CONTROLLED TRANSIENTS OF FLOW REATTACHMENT OVER STALLED AIRFOILS

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ABSTRACT
Controlled flow transients that are associated with sequenced separation and reattachment of the flow over a stalled airfoil are exploited for aerodynamic performance enhancement beyond controlled conventional quasi-steady post-stall attachment. Actuation is effected by synthetic jet actuators that are operated at frequencies are typically an order of magnitude higher than the natural frequency of the base flow. This approach to aerodynamic flow control is based on earlier observations by the authors that controlled post-stall reattachment or imposed stall by the termination of the actuation are accompanied by large transitory changes in the circulation about the airfoil before a quasi-steady level is reached. Pulsed modulation of the actuation waveform is exploited to accumulate vorticity during the initial stages of the separation process and thus to increase the lift (similar in principle to dynamic stall).

INTRODUCTION
Active manipulation of separated flows over lifting surfaces at moderate and high angles of attack with the objective of improving the aerodynamic performance and extending their flight envelope by inducing complete or partial flow reattachment has been the focus of a number of investigations since the early eighties. Reattachment is normally effected by exploiting the receptivity of the separating shear layer to external excitation that results in a Coanda-like reattachment of the flow. Control schemes that rely on the instability of the separating shear layer have employed a variety of actuation techniques including internal and external acoustic excitation (e.g., Ahuja and Burrin 1984, Zaman et al. 1987, Huang et al 1987, and Hsiao et al. 1990), oscillating flaps and ribbons (e.g., Neuburger and Wygnanski 1987), and oscillatory blowing (e.g., Wygnanski and Seifert 1994 and Seifert et al. 1996).

Smith et al. (1998) and Amitay et al. (1999 and 2001) demonstrated the utility of synthetic (zero mass flux) jet actuators for the suppression of separation over an unconventional airfoil at moderate Reynolds numbers (up to 10^6) resulting in a dramatic increase in lift and decrease in pressure drag. The jets are typically operated at frequencies that are an order of magnitude higher than the shedding frequency of the airfoil [i.e., $F^+ \sim O(10)$] and therefore their interaction with the cross flow leads to local modification of the apparent shape of the flow surface and in the streamwise pressure gradient (Honohan et al., 2001). Full or partial reattachment including the controlled formation of a closed separation bubble, can be influenced by the streamwise location and the strength of the jets. The excitation is effective over a broad streamwise domain that extends well upstream of where the flow separates in the absence of actuation and even downstream of the front stagnation point on the pressure side of the airfoil.

In more recent work Amitay et al. (1999) investigated the flow transients that are associated with the reattachment using time-modulated control input. The evolution of the airfoil wake was measured in the cross stream plane using actuation frequencies that are either well above or of the same order as the natural shedding frequency [i.e., $F^+ \sim O(10)$ and $\sim O(1)$, respectively]. At both frequency ranges, the adjustment in circulation that is associated with the collapse of the separated flow region is accompanied by the shedding of a train of vortices of alternating signs that lead to successive momentary decrease and increase in circulation. However, while at $F^+ \sim O(10)$ the shedding of organized vortical structures subsides following the initial transient, at $F^+ \sim O(1)$ actuation leads to a time-periodic shedding of a train of vortices (at the actuation frequency) that correspond to (peak to peak) lift coefficient fluctuations (at $F^+ = 0.95$) of up to 45% of the mean lift.

The present work builds on earlier results of Amitay et al. (1999 and 2001) and focuses on the notion that the transients that are associated with the adjustment of the circulation following the application and removal of the control input can be exploited for a net increase in the (quasi-steady) lift. It is shown that such an increment in lift cannot be attained by conventional time-harmonic actuation.

EXPERIMENTAL SETUP

The experimental setup is described in detail in the earlier work of Smith et al. (1998). The experiments are conducted in an open return, wind tunnel having a test section measuring 91cm on the side. The airfoil model is comprised of an aluminum leading edge circular cylinder mounted within a fiberglass aerodynamic fairing that is based on a uniformly stretched NACA four-digit series symmetric airfoil. The 62.2mm diameter cylinder spans the entire test section and can be rotated about its axis within the fairing and is tangent to the surface of the fairing at the apexes of its cross-stream edges (where the airfoils has its maximum thickness). The chord of the combined cylinder-fairing airfoil is 25.4cm, its thickness to chord ratio is 24% and its angle of attack a can be independently varied between -25^0 and 25^0.

