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Delay of Airfoil Stall by Periodic Excitation

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It was recently demonstrated that oscillatory blowing can delay separation from a symmetrical airfoil much more effectively than the steady blowing used traditionally for this purpose. Experiments carried out on different airfoils revealed that this flow depends on many parameters such as, the location of the blowing slot, the steady and oscillatory momentum coefficients of the jet, the frequency of imposed oscillations, and the shape and incidence of the particular airfoil. In airfoils equipped with slotted flaps, the flow is also dependent on the geometry of the slot and on the Reynolds number in addition to the flap deflection that is considered as a part of the airfoil shape. The incremental improvements in single element airfoil characteristics are generally insensitive to a change in Reynolds number, provided the latter is sufficiently large. The imposed oscillations do not generate large oscillatory lift nor do they cause a periodic meander of the c.p.

Nomenclature

C_d, C_D = airfoil total drag coefficient
C_{dp} = airfoil pressure drag coefficient
C_L, C_l = airfoil lift coefficient
$C_{L,\max}$ = maximum lift coefficient
$C_{L,0}$ = lift coefficient at $\alpha = 0$ deg
C_p = pressure coefficient
$\langle C_p \rangle$ = phase-locked pressure coefficient
C_μ = combined blowing momentum coefficient, $\equiv(c_\mu, \langle c_\mu \rangle)$
c = airfoil chord
c_{f1} = flap chord
c_μ = steady blowing momentum coefficient, $\equiv J/q{*}c = 2(H/c){*}(U_j/U_\infty)^2$
$\langle c_\mu \rangle$ = oscillatory blowing momentum coefficient, $\equiv 2(H/c){*}(\langle u' \rangle_f/U_\infty)^2$
F^+ = dimensionless frequency, $\equiv(f{*}x_{te})/U_\infty$
f = predominant frequency of the imposed oscillations, Hz
H = slot height
J = mean jet momentum near the nozzle exit, $\equiv \rho U_j^2 H$
M = 10^6 on some figures
M_n = Mach number
q = freestream dynamic pressure, $1/2\rho U_\infty^2$
R_c = chord Reynolds number, $U_\infty c | \nu$
U_j = average exit velocity of the jet, $\int_0^\infty U_J \, dy$
U_∞ = freestream velocity
u' = rms of the streamwise component of the velocity fluctuations
$\langle u' \rangle_f$ = phased-locked rms amplitude of the streamwise component of the velocity fluctuations
X_{cp} = c.p. location
x/c = normalized streamwise location
x_{te} = distance between the actuator and the trailing edge
α = airfoil angle of attack, deg
$\alpha_{\max}$ = α corresponding to $C_{L,\max}$
δ_f = flap deflection, deg
λ = wavelength of the oscillatory blowing
ϕ = phase of the oscillatory blowing

Introduction

BOUNDARY-LAYER separation entails great energy losses and limits the performance of most flow-related devices. It imposes severe limitations not only on the design, but the operation of any device handling fluid or moving in it. Thus, the control of separation or at least its mitigation is always of concern in engineering applications. Geometrical shaping, turbulators, and passive transpiration through slots and slats are the most commonly used in aeronautics to delay separation. Active transpiration is scarce. It is mostly limited to steady blowing in military applications because of the complexity of the systems and their large power requirements. The control of separation is being continuously and extensively investigated because of its large potential payoff and its numerous applications, and therefore its state of the art is periodically reviewed[1] and discussed in conferences.[2]

We realized long ago that jet entrainment can be used beneficially to enhance the lift generated by airfoils.[3,4] We also knew that large coherent structures could enhance the entrainment by transporting momentum effectively across a shear layer.[5] We therefore had the notion that the combination of a jet and periodic motion might be a very effective tool for boundary-layer control.[6] This is so because the introduction of periodic motion accelerates and regulates the generation of large coherent structures, particularly when the mean flow is unstable to the imposed periodicity. Since the effectiveness of the method is largely determined by the receptivity of the flow to the imposed disturbances, these have to be of the right scale and be introduced at the right location. Flexibility is provided by superposing relatively strong oscillations on weak steady blowing, which can vary according to need. The periodic input contributes to the overall momentum and has to be accounted for.

There are many parameters governing the total C_μ required to control the flow over an airfoil whenever oscillatory blowing is used: 1) the ratio between the steady and the oscillating components of the added momentum; 2) the frequency of the oscillations, expressed as a ratio between their characteristic wavelength and a typical length of the separated region; 3) the location of the actuator; 4) the shape, thickness, and attitude of the airfoil as well as the dimensions of the flap and its deflection angles, will all determine the prevailing pressure gradient and the momentum deficit in the boundary layer both upstream and

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downstream of the actuator; 5) the Reynolds number and Mach number of the flow; and 6) some secondary considerations depending on the complexity of the airfoil and the blowing system (e.g., the precise geometric position of a slotted flap on a multielement airfoil or the slot geometry).

The control of separation encompasses two distinct problems: first is the prevention of separation and second is the imposition of reattachment. The control of each requires different inputs and different optimal procedures. In this article we shall only discuss the prevention of separation that occurs as a consequence of increasing incidence, or of decreasing the Reynolds number at a fixed incidence. If we clearly understand the entire parameter space and the modes of interaction among them, then we would like to prevent separation at all flow conditions by the means at our disposal.

The purpose of the present research is to determine the most important dimensionless parameters scaling the flow and affecting the performance of airfoils, to identify the leading ones and optimize them. For this reason we considered a variety of airfoils varying in thickness ratio, camber, and flap deflection. We even considered a multielement airfoil having a slotted trailing edge flap.[7] We altered the mechanisms used for control from mechanical devices to oscillatory blowing,[6,8] we altered the location of the blowing slots on the airfoils to assess the significance of the various lengths and velocity scales involved,[6,9] and we checked the effects of roughness and forced transition[9] on the performance. We also altered the frequency and amplitude of the periodic excitation and the steady momentum added to the flow in an orderly manner. Finally, we attempted to probe some details of the flow that up to now had not been investigated, such as the coherent (phase-locked) velocity, the fluctuating lift, and the periodic motion of the c.p.[10] All of the experiments reported were done in incompressible Mach numbers. Some effects of compressibility were also investigated and will be reported elsewhere.[11]

Brief Description of the Experiments

Tests were carried out on four airfoils at chord Reynolds numbers ranging from 1.5×10^{-1} to 1.2×10^{6} at speeds ranging from 6.4 to 51 m/s. The first airfoil tested was the symmetric NACA 0015 airfoil equipped with a trailing-edge flap equivalent to 25% of its chord (Fig. 1). Thereafter all experiments were carried out on cambered airfoils: an 11% thick Eppler E-214 airfoil having a flap of 30%, a 19% thick PR8-40 airfoil (developed by Israel Aircraft Industries) having a 30% chord trailing-edge slotted flap, and an 18.3% blunt trailing-edge airfoil whose upper-trailing surface was inclined to the chord at 45 deg.

