to 1.60 and shifted the angle of attack at which it occurs from about 11 to 20 deg. The most dramatic increase in C_l (38%) was obtained at $\alpha = 20$ deg, which is the lowest angle at which separation occurs at the leading edge. The pressure distributions on the airfoil for the unforced and best forced cases at $\alpha = 20$ deg are plotted in Fig. 2. The flat pressure distribution on the upper surface in the unforced case indicates flow separation at the leading edge. The forced case exhibits an increased suction near the leading edge and a shift in separation location to about 80% chord.

The shift in separation location at $\alpha = 20$ deg was also accompanied by a profound effect on the mean and fluctuating velocity profiles, which are presented at the 50% chord station in Fig. 3. The streamwise velocity component was measured along a coordinate y perpendicular to the freestream direction. The unforced profile is shown, up to the point where clear distortion of the hot-wire readings due to flow reversal is detected. The mean velocity profile, which exhibits a large separation region for the unforced case, undergoes large changes

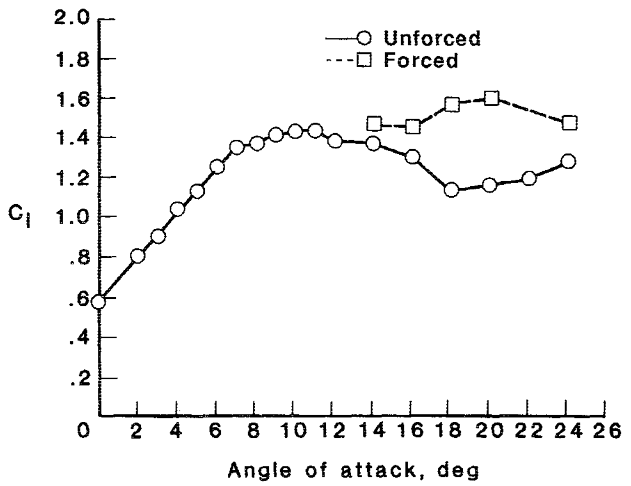

Fig. 1 Lift coefficient variation with angle of attack for unforced and best forced case ($Re = 150{,}000$).

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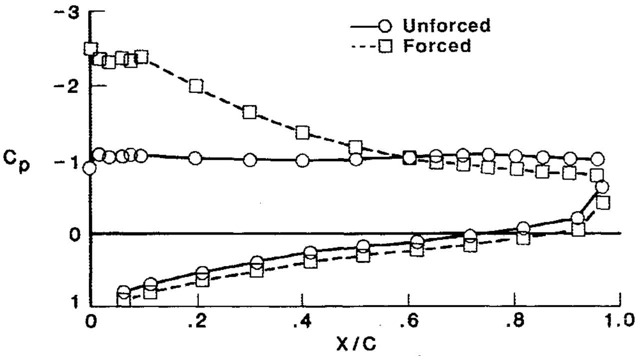

Fig. 2 Comparison of pressure distribution with and without forcing ($\alpha = 20$ deg, $Re = 150{,}000$).

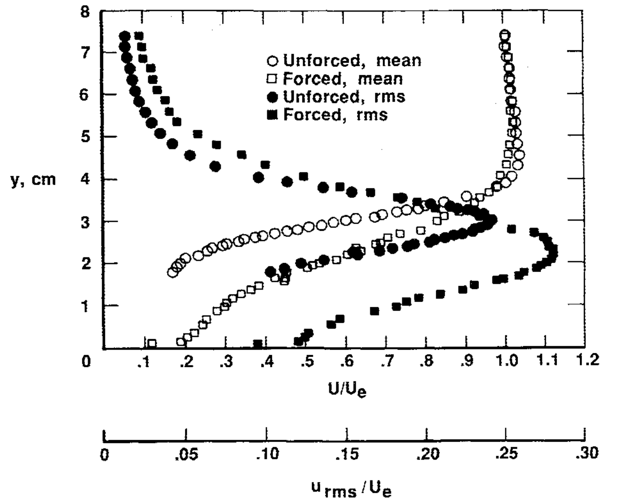

Fig. 3 Mean and fluctuation rms velocity profiles (U_e = mean edge velocity, $x/c = 0.5$, $\alpha = 20$ deg, $Re = 150{,}000$).