The center section of the cylinder houses a pair of adjacent synthetic jet actuators each having a flush-mounted rectangular orifice (0.5 mm wide and 140 mm long). The orifices are collinear with respect to the axis of the cylinder along their long dimension, and separated by 2.5 mm. The actuator performance is measured using the momentum coefficient, $C_\mu = I_j / \frac{1}{2}\rho_o U_o^2 c$, where I_j is the jet time-averaged momentum flux per unit length during the outstroke (Smith and Glezer, 1998), ρ_0 and U_0 are the free stream density and velocity, respectively, and c is the chord.

The cylinder is instrumented with 47 pressure taps that are located in the spanwise mid-plane and are equally spaced circumferentially around the cylinder. Similarly, the fairing is instrumented with 45 pressure taps along the top and bottom surfaces and at the same spanwise location as the taps on the cylinder. Cross stream distributions of the streamwise and cross-stream velocity components are measured in the wake of the airfoil using x-configuration hot wire miniature sensors that are mounted on a computer-controlled traversing mechanism. The velocity and vorticity fields in the cross-stream (x-y) plane, $z = 0$, above the airfoil (i.e., on the suction side) are measured using Particle Image Velocimetry (PIV) using a 1008 x 1016 pixel CCD camera with a magnification of 53μm/pixel (the nominal particle diameter is sub-pixel). Velocity vectors are computed on a 62 x 62 grid using a standard cross-correlation technique. Each of the ensemble-averaged data maps consists of 150 realizations (image pairs).

RESULTS AND DISCUSSION

Flow Transients during Reattachment and Separation

The modification of the aerodynamic performance of the present airfoil using synthetic jet actuators is discussed in detail by Smith et al. (1998) and Amitay et al. (2001). Separation control using these actuators leads to flow attachment at post stall angles of attack of the base flow resulting in a substantial increase in lift and reduced pressure drag. These authors also investigated the changes in the cross stream structure of the wake of the airfoil as a result of the actuation. The flow transients that are associated with controlled reattachment following a (top hat) pulsed amplitude modulation of the actuator (control) input are inferred from the phase-averaged vorticity flux in the wake of the airfoil. The nominal (dimensionless) frequency of the actuation is $F^+ = 10$ ($f_{act} = 740$ Hz) and the modulation is synchronized with the driving signal such that the leading edge of the modulating waveform coincides with a zero crossing of the actuator signal, where the modulation period is 0.5 sec. The flow transients across the wake of the airfoil are captured using x-wire anemometry at $x/c = 2$. The airfoil is set at a post-stall angle of attack $\alpha = 17.5^0$ ($Re_c = 310{,}000$), the angle of the centerline of the actuator jets with respect to the free stream is $\gamma = 60^0$, and the actuation momentum coefficient is $C_\mu = 3.5.10^{-3}$. The increment in the circulation about the airfoil $\Delta\Gamma$ that is induced by the modulation of the actuation waveform is estimated from the (phase averaged) vorticity flux within the wake using corresponding (phase averaged) cross-stream distributions of the streamwise velocity and spanwise vorticity.

The variation of the circulation increment with time following the onset of modulation is shown in Figure 1. Following a brief advection delay ($23 \cdot T_{act}$, relative to the onset of modulation), the airfoil circulation undergoes substantial transient excursions that commence with a momentary ($13 \cdot T_{act}$) increase in circulation followed by a momentary decrease. As confirmed by smoke visualization (Figure 2), the first transient following the onset of the modulation is associated with the collapse of the separated flow domain above the airfoil that results in the shedding of a strong CW vortex and therefore a momentary reduction in circulation about the airfoil. The circulation is adjusted by the shedding of a starting-like (i.e., CCW) vortex from the pressure side of the airfoil, which apparently causes partial trailing edge separation and consequently the shedding of another (weaker) CW vortex. The latter is followed by another CCW vortex and thereafter a train of vortices of alternating signs and diminishing strength. Following these transients, the circulation ultimately reaches a steady level. When the control is turned off, the circulation about the airfoil initially decreases before settling to the level that corresponds to the stalled baseline. The transient increase in circulation that is associated with the termination of the actuation (nominally $60 T_{act}$) is reminiscent of the transient variation of lift on a pitching airfoil during dynamic stall.

