Control of "Laminar Separation" Over Airfoils by Acoustic Excitation

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CONTROL OF "LAMINAR SEPARATION" OVER AIRFOILS BY ACOUSTIC EXCITATION

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Abstract

The effect of acoustic excitation in reducing "laminar separation" over two-dimensional airfoils at low angles of attack is investigated experimentally. Airfoils of two different cross sections, each with two different chord lengths, are studied in the chord Reynolds number range of 25,000 < \( R_C \) < 100,000. While keeping the amplitude of the excitation-induced velocity perturbation a constant, it is found that the most effective frequency scales as \( U_\infty^{3/2} \). The parameter \( S_t/R_C^{1/2} \), corresponding to the most effective \( f_p \) for all the cases studied, falls in the range of 0.02 to 0.03, \( S_t \) being the Strouhal number based on the chord.

Nomenclature

- \( \alpha \): angle of attack
- \( C_l \): lift coefficient
- \( c \): chord of airfoil
- \( f_{mn} \): tunnel cross resonance frequency with \( m \) sound pressure nodes in \( y \), and \( n \) sound pressure nodes in \( z \)
- \( f_p \): excitation frequency
- \( L_r \): sound pressure level at reference microphone location
- \( R_C \): chord Reynolds number
- \( S_t \): Strouhal number, \( f_p c/U_\infty \)
- \( U,V \): mean velocities in \( x,y \) directions, respectively
- \( \langle U \rangle \): mean velocity measured with a single hot wire approximating \( (U^2 + V^2)^{1/2} \)
- \( U_\infty \): freestream \( U \)
- \( u',v',w' \): rms velocity fluctuations in \( x,y,z \) directions; subscript \( r \) denotes values at reference location
- \( \langle u' \rangle(f) \): one-dimensional spectrum of \( u' \)
- \( \langle u',u'_2 \rangle \): rms total and fundamental fluctuation in the direction of \( \langle U \rangle \), as measured by a single hot wire
- \( \langle u'_r \rangle \): \( (u_r^2 + v_r^2)^{1/2} \)
- \( x' \): streamwise distance from leading edge
- \( x,y,z \): streamwise, transverse, and spanwise coordinates

Introduction

Several experiments have demonstrated that artificial excitation can reduce the tendency towards separation in the flow over an airfoil and thereby improve its performance.\(^1\) The separation process, and the effect of excitation thereupon, has been noted to be different depending on the ranges of the angle of attack and the Reynolds number.\(^5\) While at all \( R_C \) the flow separates ultimately at large \( \alpha \) (poststall), an unsteady separation may occur around the static stall condition.\(^5\) At sufficiently low \( R_C \) on the other hand, extensive separation on the suction side may take place even at low \( \alpha \). This is accompanied by a rapid deterioration of the airfoil performance with decreasing \( R_C \), approximately in the range \( R_C < 100,000 \).

The low \( \alpha \) separation at \( R_C = 40,000 \) is illustrated in Fig. 1 by visualization pictures taken from Ref. 5. Note that the flow on the upper surface is separated for all the lower \( \alpha \)’s but has reattached at the highest \( \alpha \), presumably due to earlier transition of the separated shear layer in that condition. Stability analysis, carried out in Ref. 5, indicated that the boundary layer prior to separation for the low \( \alpha \) cases must be stable and thus laminar. The flow separation at the low \( \alpha \) and low \( R_C \) is simply referred to in the following as "laminar separation". The effect of excitation on this separation is the focus of the present study.

In the references cited above, the effect of artificial excitation has been studied mostly for poststall conditions. References 2, 3, and 5 provided some data showing that acoustic excitation can also reduce the extent of the laminar separation. However, the excitation data in all previous studies covered only limited parametric ranges. Much of the data were of demonstration type and insufficient to address the scaling of the effective excitation parameters in any of the situations described above.