Oscillatory blowing was added to the boundary layer through thin slots machined in the surface of the airfoils. The location of the actuators is marked on Fig. 1. Most of the slots are approximately 1 mm thick and are located on the upper surface at the flap–knee. One slot was located at the leading edge of the NACA 0015 airfoil to determine the most appropriate length scale to be used in reducing the frequency of excitation. The oscillations on the slotted PR8-40 airfoil emanated also from two alternative locations: one from the trailing edge of the main element while the other was from the leading edge of the flap. In this airfoil we wanted to determine the effect of the passive blowing, occurring between the main element and the flap, on the effectiveness of the location from which the perturbations are introduced.

The wind tunnel, the oscillatory blowing apparatus, the calibration procedure, and the measuring techniques are described in earlier articles,[6,9] therefore only some additions and alterations will be discussed. The oscillatory component of the jet momentum was redefined from being based on the maximum amplitude[6] of the velocity oscillations to being based on their rms value.[9] Thus, the total momentum coefficient is presently given by the simple sum of $(c\mu + \langle c\mu \rangle)$ rather than $(c\mu + 0.5\,\langle c\mu \rangle)$ as defined in Ref. 6.

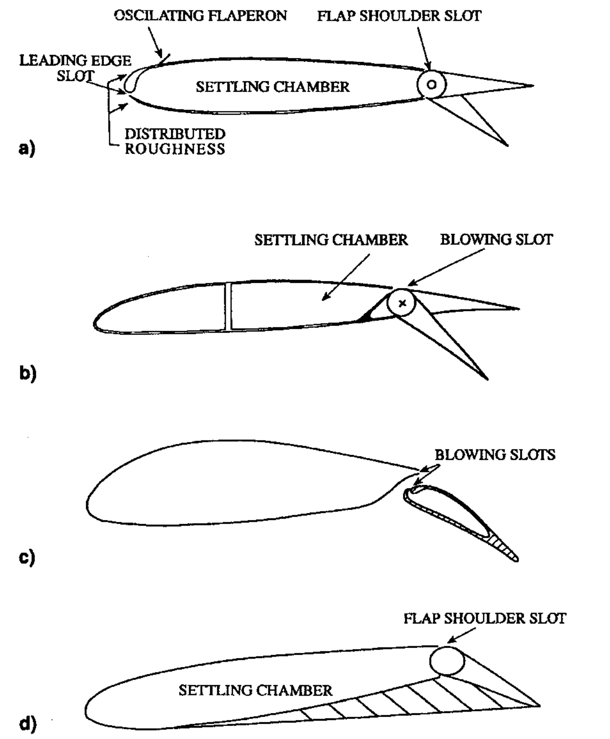

Fig. 1 Sketch of the airfoils tested: a) NACA 0015, b) E214F, c) PR8-40, and d) SPCA-1.

Coarse, randomly distributed (equivalent sand) roughness was placed on some surfaces to trip and thicken the boundary layer in some experimental runs. Instantaneous pressure distributions on an entire surface or airfoil were measured by using a multichannel, digital pressure scanner (model PS-4000) manufactured by A.A. Lab Systems. This instrument can sample data at an aggregate rate of 400,000 samples/s. Since each transducer is connected to a pressure tap by a tube, the attenuation of each frequency within the range of interest had to be accounted for. This required an in-situ calibration of the instrument. The phase shift between adjacent channels was negligible. Thus, the use of this instrument enabled us to correlate between the input oscillation and the pressure distribution on the airfoils and surfaces investigated.

Discussion of Results

Blowing over the Flap or from the Leading Edge of a NACA 0015 Airfoil

In the early stages of concept evaluation, sinusoidal perturbations were introduced by placing a vibrating ribbon on the upper surface of the airfoil.[8] It was immediately apparent that the method worked at stall and poststall angles of attack, mitigating separation, and increasing the maximum lift generated by the airfoil. The power consumed by the system activating the flaperon was surprisingly small.[8,12] We understood that we could easily prove the conceptual efficiency of the system by deploying it over a trailing-edge flap. Since our airfoil was outfitted with blowing slots for boundary-layer control, we endeavored to generate the oscillations internally and switch from the mechanical flaperon to oscillatory blowing. We also expected that oscillatory blowing would provide an additional flexibility not possible in conjunction with mechanical devices, i.e., the superposition of steady blowing on the imposed oscillation. The rationale for the addition of steady blowing stems from the fact that the amplification and the propagation velocity of the imposed fluctuations will change with the addition of steady motion, however weak. Proper understanding of the flow can enable us to maximize the intensity of the perturbations at the location at which the boundary layer is about to separate. These results are presented in Ref. 6, but some relevant data are used presently for the sake of comparison.

The efficiency of the oscillatory blowing emanating from the flap–shoulder slot when the NACA 0015 flap was deflected at 20 deg to the chord may be deduced from Fig. 2, where the dependence of the lift coefficient on incidence (Fig. 2a) is plotted together with the form–drag polar (Fig. 2b). The basic airfoil characteristics at this flap deflection are accentuated in this plot. A steady blowing at $c_\mu = 0.8\%$, which is also modulated at $\langle c_\mu \rangle = 0.8\%$ [i.e., total $C_\mu = (0.8\%, 0.8\%)$], at $F^+ = 2$ shifted the entire lift curve upwards by $\Delta C_L = 0.65$ prior to stall and by $\Delta C_L = 0.9$ at α_{max} of the basic configuration. This represents an increase of 64% in $C_{L,max}$ (Fig. 2a). The form-drag was eliminated by this oscillatory blowing at incidences corresponding to $0.7 < C_L < 1.5$ (Fig. 2b). The introduction of pure oscillations at $F^+ = 2$ had the most profound effect on the total drag, which was reduced by a factor of 3.6 (i.e., to 28% of its basic value), at $C_L = 1$ (Fig. 2c). Comparable drag reductions were observed at all lift coefficients smaller than $C_{L,max}$ because the base flow over the flap was separated even at an incidence corresponding to $C_L = 0$. Changing the endurance factor or the glide ratio at $C_L = 1$ by more than 300% at a total $\langle c_\mu \rangle = 0.8\%$ is no small feat. Replicating this form–drag polar by steady blowing required a total $C_\mu = 0.1$, i.e., a factor of 6.25 larger (Fig. 2b). Experiments similar to the ones described previously were repeated at various flap deflections, Reynolds numbers, and blowing intensities. The additional observations were qualitatively similar, with some effects accentuated at the larger flap deflections.[6]