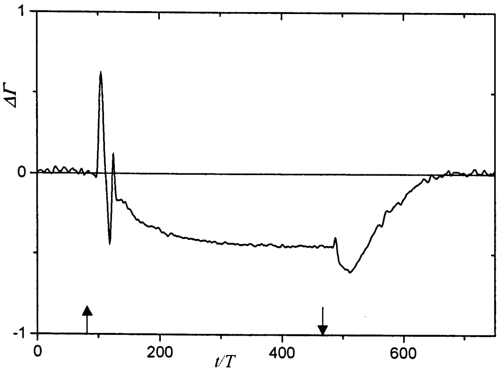

Figure 1. The incremental change in circulation for $\alpha = 17.5^0$, $\gamma = 60^0$ and $F^+ = 10$.

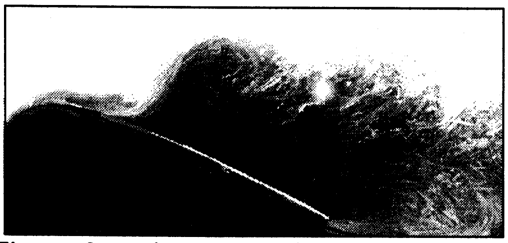

Figure 2. Phase-averaged image during the reattachment process.

Pulse Modulated Reattachment

The flow transients that associated with controlled reattachment and separation described in the previous section can be exploited to enhance the effectiveness of the actuation. In particular, this capability is demonstrated in situations where either the streamwise location of the jet actuators or the strength of the actuation is sub-optimal. To this end, the jets are placed at an azimuthal position ($\gamma = 42^0$) where, as shown in the earlier work of Smith et al. (1998), variation of the momentum coefficient C_μ yields some measure of proportional control of the lift. At this location, an 18% reduction in C_μ (from $4.6 \cdot 10^{-3}$ where the flow is completely attached to $3.7 \cdot 10^{-3}$) results in a substantial degradation of the lift coefficient (from 0.99 to 0.64). At the lower C_μ the pressure distribution (not shown) exhibits a smaller suction peak near the leading edge followed by a separation bubble that extends along most of the upper surface of the airfoil. The performance of the actuators at the reduced level of the momentum coefficient is substantially enhanced by pulse modulation of their resonance waveform (nominally $F^+ = 10$). In addition to the modulation frequency, the period and duty cycle of the modulating pulse train can also be independently varied (in the present work, the duty cycle is 0.25 and the modulating frequency f^+ is varied between 0.27 and 5.0).

The variation with f^+ of the phase-averaged circulation (measured phase locked to the modulating wave train) following the decay of startup transients is shown in Figures 3a-d for $f^+ = 0.27$, 1.1, 3.3 and 5.0, respectively. (The time trace in the absence of modulation is shown for reference in each plot using open symbols). The modulation frequency $f^+ = 0.27$ (Figure 3a) corresponds to the characteristic passage frequency of the vortices that are shed during the initial (transient) stages of the controlled reattachment (Figure 1 above). The resulting quasi-steady circulation exhibits oscillations that are similar in magnitude and duration to the fluctuations caused by the reattachment transients and are associated with shedding of similar vortical structures. Although the phase of each pulse of the modulating wave train is timed to re-trigger reattachment before the flow separates again, the circulation exhibits low frequency variations (having a period of the order of $60 T_{act}$).