The purpose of the present experiment is to gain a better understanding of the excitation effect, specifically focusing on the laminar separation. The principal objective is to determine the envelopes of excitation frequencies effectively reducing the separation. The experiment is designed to cover a wide excitation frequency range, and the available parametric ranges are explored systematically. Airfoils of two different cross-sectional shapes having different stalling characteristics, each with two different chords, are tested. The tunnel resonant frequencies, as will be addressed further, are given reasonable consideration. The effect on the lift coefficient is used as the primary diagnostic for assessing the influence of the excitation. The scaling of the effective frequency envelopes is then analyzed. Details of the flow field for a specific excitation case are also studied in comparison with the corresponding unexcited flow field.
The experiments are carried out in the NASA Lewis Low Speed Wind Tunnel, which has been described in detail elsewhere. It has a test section with 75- by 51-cm cross section. The freestream turbulence intensity is less than 0.1 percent. Two-dimensional models of a LRN-(1)-1007 and a Wortmann FX 63-137 airfoils are used. For each type, two models with chords 12.7 and 25.4 cm are employed. The airfoils are supported at midchord and span the entire test section. Figure 2(a) is a photograph of the test section fitted with the c = 12.7 cm LRN airfoil.

A schematic of the test section is shown in Fig. 2(b). Two acoustic drivers (Altec Lansing 291-16K: rated 0.5 to 20 kHz) and a 40.6 cm woofler (Altec Lansing 515-8G: rated 40 Hz to 4 kHz) were mounted on the ceiling. Even though the amplitude fell off, the woofler could be used for excitation at f_p < 700 Hz, as low as 15 Hz. The sound from the woofler entered the test section through a 30.5 cm diameter opening. The opening was covered with a 64-mesh screen. The sound from the acoustic drivers entered the test section via 3.8 cm holes in the ceiling. For all data presented, only one speaker was used at a time; for f_p < 700 Hz the woofler was used, for f_p > 700 Hz one of the acoustic drivers was used.

A 1/4-in (B & K) microphone, flush mounted on the ceiling, was used to measure a reference sound pressure level (L_r). A crossed hot-film probe (DISA 55R53) was used to measure velocity fluctuation amplitudes (u' and v'). The probe, at the reference location, can be seen in Fig. 2(a). The DISA 55R53 probe was replaced by a DISA 55R54 probe to determine the correlation of the velocity field around the airfoil. The coordinate origin is at the tunnel midheight (y = 0) and the streamwise coordinate (x') for some data has been referenced to the airfoil leading edge.

Results and Discussion

C_l versus α for the c = 12.7 cm LRN airfoil is shown in Fig. 3(a) for various R_c. The cross section of the airfoil is shown by the inset in the figure. Note that the curves are staggered. For R_c > 35 000, the C_l curves are marked by a "sag" at low α. This is due to the laminar separation. Note that at relatively higher α, the airfoil recovers to the high lift condition due to reattachment of the flow occurring naturally (Fig. 1). This occurs presumably due to the earlier transition of the separated shear layer at the higher α, the exact mechanism remains unclear. Note that the sag in the C_l curve becomes more pronounced at lower R_c. At R_c = 25 000, the flow remains separated throughout the α range, and the airfoil completely loses its efficiency in producing high lift.

Essentially the same behavior is observed with the Wortmann airfoil (Fig. 3(b)). Note that complete separation commences at R_c = 50 000 in this case. Another difference is in the stall characteristics. The Wortmann clearly shows stall hysteresis while the LRN does not in the same wind tunnel environment. The Wortmann airfoil is of the "leading edge stall" type whereas the LRN airfoil is approximately of the "trailing edge stall" type. In the following, attention is focussed on the laminar separation at low α; all subsequent data are for α = 6°.

Figure 4 shows the Reynolds number effect on C_l of the two airfoils. Clearly, laminar separation persists up to R_c = 60 000 for the LRN airfoil, and up to R_c = 75 000 for the Wortmann airfoil. While these data are for the c = 12.7 cm models, the jump to the higher C_l occurred at somewhat higher R_c with the c = 25.4 cm models. Note that the jump in the C_l, associated with the elimination of the laminar separation, does not involve hysteresis even for the Wortmann airfoil.