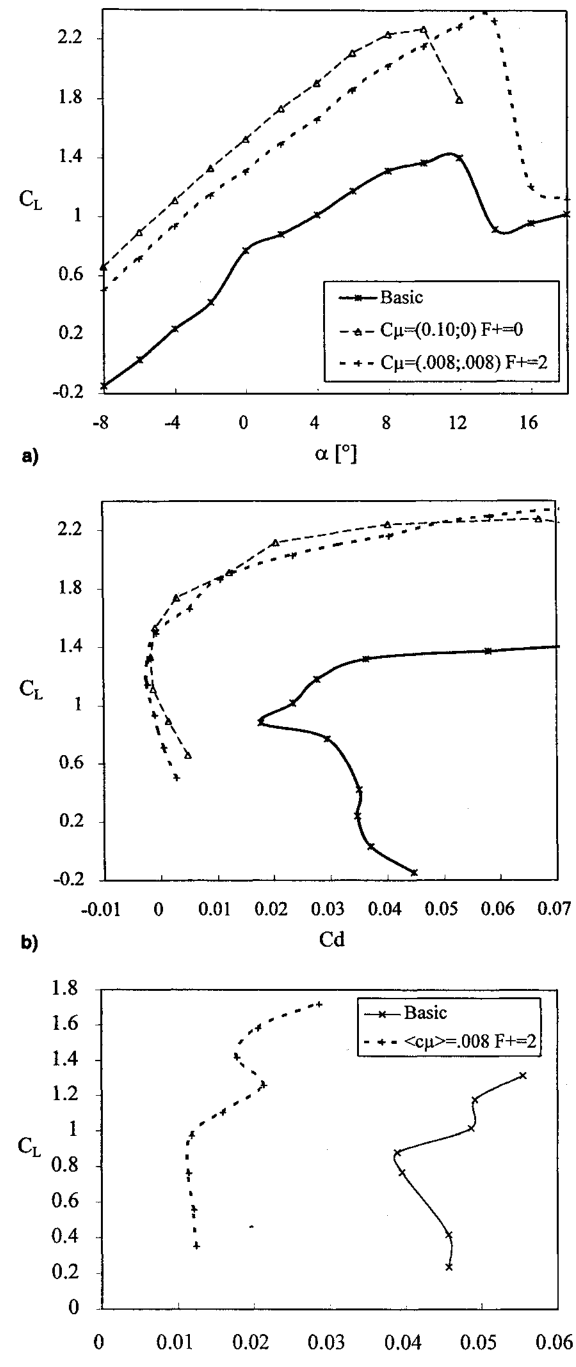

Fig. 2 **Effect of steady and/or oscillatory blowing on the a) C_L of the NACA 0015 airfoil, b) the C_L-form drag polar, and c) the $C_L - C_d$ polar.**

The complex dependence of C_L on C_μ and on F^+ may stem from its dependence on the length over which an attached flow has to be maintained at a prescribed incidence and flap deflection. For example, we used $F^+ = f^* c_{flap}/U_\infty$ when only the flow over the flap was separated. Clearly, when $\alpha > \alpha_{max}$ and separation occurred near the leading edge, the length of the flap became irrelevant since the eddies generated by the excitation did not reach the separation occurring far upstream. Perhaps the definition of F^+ should have been modified to contain a variable length scale corresponding to the length of the naturally separated region over the airfoil or the length of the separation bubble. If the location of the actuator corresponds to the location at which separation occurs, one may use x_{te} instead. To test this hypothesis we used the blowing slot located near the leading edge of the airfoil and tested the effects of the oscillations at $\alpha > \alpha_{max}$, mostly without flap deflection. The results presented in Fig. 3 prove that in spite of the differences in geometry the length suggested to scale the frequency is the correct one. It appears that only a small number of eddies, perhaps no more than two, should reside at any instant over the previously separated region. Thus, to maintain the same reduced frequency during the present experiment and the one described previously,[6] the actual frequencies imposed at identical airfoil Reynolds numbers were four times lower.

One may assess the effect of c_μ and $\langle c_\mu \rangle$ on the lift by setting the airfoil at a prescribed attitude (corresponding to poststall condition), and increasing either the intensity of steady blowing or the amplitude of the oscillations issuing from the leading edge at a prescribed F^+, independently. In the example chosen (Fig. 4), steady blowing at the leading edge had no effect on C_L unless $c_\mu > 1.5\%$. One may double the value of C_L at this attitude by increasing $c_\mu > 3\%$; the same lift might have been achieved by oscillatory excitation emanating from the same location at values of $\langle c_\mu \rangle$, which are between one to two orders of magnitude smaller. Such a reduction in the momentum required to improve

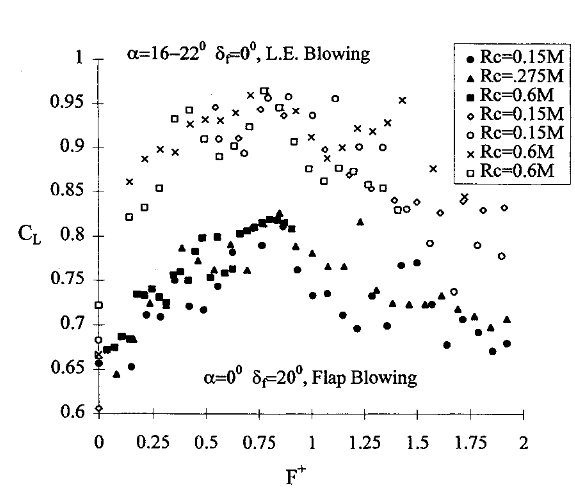

Fig. 3 **Effect of $F^+ = f^*(c - X_{sep})/U_\infty$ on ΔC_L, X_{sep} is streamwise location of separation, NACA 0015: leading edge, open symbols; flap–knee, filled symbols.**

the lift of an airfoil by the same amount may not always be achievable, but the relative efficiency of the oscillatory blowing in eliminating separation is very attractive. It should also be mentioned that distributed roughness had no adverse effect on the incremental lift gained by the excitation.[9] It was also observed that an increase in R_c (an increase of four-fold was tested) resulted at times in an enhanced effectiveness of the oscillatory blowing whenever the imposed oscillations could be amplified by the boundary-layer instability upstream of the separation point. However, taking advantage of this process requires a careful optimization.