When f^+ is increased to 1.1 (Figure 3b), the elapsed time between pulses within the modulating wave train is decreased and the oscillations in the circulation are substantially attenuated. This indicates that the timing of the modulating pulse train effectively prevents the time-periodic formation and shedding of discrete vortical structures and therefore the corresponding variations in circulation. Moreover, the asymptotic increase in circulation suggests that the actuation leads to an accumulation of (clockwise) vorticity on the suction side of the airfoil even though the flow reattachment is unsteady and the circulation oscillates with peak-to-peak variations of 42% of its asymptotic mean level. A further increase in f^+ to 3.3 (Figure 3c) results in circulation level that is similar in magnitude to the piecewise-averaged circulation in Figure 3b ($f^+ = 1.1$). However, the absence of oscillations at the modulating frequency indicates optimal timing between the modulating pulses. It is remarkable that pulse modulation not only yields an increase of approximately 400% in the (steady state) lift coefficient compared to unmodulated high-frequency actuation, but also that this is accomplished at only 25% of the jet momentum coefficient. Finally, when the modulating frequency is further increased to $f^+ = 5$ (Figure 3d), the time between successive pulses of the modulating wave train is apparently too short to induce the accumulation of vorticity and the enhancement of lift. The effectiveness of the modulation is minimal and the circulation returns to the same levels obtained with the unmodulated actuation.

To further demonstrate the effectiveness of pulse modulated reattachment, the flow field above the airfoil (for $\alpha = 20^0$, $Re_c = 310{,}000$, $\gamma = 45^0$, and

$C_\mu = 4.5 \cdot 10^{-3}$) is computed from a sequence of PIV images taken in the x-y plane ($z = 0$) over the upper surface of the airfoil. Each image is comprised of three partially overlapping frames measuring 10 cmx10 cm. Cross-stream maps of time-averaged distributions of the spanwise vorticity are shown in Figures 4a-d. In the absence of actuation (Figure 4a), the separated flow exhibits a large recirculating flow domain above the entire upper surface of the airfoil. At this low C_μ, unmodulated actuation at $F^+ = 10$ (Figure 4b) leads to a slight downstream migration (to $x/c = 0.3$) of the point of separation and the flow is completely separated thereafter.

When the flow is actuated using pulse modulated actuation at $f^+ = 1.1$ of the actuator carrier waveform the flow is attached over the entire surface of the airfoil (Figure 4c). It is interesting to note that for $x/c > 0.7$, the thickness of the vorticity boundary layer becomes noticeably thicker presumably as a result of a sub-optimal pressure recovery. The vorticity distribution suggests that the flow may be separated just upstream of the trailing edge of the airfoil. A comparison of this vorticity map with the corresponding map for unmodulated actuation at $F^+ = 1.1$ (Figure 4d) shows that the unmodulated actuation results in thickening of the vorticity layer that commences much farther upstream (i.e., $x/c > 0.3$).

Pairs of phase-averaged spanwise vorticity maps that result from unmodulated low-frequency and pulse-modulated (high frequency) actuation programs are shown in Figures 5a, b and c, d. It is evident that unmodulated actuation at $F^+ = 1.1$ (Figures 5a and b) results in the rollup and advection of distinct vortical structures at the actuation frequency having a nominal characteristic wavelength of 0.4c. These maps suggest that the formation of these vortices is accompanied by the time-periodic accumulation of CW vorticity prior to their release and therefore a momentary increase in circulation. In contrast, the phase-averaged maps for actuation at $f^+ = 1.1$ (Figures 5c and d) exhibit a flow that is nominally attached and has only relatively weak coherent concentrations of spanwise vorticity within the boundary layer. It also appears that while in Figure 5c the vorticity layer near the leading edge is somewhat displaced in the cross stream direction, there is no shedding of concentrated vorticity that would contribute to fluctuations in circulation.

In connection with the nominal increase in the time-averaged lift that is associated with pulse modulated actuation, it is important to emphasize that the corresponding accumulation of (CW) vorticity takes place following the initial transients that are imposed by the onset of the modulated control input (Figure 3 above). Detailed phase averaged traces of the phase-averaged circulation immediately following the onset of actuation for unmodulated ($F^+ = 10$) and modulated ($f^+ = 3.3$) actuation programs are shown in Figure 6. These data show that despite the ultimate differences in the levels of attained lift for the actuated flow, the initial transients that are effected by both actuation programs cases are similar. However, while the unmodulated actuation settles to a low circulation level, the modulation (at *lower* C_μ), results in a monotonic increase in circulation (i.e., accumulation