The tunnel resonance characteristics were documented by measuring the reference velocity and sound pressure amplitudes while exciting the flow with the loudspeakers. The LRN airfoil at α = 6° was in the flow with R_c = 50 000. The woofer was used for f_p < 700 Hz and one acoustic driver for f_p > 700 Hz. The input voltage to each speaker was held constant. L_r and the reference velocity amplitudes were measured while f_p was varied in discrete steps. These data are shown in Fig. 5.

The u' data show that longitudinal resonances are set up at the lower end of the f_p range covered. The 23 Hz peak ought to correspond to half wave resonance involving the entire length of the tunnel. The 59 Hz peak must be the half wave resonance corresponding to the length of the test section on either end of which the cross-sectional area diverges. Resonances at several higher harmonics of 59 Hz also occur in the u' data. Note that the induced v' and w' at these lower f_p's are essentially equal to the freestream amplitudes. The freestream amplitudes (without excitation) have been shown at 10 Hz; these amplitudes are somewhat underestimated due to noise from the anemometer circuitry.

The fundamental cross resonance in the y direction occurs around 342 Hz. Note that v' is very large at this frequency, but u' is practically zero. (Thus, a single hot wire at the reference location would fail to sense this resonance.) Several peaks occur in the v' data, notably at 570 Hz, 995 Hz, 1400 Hz, etc. The frequencies of the cross resonances at low Mach number are given by:

\[ f_{mn} = \frac{a_0}{2\left[(mH)^2 + (nH)^2\right]^{1/2}} \]

where m and n are integers, H and W are the height and the width of the test section, respectively, and a_0 the speed of sound.

Note that with the given orientation of the loudspeakers, little w' fluctuation is induced. The woofer fails to excite the fundamental cross resonance in the z direction, which if induced should have marked the w' data by a peak around 224 Hz. Note also that for constant voltage input to the speakers the SPL, L_r, is strongly affected by especially the cross resonances. Here, let us mention that data similar to those in Fig. 5 were also obtained in the empty tunnel with the airfoil taken out but with all other conditions remaining.
constant. Essentially similar variations for the major resonance peaks were observed, except that the amplitudes were somewhat lower.

The \( u' \) and \( v' \) amplitudes were measured as a function of \( y \) (with the airfoil in), at \( z = 0 \) and the reference \( x \) location, for a few resonant frequencies. These are shown in Fig. 6(a). Corresponding spanwise variations of the amplitudes, at the reference \( x \) and \( y \), are shown in Fig. 6(b). These data indicate that the \( u' \) amplitude at 59 Hz is approximately constant over the entire cross section. Data at a few other low \( f_p \)'s (\(<280 \text{ Hz}, \text{ not shown}\)) also showed similar uniform amplitudes.

For \( f_p \) = 342 Hz and higher the \( v' \) data exhibit expected nodal patterns, which can also be used to identify the specific cross resonance modes. Thus, the frequencies 342, 570, and 688 Hz can be identified as the \( f_{31}, f_{32}, \) and \( f_{20} \) modes, respectively. 995 Hz appears to correspond to the effective \( f_{32} \) mode from the \( v' \) distribution, but the frequency computed from the equation of \( f_{mn} \) differs significantly. The difference remains unexplained; however, one should note that the tunnel conditions are different from those of an idealized resonating duct, especially in view of the presence of the airfoil.

The excitation amplitude effect on various parameters is documented in Fig. 7(a). \( C_l \) versus \( L_f \) data are shown in the bottom graph. For the flow under consideration, the most pronounced effect on \( C_l \) occurs in the \( f_p \) range of 116 to 342 Hz. Corresponding variations in \( u' \) and \( v' \), with \( L_f \) are shown on the top of Fig. 7(a). Note that at 116 and 253 Hz, \( u' \) is large and \( v' \) is essentially zero while the reverse is true for 342 Hz. Yet the flow is influenced at each frequency in a consistent pattern. This indicates that inducing either velocity component upstream of the leading edge is equally effective in the excitation of the flow.