The efficiency of the active control method depends on the location at which it is applied whenever one prescribes all the other dimensionless variables of significance (i.e., R_c, δ_f, F^+, c_μ, $\langle c_\mu \rangle$). It turns out that blowing from the shoulder of a deflected flap is much more effective than blowing from the leading edge, provided the flow separates from the flap and not from the main body of the airfoil. For example, superposition of oscillations on the mean blowing emanating from the leading edge at $(C_\mu)_{LE}$ = (0.8%, 0.8%) caused a partial attachment of the flow to the flap leading to a moderate increase in C_L at small α and a delay of 2 deg in α_{max} (Fig. 5). Application of the same C_μ to the flap–shoulder increased the basic C_L by 0.7 at small α, and also increases α_{max} by 2 deg while generating a substantial difference in $\Delta C_{L,max}$ relative to the basic airfoil [i.e., $\Delta C_{L,max} = 0.9$ resulting in $(\Delta C_L/C_{L,0})_{max} = 0.64$]. It required approximately a four-fold increase in both steady and oscillatory components of C_μ to obtain the same increment in $\Delta C_{L,max}$ by blowing from the leading edge instead of the flap–shoulder (Fig. 5). Thus, only a strong blowing [C_μ = (3.2%, 2.7%)] from the leading edge could

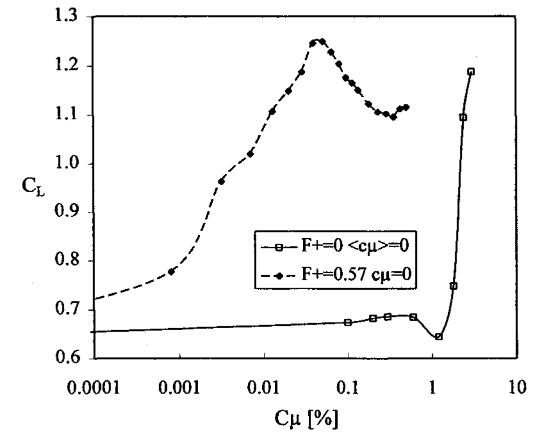

Fig. 4 Effects of c_μ and $\langle c_\mu \rangle$ on C_L of the NACA 0015 at α = 22 deg, δ_f = 0 deg, and $R_c = 0.3 \times 10^6$.

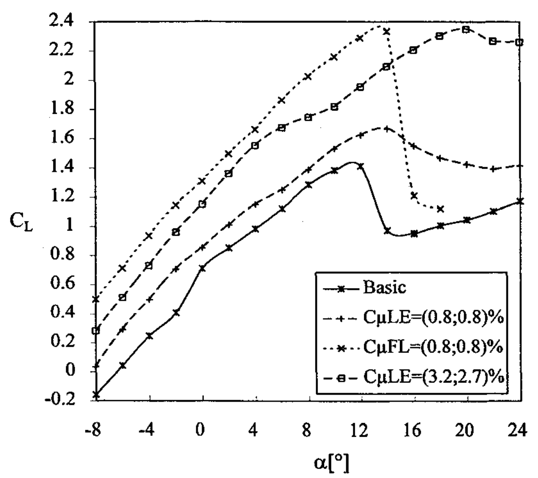

Fig. 5 Comparison between control applied from the leading and flap–knee (effect on lift of the NACA 0015).

overcome the pressure gradient over the high-attitude airfoil. In the case shown the attachment was maintained only up to α = 4 deg, as deduced from the pressure distribution over the flap. The much weaker blowing from the flap–shoulder (i.e., at ~25% of the c_μ introduced at the leading edge) maintained attached flow at the trailing edge resulting in a much higher lift (i.e., $\Delta C_L = 0.35$), even at α = 10 deg. One may argue that the length used in the definition of C_μ should be based on the distance between the slot and the trailing edge. A definition on this basis would have reduced the discrepancies between results at the two locations, but not have eliminated them (Fig. 5), and it would have created confusion with regard to the momentum input required. We thus left the classical definition[3] unaltered, although it is clear that the chord is not the appropriate length scale in this case.

The strong blowing from the leading edge increased the lift (in comparison to the basic airfoil) at small α, but the slope $(dC_L/d\alpha)$ was not constant even at $\alpha < \alpha_{max}$ (Fig. 5). Between $6 < \alpha < 10$ deg the flap stalled and $(dC_L/d\alpha)$ decreased. The strong oscillatory blowing from the leading edge maintained the flow partially attached to the upper surface up to α = 20 deg, whereupon $C_L > 2.3$. Thus, the airfoil with blowing from the leading edge stalls very gently without losing much lift as α increases beyond α_{max}. This is in clear contrast to the stall encountered with blowing from the flap–shoulder, where C_L dropped abruptly from 2.3 to 1.2. The abrupt drop in C_L is a result of an upstream movement of the separation point from the flap–shoulder to the leading edge.

Instantaneous pressure distributions enabled us to assess the dynamic effects of the imposed periodic oscillations on the airfoils. For the case shown in Fig. 6, the oscillations were introduced from the leading edge of the NACA 0015 at α = 22 deg. The pressure distribution (Fig. 6a) in the absence of the imposed oscillations over the airfoil is marked by a solid line, while the dotted line represents the average pressure realized by their presence. The difference between these two curves reflects the differences in the measured C_L discussed previously (Fig. 5).

A separate plot of the phase-locked pressure fluctuations about the mean is provided (Fig. 6b) to show more clearly the presence of at least two large coherent structures at every phase of the imposed oscillation at $F^+ = 1.1$. A typical wavelength of the large eddies (the size of their footprint in the x direction) is effectively doubled during their travel above the upper surface of the airfoil. Furthermore, the addition of steady blowing increases the streamwise wavelength of the forced oscillations. This is consistent with the visual observations suggesting that the large eddies generated above a solid surface resemble the large coherent structures observed in the classical mixing layer generated between two parallel streams. Since the frequency of the pressure fluctuations is constant throughout, the phase velocity of these eddies must increase in the direction of streaming so that their wavelength will also increase with X. The increase of propagation speed of the dominant eddies with X is contrary to the decrease in the ambient velocity above them and the concomitant increase in the average pressure (Figs. 6a and 6b). Thus, the use of U_∞ in the definition of F^+ is somewhat arbitrary. The scale of the large eddies also suggests that they transport momentum in Y as effectively as they do in X. This might be associated with a rapid thickening of the boundary layer and may violate Prandtl's boundary-layer approximations.