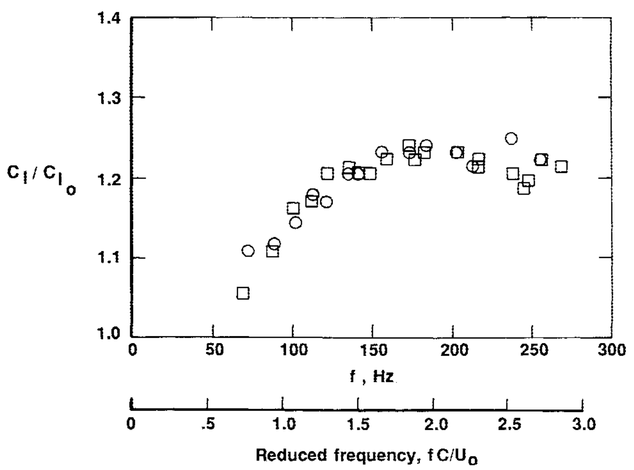

Fig. 4 Variation of lift coefficient with forcing frequency (C_{l_0} = lift coefficient for the unforced case, U_0 = mean freestream velocity, $\alpha = 20$ deg, $Re = 150{,}000$).

when forced, bringing about full attachment. Turbulence intensities as high as 25% were measured for the unforced case. The profile of turbulence intensities for the forced case shows considerable broadening of the peak as well as increased maximum value, indicating a substantial addition of energy. Velocity spectra taken at various heights at the same station for the forced case show a strong presence of the forcing frequency but no significant energy at the harmonics or subharmonics.

The effect of forcing frequency f on lift at $\alpha = 20$ deg is presented in Fig. 4. Two sets of data are plotted to show repeatability. The wire oscillation amplitude was kept constant at all forcing frequencies. A substantial drop in forced lift occurs at the low range of forcing frequencies. Note that the reduced frequency based on chord length and freestream velocity is of the order of one at this range. A possible interpretation is that forced vortical structures having a length scale of the order of the chord are too large to effectively promote attachment. Another possible explanation is that wire velocity rather than wire amplitude is the appropriate measure of forcing amplitude; since velocity is proportional to frequency, the effective amplitude decreased at lower frequencies. Also note the absence of the sharp peaks that characterize acoustic excitation results.[2,3] This provides further evidence that those peaks are the result of acoustic resonance.

Reynolds number effects were studied in the range 100,000–350,000. At $\alpha = 20$ deg, no significant changes were found in either unforced or forced lift. At lower α, however, there were increases in unforced lift as Reynolds number exceeded 150,000. This led to the choice of $\alpha = 20$ deg as the case where the bulk of the data was acquired. Reducing the extent of separation has also benefited drag. Measurements have shown that forcing can reduce drag by up to 30% at $\alpha = 20$ deg. However, the forcing amplitudes required to realize any improvement in drag were significantly higher than the amplitudes that produced lift increases. These amplitudes, unfortunately, were not attainable at all frequencies.

Conclusions

The introduction of transverse velocity fluctuations into a separated shear layer on an airfoil at high angles of attack was shown to be an effective separation control technique. The aerodynamic characteristics of the airfoil including poststall lift and drag as well as $C_{l,\max}$ and α_{stall} have all been improved. Controlled forcing at $\alpha = 20$ deg has led to increased spreading of the mean velocity profile accompanied by increased turbulence activity and has moved separation from the leading edge to about 80% chord. A wide band of forcing frequencies were found to be effective, with decreasing influence at lower frequencies.

Acknowledgments

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