Referring back to Figs. 5 and 6, note that for a given \( f_p \), either \( u' \) is large and \( v' \) is small or vice versa. For the study of excitation frequency effect, it was desirable to keep a particular component of the velocity amplitude in the incoming flow a constant. However, because of the resonances it would be impossible to achieve that in a wind tunnel. Since inducing either \( u' \) or \( v' \) seemed to have the same effect, it was decided that the resultant \( \sqrt{u'^2 + v'^2} \) would be kept constant for the subsequent data. For the lower \( f_p \)’s (\(<280 \text{ Hz}\)), this reasonably approximated the condition where \( u'_2 \) was held constant in the incoming flow over the entire tunnel cross section. For the specific modes like \( f_{10} (=342 \text{ Hz}), f_{30} (=1026 \text{ Hz}), \) etc., this approximated a constant \( v' \) near the leading edge over the entire span of the airfoil. At other \( f_p \)'s the amplitude can be expected to be nonuniform along the span. However, it should be obvious that \( u' \) at the chosen reference location should be a much more meaningful amplitude parameter than a velocity amplitude elsewhere or the SPL anywhere in the tunnel.

\( C_l \) versus \( \sqrt{u'^2 + v'^2} \) are cross plotted in Fig. 7(b). The corresponding value of \( \sigma_{C_l} \) turns out to be about 0.78.
Figure 11 shows the boundary layer mean velocity ((U)) profiles at various streamwise locations on the upper surface of the airfoil. Note that the curves are staggered laterally, but for each x', the pair of profiles with and without excitation are shown with the same scale. For each profile, the bottommost data indicate the location of the airfoil surface. Clearly, the excitation reduces the size of the latter, and reattachment is achieved up to about 50 percent chord location. However, it is clear that for this case complete reattachment has not occurred and there exists a separated region even with the excitation.

Estimates of the boundary layer momentum thickness, θ, were obtained from these data. The integration was truncated at the point where (U) was 20 percent of local (U) maximum, to avoid contribution from the erroneous data in the separated region. The integration was truncated at the other end at 95 percent (U) maximum point. (Note that this way θ is reasonably measured in the boundary layer at the upstream locations; however, it is underestimated for the separated shear layer as the momentum defect in the reversed flow is not taken into account.) θ (mm) for three x' locations are listed below. The Reynolds number and the Strouhal number of excitation, based on θ at x'/c = 0.3, for the unexcited flow, turn out to be 79 and 0.012, respectively.

\[
\begin{align*}
\text{x'/c} & \quad \theta, \text{Unexcited} & \quad \theta, \text{Excited} \\
0.3 & \quad 0.2 & \quad 0.28 \\
0.5 & \quad 0.27 & \quad 0.28 \\
0.7 & \quad 0.47 & \quad 0.47 \\
\end{align*}
\]

The fluctuation intensity profiles in the boundary layer corresponding to the data of Fig. 11 are shown in Fig. 12. Note that with the excitation the total fluctuation intensity is reduced somewhat at all stations. The fundamental amplitudes show that the instability wave, for the case documented, grows perceptibly beyond 50 percent chord location (discussed further in the following).

Figure 13 shows the (u') spectra in the boundary layer at transverse locations where (U) is 70 percent of the local (U) maximum. At this transverse location the fundamental fluctuation intensity is approximately the maximum. It is apparent that the amplitude of the peak at 253 Hz ((u')) starts growing substantially beyond the 50 percent chord location. At 80 percent chord location, the evolution of a subharmonic is apparent (dashed curve). Further downstream the spectral peaks are lost beneath the broadband turbulence. It is also evident that the effective excitation frequency closely matches the natural instability in the corresponding unexcited flow as apparent from the pairs of spectra at 60 and 70 percent chord locations.

The fundamental amplitude growth along the 70 percent velocity point was measured for three fp's, and are shown in Fig. 14. The inset shows variations of the amplitudes upstream, not covered in the main figure, but along a constant height (y) passing through the 70 percent velocity point at x'/c = 0.2. Note that the reference amplitude (u') was held constant at 0.5 percent of U,. However, at 342 Hz, only u' is induced upstream of the leading edge, u' being very small. Thus, the measured amplitude (u') there is small since the single hot wire primarily senses the amplitude in the direction of the mean flow. As the leading edge of the airfoil is approached u' for 342 Hz becomes large, even larger than the amplitudes for the other two fp's.