The amplitude of the pressure oscillations above the upper surface of the airfoil decreased with increasing streamwise distance and essentially vanished near the trailing edge (Fig. 6b). The amplitude of the pressure oscillations along the entire lower surface of the airfoil was negligible. The robustness of the physical interpretation of the Kutta condition, requiring that the freestream velocities above and below the surface be equal at all phases of the imposed oscillation, is worth noting. The addition of tangential blowing at otherwise identical con-

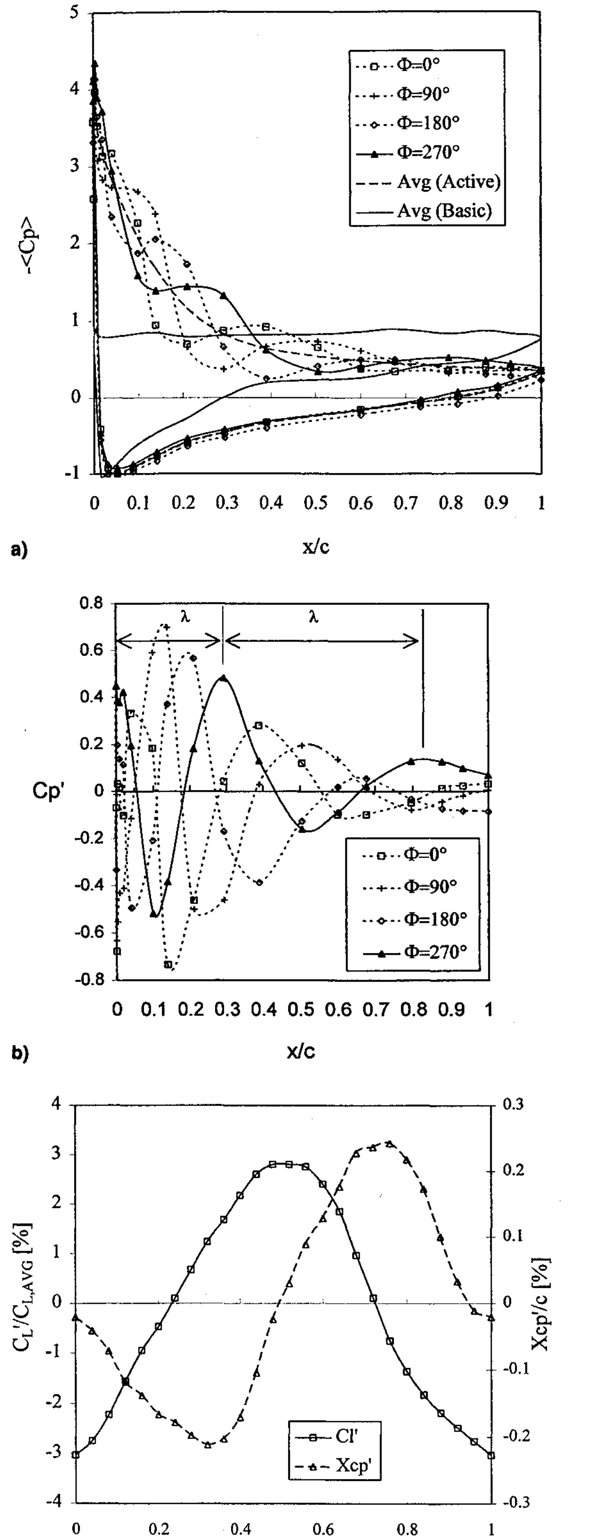

Fig. 6 NACA 0015 phase locked data, α = 22 deg, δ_f = 0 deg, R_c = 0.15 × 10^6, F^+ = 1.1, and C_μ = (0:1.3%). Phase-locked a) pressure distributions, b) pressure fluctuations, and c) lift and c.p. fluctuations.

ditions affects the amplitude and wavelength of the pressure oscillations, but since it also affects the mean pressure gradient it is difficult to separate the cause from the effect.

The practical implication of the presence of two or more eddies above the surface of the airfoil is that the integration of the instantaneous pressure distributions did not result in major oscillations of the normal force or in the location of the c.p. Typical oscillations in the lift and the location of the c.p. are plotted in Fig. 6c. The rms variations of C_L are approximately 3%, resulting in the rms excursions of the c.p. of 0.2% of the chord in the absence of steady blowing.

Experiments on the Eppler E-214 Airfoil

The NACA 0015 is a moderately thick, uncambered airfoil, having $C_{L,\max} \approx 1$ at $\delta_f = 0$ deg. It is used almost exclusively on struts, but not on wings. We therefore wanted to compare our experience on this airfoil with results obtained on a lifting airfoil used on wings. The E-214 is 11% thick and has a long fetch of laminar flow on its suction surface. It was equipped with a 30% flap (Fig. 1).

The flapped configuration at δ_f = 20 deg provided a $C_{L,\max}$ = 1.65 at α = 10 deg and R_c = 2 × 10^5 (Fig. 7). The flap deflection tripled C_L at α = 0 deg from being 0.38 to 1.17, but thereafter ($dC_L/d\alpha$) decreased as a result of a partial separation over the flap upper surface. A pure oscillatory blowing over the flap at $\langle c_\mu \rangle$ = 0.3% provided an additional ΔC_L = 0.44, making $C_{L,0}$ = 1.61. Adding a steady blowing of equal momentum [i.e., making C_μ = (0.3%, 0.3%)] did not improve the performance by much, while it required a pure steady blowing of c_μ = 3% to outperform the oscillatory blowing at $\langle c_\mu \rangle$ = 0.3% (Fig. 7). More impressive perhaps, is the concomitant decrease in total drag with increasing $\langle c_\mu \rangle$. An example plotted in Fig. 8 for R_c = 4 × 10^5 and at α = 8 deg indicates a decrease in C_d of 40% (i.e., from 0.056 to 0.033) by switching on the oscillations and increasing their amplitude to $\langle c_\mu \rangle$ = 0.34%. Thus, oscillatory blowing over a thin cambered airfoil having a cambered flap is also very effective, particularly at low incidence.

Active Control of Separation on a Slotted, Thick Airfoil (I.A.I. PR8-40)

The efficiency of thick airfoils is significantly reduced at low R_c because of flow separation. The separation creeps up from the trailing edge on the upper surface with increasing incidence. To stop this process, slots are introduced in the aft section of the airfoil. The high-momentum flow emerging from the slot mixes with the sluggish boundary-layer flow above it, making it more resistant to separation. The amount of momentum needed to overcome the strong adverse pressure gradient at high flap deflections is never sufficient, and this deficiency is exacerbated by viscous effects at low R_c.