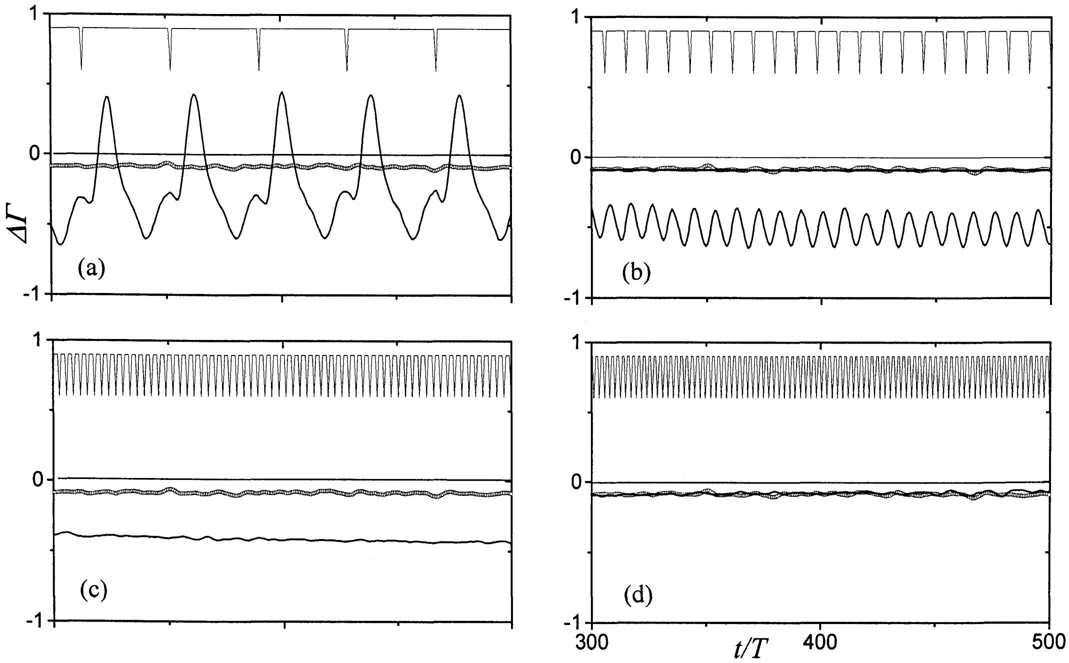

Figure 3. Long-term variation of the phase-averaged circulation increment for $\alpha = 17.5^0$ and $\gamma = 42^0$. $f^+ = 0.27$ (a), 1.1 (b), 3.3 (c) and 5.0 (d). Unmodulated actuation is shown with symbols.

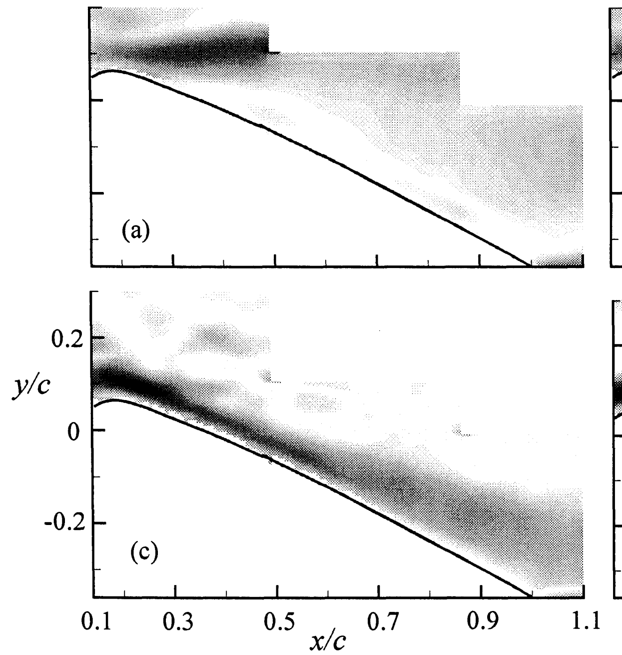

Figure 4. Time-averaged spanwise vorticity fields. Baseline (a), $F^+ = 10$ (b), $f^+ = 1.1$ (c), and $F^+ = 1.1$ (d).