Downstream of the leading edge the amplitude variations show standing wave patterns, reminiscent of the acoustically excited boundary layer data of Ref. 11. This occurs due to the interference of the excited instability wave and the exciting acoustic wave when the amplitudes due to the two are comparable. The wavelength of the standing wave should exactly equal the shorter hydrodynamic (instability) wavelength (λ). λ for the third fp's were obtained from Fig. 14; λ and fp provided the phase velocity of the instability wave. These quantities and the Strouhal number based on θ at x'/c = 0.3 are listed below.

\[
\begin{align*}
fp & \quad λ/c & \quad λfp/U_\infty & \quad fpθ/U_\infty \\
168 & \quad 0.14 & \quad 0.51 & \quad 0.008 \\
253 & \quad 0.10 & \quad 0.55 & \quad 0.012 \\
342 & \quad 0.077 & \quad 0.57 & \quad 0.016 \\
\end{align*}
\]

Further downstream, one observes that the amplitude at 168 Hz grows to the largest value. This appears anomalous as, referring back to Fig. 8, 253 Hz is found to be the center frequency in the band of effective fp's. This results in a significant improvement in the lift coefficient. It is inferred from data with airfoils of two cross-sectional shapes, each with two different chords, that the optimum effect occurs when the parameter St/Re½, corresponding to the excitation frequency, falls in the range of 0.02 to 0.03. Detailed flow field data recorded for a specific case, indicate that a separated region still exists under the excitation, and the amplification of the imposed perturbation takes place in the downstream shear layer rather than in the upstream boundary layer.

Conclusion

Small amplitude acoustic excitation at an appropriate frequency can effectively reduce laminar separation occurring on the suction side of airfoils at low α and low Re. This results in a significant improvement in the lift coefficient. It is inferred from data with airfoils of two cross-sectional shapes, each with two different chords, that the optimum effect occurs when the parameter St/Re½, corresponding to the excitation frequency, falls in the range of 0.02 to 0.03. Detailed flow field data recorded for a specific case, indicate that a separated region still exists under the excitation, and the amplification of the imposed perturbation takes place in the downstream shear layer rather than in the upstream boundary layer.

References


FIG. 1 - SMOKE-WIRE FLOW VISUALIZATION PICTURES FOR VARIOUS $\alpha$ FOR LRN AIRFOIL ($c = 10.2$ cm) AT $R_C = 4 \times 10^6$. REF. [5].
FIG. 2(a) - PHOTOGRAPH OF WIND TUNNEL TEST SECTION. (b) - SCHEMATIC OF TEST SECTION; DIMENSIONS ARE IN CENTIMETERS.
FIG. 3(a) - $C_1$ VERSUS $\alpha$ FOR $c = 12.7$ cm LRN AIRFOIL AT VARIOUS $R_c$. ORDIANATE APPLIES TO BOTTOM CURVE, OTHERS ARE STAGGERED SUCCESSIVELY BY ONE DIVISION. SOLID CURVES FOR INCREASING $\alpha$, DASHED CURVES FOR DECREASING $\alpha$. (b) - $C_1$ VERSUS $\alpha$ FOR $c = 12.7$ cm WORTMANN AIRFOIL.
FIG. 4 - $C_1$ VERSUS $R_C$ AT $\alpha = 6^\circ$ FOR THE TWO AIRFOILS; $c = 12.7$ cm.
FIG. 5 - REFERENCE AMPLITUDE PARAMETERS VERSUS $f_p$. HOT-WIRE AT $x = -11.4$ cm, $y = 1.27$ cm, AND $z = 0$; MICROPHONE LOCATED AS SHOWN IN FIG. 2(b). $c = 12.7$ cm LRN AIRFOIL AT $\alpha = 6^\circ$ WITH $R_c = 50,000$. 
Fig. 6(a) - $u'$ and $v'$ amplitudes versus $y$ measured at $x = -11.4$ cm and $z = 0$, for indicated $f_p$'s. Same flow as in Fig. 5. (b) - $u'$ and $v'$ amplitudes versus $z$ measured at $x = -11.4$ cm and $y = 1.27$ cm.
FIG. 7(a) - EXCITATION AMPLITUDE EFFECT ON $C_g$ AT INDICATED $f_p$'S. REFERENCE $u_f$ AND $v_f$ VERSUS $L_f$ SHOWN ON TOP. SAME FLOW AS IN FIG. 5.
(b) - $C_g$ DATA OF FIG. 7(a) CROSS PLOTTED AS A FUNCTION OF $(u_f^2)$. 
FIG. 8(a) - $C_l$ VERSUS $f_p$ FOR THE LRN AIRFOILS AT $\alpha = 6^0$; $(u'_c)/U_{\infty} = 0.005$. ORDI NATE APPLIES TO THE BOTTOM CURVE. OTHERS ARE STAGGERED SUCCESSIVELY BY TWO DIVISIONS. SOLID LINES FOR $c = 12.7$ cm MODEL. DASHED LINES FOR $c = 25.4$ cm MODEL. (b), (c), (d) - DATA REPLOTTED AS A FUNCTION OF INDICATED ABS CISSAE.
FIG. 9 - $C_L$ VERSUS $f_p$ DATA, AS IN FIG. 8, FOR THE WORTMANN AIRFOILS.
FIG. 10 - $\langle U \rangle$ VERSUS $x'$ MEASURED AT CONSTANT $y$: $y = 1.65$ cm for the upper two curves, $y = -1.4$ cm for the lower two curves. Solid line, no excitation; dashed line, excitation at $f_D = 253$ Hz with $\langle u'_x \rangle / U_\infty = 0.005$. LRN airfoil at $\alpha = 6^0$, $R_c = 50 000$.