In this section we shall describe some experiments carried out on a slotted airfoil, PR8-40, designed by the Israel Aircraft Industries to operate at $R_c > 6 \times 10^5$ (Fig. 1c). The airfoil was

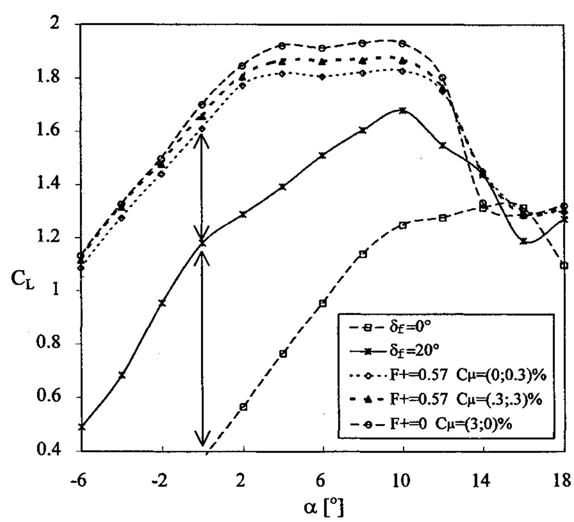

Fig. 7 Increase in lift caused by active control over a 20-deg deflected flap of Eppler 214 airfoil, R_c = 0.2 × 10^6.

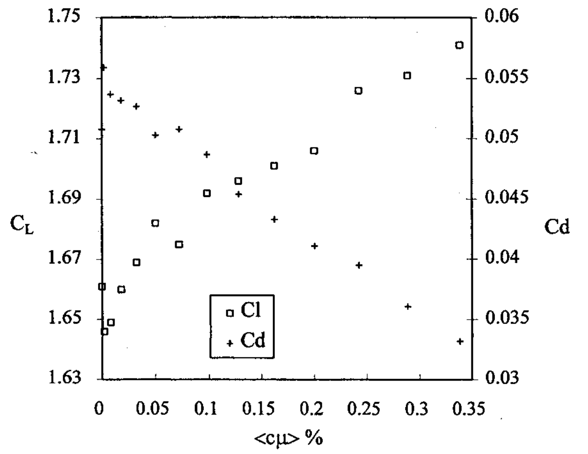

Fig. 8 Increase in C_L and the decrease in C_d with increasing $\langle c_\mu \rangle$ on the Eppler 214. $\alpha = 8$ deg, $\delta_f = 20$ deg, $R_c = 0.4 \times 10^6$, $F^+ = 0.7$, and $c_\mu = 0.3\%$.

19% thick and the flap was deflected at angles of 15–40 deg while the Reynolds numbers varied between 1.4×10^5 and 6×10^5. The main purpose of the experiment was to recover the lift lost because of separation over the flap as a consequence of lowering R_c below its designed value and to explore the optimum location for introducing these oscillations.[7] The oscillations interacting with the flow through the slot could emanate from two places: one from the trailing edge of the main element and the other from the leading edge of the flap (Fig. 1c).

The data shown in Fig. 9 indicate that it is much more effective to introduce the oscillations from the top surface of the flap than from the trailing edge of the main element. The lift coefficient increased from 1.9 to 2.5, whereas the corresponding drag coefficient decreased from 0.125 to 0.06 when $\langle c_\mu \rangle = 0.015\%$ was introduced on the flap. It required a $\langle c_\mu \rangle = 0.07\%$ to generate a comparable C_L and a $\langle c_\mu \rangle \geqq 0.25\%$ to generate a comparable glide ratio (C_L/C_d, see Fig. 9), when the perturbations were introduced from the trailing edge of the main element. In the latter case, the oscillations enhanced the mixing between the wake of the main element and the potential flow above it, while the perturbations introduced from the flap interacted first with the new boundary layer initiated by the flow through the slot.

An increase in C_L is invariably associated with a decrease in C_d and vice versa. This observation was made on other airfoils as well, regardless of the location and form of the actuator. Periodic forcing emanating from the flap at $\langle c_\mu \rangle = 0.12\%$ causes, in this case, a second separation of the flow over the flap, reducing C_L and increasing C_d approximately to their unforced levels (Fig. 9). This is an indication that a stronger oscillatory $\langle c_\mu \rangle$ emanating from the flap surface enhances the mixing sufficiently to bring in the low momentum fluid of the wake of the main element to the surface of the flap, restoring separation. A much larger $\langle c_\mu \rangle$ is required (i.e., 0.32%) to restore the same glide ratio that was attained at $\langle c_\mu \rangle = 0.02\%$. In the latter case, the strong periodic motion is capable of bringing in high-momentum fluid existing in the potential flow above the upper surface of the main element. The efficiency of blowing from the surface of the flap must therefore depend on the gap between the two elements of the airfoil and on the overlap between them. A large gap will require a higher $\langle c_\mu \rangle$ before the wake of the main element will interact with the boundary layer generated on the upper surface of the flap.

Three pressure distributions measured on the surface of the airfoil, with and without excitation at $\langle c_\mu \rangle = 0.02\%$ for perturbations emanating from the two slot locations, are plotted in Fig. 10. The flow over the flap was completely separated without the oscillations and was mostly separated when the oscillations emanated from the main element. The flow was fully attached when identical $\langle c_\mu \rangle$ was applied along the flap surface, the minimum pressure coefficient C_p over the leading edge of the flap was -2, and it decreased steeply to -0.1 near the flap trailing edge. The performance of the entire airfoil was greatly improved because of the increased suction over the entire upper surface as a consequence of the flow reattachment over the flap.

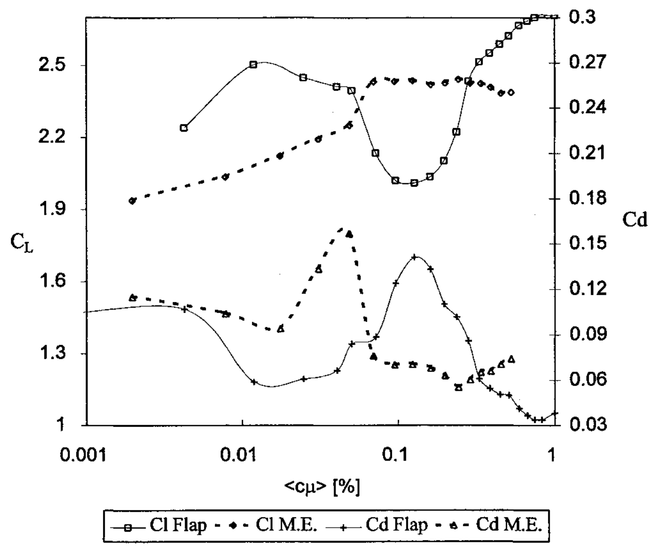

Fig. 9 Effect of $\langle c_\mu \rangle$ on C_L and C_d on a slotted airfoil, the IAI PR8-40. $R_c = 0.2 \times 10^6$, $F^+ = 2$, $\alpha = 8$ deg, and $\delta_f = 30$ deg.