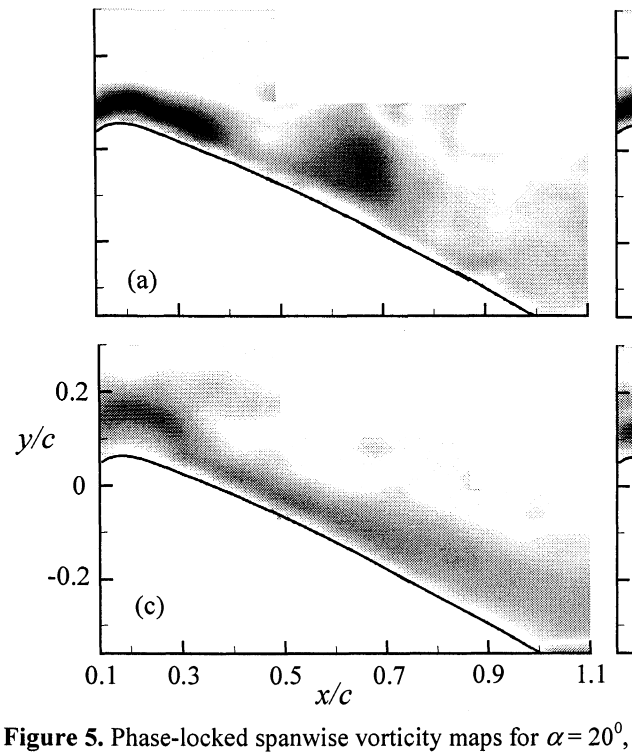

Figure 5. Phase-locked spanwise vorticity maps for $\alpha = 20^0$, $\gamma = 45^0$, $F^+ = 1.1$(a, b) and $f^+ = 1.1$(c, d).

of CW vorticity) over 60 cycles of the modulating waveform (or 200 cycles of the actuator's waveform). These characteristic time for reaching the desired level of circulation must be taken into account in the implementation of this type of active control. It may be possible to significantly shorten this time by implementing close-loop feedback control algorithms.

CONCLUSIONS

The manipulation of post stall global aerodynamic forces on a thick airfoil by exploiting flow transients associated with time-modulated control input is discussed. Control is effected using surface mounted synthetic jet actuators that operate at a frequency that is at least an order of magnitude higher than the characteristic shedding frequency of the stalled airfoil. The response of the flow over the surface of the airfoil and in the cross-stream plane of its wake is measured using phase-locked particle image velocimetry and two-component hot-wire anemometry, respectively. The flow reattachment following the onset of actuation is characterized by strong transients in circulation that begin with the shedding of a clockwise vortex and a reduction in circulation as a result of the collapse of the separated flow domain. The shedding of this vortex is followed by a brief train of counter rotating vortices of diminishing strength that lead to the establishment of quasi-steady circulation.

The present paper shows that within some range of the operating envelope at post stall angles of attack, the transients that are associated with the onset and termination of the actuation can be exploited to achieve higher circulation levels that cannot be attained by continuous (time-harmonic) actuation. This is achieved by employing pulse modulation of the actuation input that also enables operation of the actuators at reduced levels of momentum coefficient. The present data suggests that successive (modulated) bursts of the actuation waveform helps to capture and retain some of the the vorticity that is produced during the initial stages of the (controlled) flow separation on the suction side of the airfoil and thus to increase the ultimate circulation (and lift).

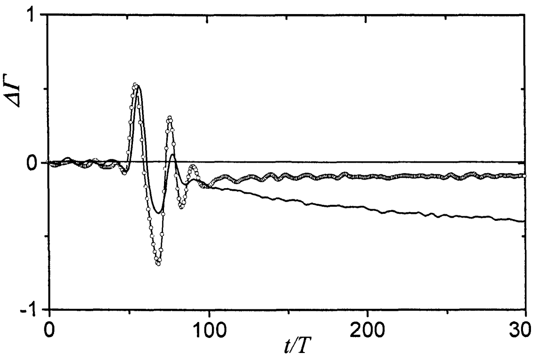

Figure 6. Variation of the phase-averaged circulation increment immediately following the onset of the actuation. Unmodulated $F^+ = 10$ (symbols) and $f^+ = 3.3$ (solid line).

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