FIG. 11 - BOUNDARY LAYER PROFILES OF $\langle U \rangle$ AT DIFFERENT $x'$ FOR THE SAME FLOW AS IN FIG. 10. SOLID LINES FOR UNEXCITED FLOW. DASHED LINES FOR EXCITATION AT $f_D = 253$ Hz AND $\langle u'_x \rangle / U_\infty = 0.0025$. ABSCISSA APPLIES TO PAIR ON LEFT, OTHERS ARE SHIFTED TO THE RIGHT SUCCESSIVELY BY ONE MAJOR DIVISION.
FIG. 12 - R.M.S. AMPLITUDE PROFILES CORRESPONDING TO THE DATA OF FIG. 11. SOLID LINE, TOTAL \( u' \) FOR THE UNEXCITED FLOW; SHORT DASHED LINE, TOTAL \( u' \) FOR THE EXCITED FLOW; LONG DASHED LINE, FUNDAMENTAL \( u_1 \) FOR THE EXCITED FLOW. SUCCESSIVE SET OF CURVES SHIFTED TO RIGHT AS IN FIG. 11.

FIG. 13 - \( \langle u' \rangle \) - SPECTRA IN THE BOUNDARY LAYER AT 70% VELOCITY POINT. SOLID LINE, FOR UNEXCITED FLOW; DASHED LINE, FOR EXCITATION AT \( f_0 = 253 \) Hz, \( \langle u_1' \rangle / U_\infty = 0.0025 \). ORDI-NATE APPLIES TO BOTTOM PAIR, OTHERS STAG-GERED SUCCESSIVELY BY TWO DIVISIONS.
FIG. 14 - \( \langle u' \rangle \) VERSUS \( x' \) MEASURED ALONG 70\% VELOCITY POINT ON THE UPPER SURFACE FOR INDICATED \( f_p \)'s. SAME FLOW AS IN FIG. 10: \( \langle u' \rangle / U_\infty = 0.005 \).
Control of "Laminar Separation" Over Airfoils by Acoustic Excitation

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The effect of acoustic excitation in reducing "laminar separation" over two-dimensional airfoils at low angles of attack is investigated experimentally. Airfoils of two different cross sections, each with two different chord lengths, are studied in the chord Reynolds number range of $25\,000 < R_e < 100\,000$. While keeping the amplitude of the excitation induced velocity perturbation a constant, it is found that the most effective frequency scales as $U_e^{1/2}$. The parameter $St/R_e^{1/2}$, corresponding to the most effective $f_e$ for all the cases studied, falls in the range of 0.02 to 0.03, $St$ being the Strouhal number based on the chord.

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