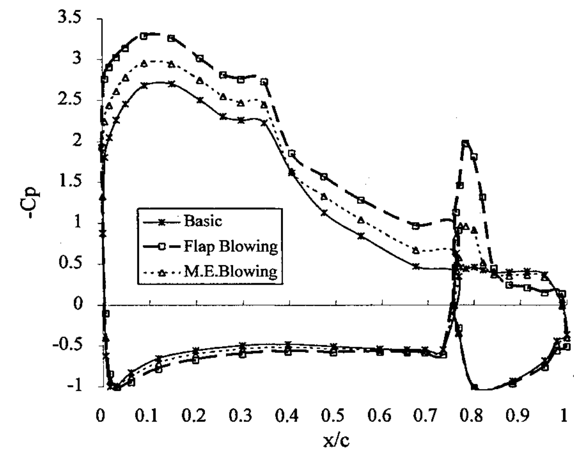

Fig. 10 Upstream effect of oscillatory blowing flow control on $-C_p$ of the IAI PR8-40. $R_c = 0.2 \times 10^6$, $F^+ = 2$, $\alpha = 8$ deg, $\delta_f = 30$ deg, and $\langle c_\mu \rangle = 0.02\%$.

The dependence of the maximum lift generated by this airfoil on R_c is plotted in Fig. 11 for a flap deflection of 30 deg. The maximum lift generated by the airfoil was reduced from $C_L = 3$ to $C_L = 1.9$ when R_c decreased from 6×10^5 to 1.4×10^5. Placing a transition strip (a 5-mm-wide strip containing grit no. 100) at the flap leading edge caused a partial recovery of the lift at $R_c > 2 \times 10^5$, but it failed to help at lower Reynolds numbers. Forced oscillations are capable of maintaining the design C_L in the low R_c range.

The efficiency of the oscillatory blowing was again demonstrated by its ability to create an attached flow over the flap with $\langle c_\mu \rangle = 0.015\%$ rather than the $c_\mu = 1\%$, which was needed to achieve a similar result by using a steady blowing from the same slot (Fig. 12). The natural separation over this airfoil having a flap deflected at $\delta_f < 35$ deg occurred over the main element, at moderate R_c. It was initiated at its trailing edge and at $\alpha_{max} = 10$ deg, it was stabilized around the midchord of the main element, even at the design R_c. The introduction of os-

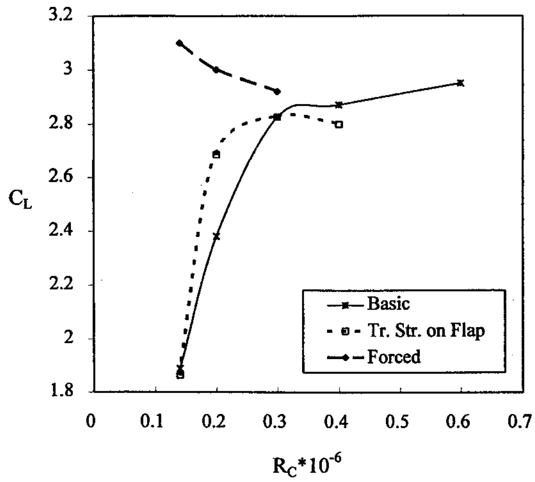

Fig. 11 Dependence of the IAI PR8-40 $C_{L,\max}$ on R_c for basic flow condition, tripped boundary layer over the flap and controlled flow (flap blowing).

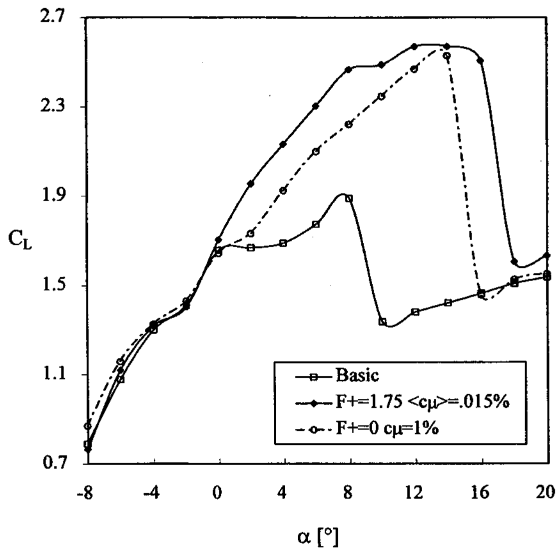

Fig. 12 Comparison of the effect of oscillatory and steady blowing on the lift of the IAI PR8-40 airfoil at low R_c. δ_f = 30 deg and $R_c = 0.14 \times 10^6$.

cillations by using a flaperon attached to the main element increased $\alpha_{\max}$ to 16 deg and increased the maximum lift generated by the airfoil.

Thus, oscillations in general, and oscillatory blowing in particular, were effective in controlling separation over slotted airfoils. It may require extensive optimization to apply the system to a complex airfoil because it will have to tie together the detailed geometry of the airfoil and Reynolds number, to the oscillatory input parameters consisting of amplitude, frequency, and the location from which the oscillations emanate.

Aerodynamic Characteristics of an SPCA-1 Airfoil

Active control was beneficial on existing airfoils whenever the incidence or flap deflection exceeded its optimum limits, resulting in flow separation. It would be desirable to design very thick airfoils whose effectiveness would rely on active control and whose performance at a prescribed R_c would sufficiently exceed the performance of existing airfoils to warrant the added complication. This is a difficult task because the parameters defining the control of separation are not well known and the analytical design tools are missing. We created a new airfoil by deflecting the flap of the NACA 0015 airfoil to 40 deg and attaching a flat plate to the lower surface that spanned the gap between the trailing edge of the flap and the lower contour of the airfoil at x/c = 23% (Fig. 1d). The airfoil became 18.3% thick and the closing angle between the upper and lower surface was approximately 44 deg. Oscillatory blowing emanating from the original flap–knee was used for flow control.

The flow separated from the upper surface at x/c = 0.75, even at negative incidence. The positive camber of the airfoil was of no help because of the massive separation, and even at α = 0 deg the flow left the trailing edge inclined upwards, generating a negative $C_L = -0.18$ (Fig. 13a). The stagnation point was at the leading edge and the pressure coefficient on the upper surface continuously decreased from $C_p = 1$ at the leading edge to $C_p = -0.5$ at $x/c > 0.8$. Deep stall occurred at α = 16 deg, where $C_{L,\max} = 1.3$, at $R_c = 0.15 \times 10^6$. The basic lift slope of the airfoil was independent of R_c. Weak steady blowing at c_μ = 0.8%, over the blunt upper surface did not increase C_L between $0 < \alpha < 12$ deg; it only increased $C_{L,\max}$ and $\alpha_{\max}$ (Fig. 13a). The introduction of oscillations at F^+ = 0.75 and $\langle c_\mu \rangle$ = 0.8% increased C_L at α = 0 deg by 0.6. Although partial separation from the blunt trailing surface occurred at α = 8 deg, the lift continued to increase attaining a $C_{L,\max}$ = 1.8 at α = 20 deg. Repeating the same experiment at F^+ = 2 did not alter $C_{L,0}$, but it prevented the occurrence of the partial stall at α = 8 deg and maintained a more constant $(dC_L/d\alpha)$ until α = 20 deg, achieving $C_{L,\max}$ = 2. More significant perhaps is the halving of the form drag (Fig. 13b) caused

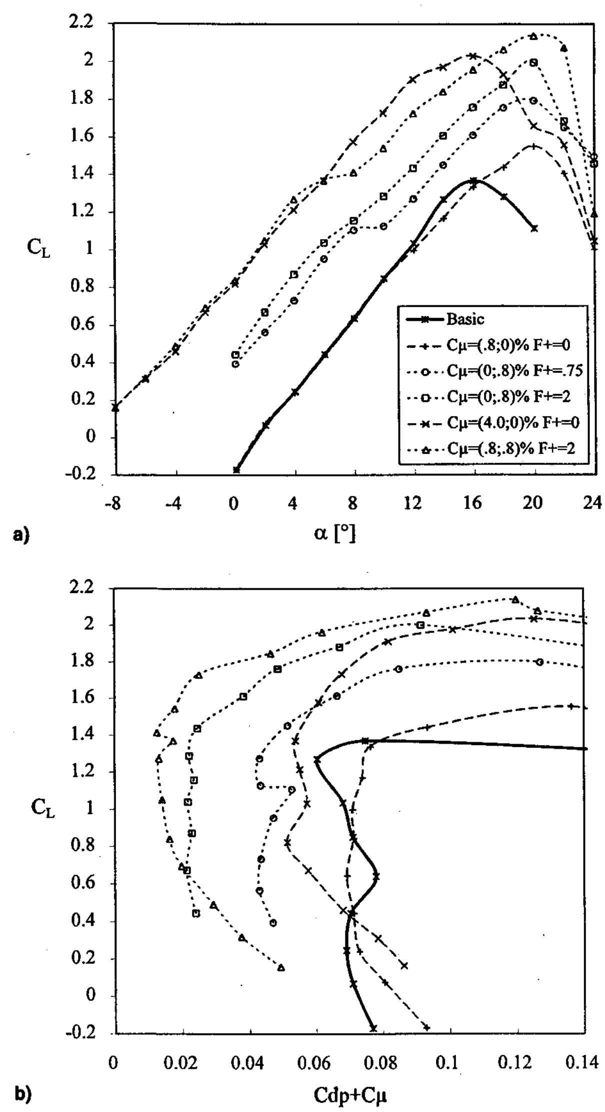

Fig. 13 Effect of active control on the a) lift and b) form drag of the SPCA-1.

solely by the increase in the forcing frequency F^+. The form drag in the latter case remained constant (i.e., $C_{dp} + C_\mu \approx 0.02$) between $\alpha = 0$ and 8 deg. Adding a steady blowing to the oscillations at $F^+ = 2$ [i.e., $C_\mu = (0.8, 0.8\%)$] resulted in a lift increment of $\Delta C_L = 1$ between $0 < \alpha < 6$ deg above the basic configuration and net form drag reduction $\Delta(C_{dp} + C_\mu) = -0.06$. This means a six-fold reduction in the form drag at a fixed C_L of 1. A similar lift curve is attainable by using steady blowing at a $c_\mu = 4\%$, but the total form drag ($C_{dp} + C_\mu$) is almost five-fold larger. Increasing the Reynolds number by a factor of 2 (to $R_c = 0.3 \times 10^6$), while maintaining all other parameters, did not result in any deterioration in the airfoil performance.

Conclusions

The introduction of two-dimensional, periodic oscillations into a turbulent boundary layer enables it to resist larger adverse pressure gradients without separating. It therefore increases the lift and reduces the drag generated by airfoils at angles of incidence and flap deflections at which the flow would otherwise be separated. For an effective control of separation, the amplitude of the imposed oscillations should peak in the vicinity of the natural separation location, and the most efficient location of the actuator coincides with this point unless the flow in the upstream boundary layer amplifies the imposed oscillations. The effectiveness of the method is not hindered by triggering early transition, thickening an already turbulent boundary layer, or changing the Reynolds number. The method has very little in common with stationary vortex generators that introduce streamwise vortices at much smaller scales.

The most effective frequency of forcing the flow over airfoils seemed to be one in which the streamwise length requiring control was comparable to the calculated, average wavelength of the imposed periodic perturbations (i.e., such that F^+ was of order unity). However, the sensitivity of the flow to the reduced frequency was not large and it diminished with the introduction of steady blowing or with increasing α. Phase-locked pressure measurements revealed that at least two eddies were present over the upper surface of the airfoil at any instant of time and that their size increased in the direction of streaming. There is little doubt that the length of the surface downstream of the natural separation location is the most significant length scale of this control problem and not the thickness of the upstream boundary layer. Finally, the time-dependent, dynamic effects of the imposed oscillations on the instantaneous pressure distribution around the airfoil or on the integral parameters such as lift and c.p. are very mild indeed.

The complexity of the flow requires extensive future investigation accompanied by an effective numerical simulation to determine the leading parameters governing this phenomenon. The instantaneous details of the flow will be investigated with the aid of a particle image velocimetry, particularly the oscillatory movement of the separation point and the vortical structures surrounding it. The flow near the reattachment point of a long bubble is another region of great interest for future implementation of effective control.

From the practical point of view we shall explore the effects of compressibility, sweep-back, and finite wing planforms. We would also attempt to control dynamic stall. Preliminary experiments carried out at the National Diagnostic Facility[11] (NDF) on the NACA 0015 airfoil at Mach numbers generating locally transonic flow (i.e., up to $M_n = 0.43$) proved the effectiveness of the method and will be reported separately. One may also use this form of flow control to design very thick airfoils (having a maximum thickness-to-chord ratio of the order of 30%), which would only be effective when coupled with forced periodic oscillations. The quest for thick airfoils is not new: Glauert[13] tried to achieve one by using continuous suction (e.g., the Glass II airfoil), but the large power consumption necessary to restore attached flow and the hysteresis associated with the suction made it impractical. By using the presently proposed method the power needed is low and the possible mechanical installation is relatively simple. This may permit the adoption of such airfoils to span-loaders and flying wings. Finally, the method may lend itself to replace ailerons or flaps, which will enable the removal of large moving parts from the wings.

Acknowledgments

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