Transitory Control of Unsteady Separation using Pulsed Actuation

George T. K. Woo
Woodruff School of Mechanical Engineering, Georgia Institute of Technology, 771 Ferst Drive, Atlanta GA 30332, USA
E-mail: gtkwoo@gatech.edu

Ari Glezer
Woodruff School of Mechanical Engineering, Georgia Institute of Technology, 771 Ferst Drive, Atlanta GA 30332, USA
E-mail: ari.glezer@me.gatech.edu

Abstract. The dynamic mechanisms of transitory flow attachment effected by pulsed actuation of the separated flow over a stalled airfoil are investigated experimentally. Actuation is effected by momentary pulsed jets generated by a spanwise array of combustion-based actuators such that the characteristic time of jet duration is nominally an order of magnitude shorter than the flow’s convective time scale. The transitory flow field in the cross stream plane above the airfoil and in its near wake is investigated using multiple high-resolution PIV images that are obtained phase-locked to the actuation for continuous tracking of vorticity concentrations. The brief actuation pulse leads to severing of the separated vorticity layer and the subsequent shedding of large-scale vortical structures owing to the collapse of the separated flow domain which is accompanied by strong changes in the circulation about the entire airfoil. By exploiting the disparity between the characteristic times of flow response to actuation and relaxation, it is shown that successive actuation pulses can extend the flow attachment and enhance the global aerodynamic performance. It is also shown that coupling of the actuation to the airfoil’s motion during cyclical pitch enhances the effect of transitory flow control and leads to a significant suppression of dynamic stall.

I. Overview

Earlier investigations demonstrated that separated flow over stalled airfoils is extremely susceptible to transitory actuation and that substantial control authority can be achieved when the actuation input is applied on time scales that are significantly shorter than the characteristic advection time over the separated flow domain (Brzozowski & Glezer 2006, Woo et al 2008 and Brzozowski et al 2010). The present investigation builds on the findings of Woo et al (2010 and 2011) who used pulsed actuation to control flow separation over an airfoil undergoing time-periodic pitch oscillations beyond the static stall margin, and demonstrated significant improvements in its aerodynamic performance. The paper focuses on the changes induced in the unsteady baseline flow of the pitching airfoil (in the absence of actuation) by controlled flow transients with emphasis on the connection between the time dependent flow field and the instantaneous global aerodynamic forces, and the mitigation of dynamic stall and reduction in negative pitch damping.
\sin(\omega t) where \( \alpha_o \) is the nominal average angle of attack, \( \alpha_0 \) is the oscillation amplitude, and \( k = \alpha/2U_o \) is the reduced frequency. Figure 2 shows a schematic representation of the oscillatory motion and the actuation timing used for the control experiments. The flow over the airfoil and in the wake is characterized using phase-locked particle image velocimetry (PIV) in the cross-stream plane \( z = 0 \) which is illuminated using a double-pulse Nd-YAG laser. Sets of PIV images are captured at sequences of predetermined time delays relative to the time-periodic model trajectory. The PIV measurements across the wake of the airfoil (near its trailing edge) are used to assess the time-dependent circulation about the airfoil.

II. Interaction of Pulsed Actuation with a Separated Cross Flow

Figure 3. Phase-averaged raster plots of spanwise vorticity and velocity fields showing the formation of a vortex pair following a single-pulse actuation at \( t/T_{conv} = 0 \) (a), 0.24 (b), 0.28 (c), 0.32 (d), 0.40 (e), and 0.44 (f). Normalized vorticity levels: -40, -31, -20, -15, -10, -5, 0, 5, 10, 15, 20, 31, 40.

The PIV images in Figures 3a–f show the vorticity dynamics within the interaction domain above the static airfoil (\( \alpha = 18^\circ \)) between a pulsed jet and the separated cross flow. The separated baseline flow is shown in Figure 3a. Figure 3b shows the initial formation of a vortex pair at \( t/T_{conv} = 0.24 \) following the actuation pulse. It is apparent that the momentum of the pulse jet is sufficiently strong such that the jet vortices can penetrate into the boundary layer, and interact with the separating shear layer. Note the significant spreading of the CW vorticity within the embedding CW vorticity in the boundary layer, while the CCW vorticity remains concentrated near the orifice (Figure 3c). At this early stage of actuation, the CW jet vortex is dominant in the presence of the cross flow. The strength of this vortex is crucial for the severing of the separated shear layer. As shown in Figure 3d, the actuation results in a discontinuity in the vorticity field of the shear layer (at \( x/c = 0.2, t/T_{conv} = 0.32 \)) that leads to the rollout of a new large-scale CW vortex that is advected downstream. At the same time, a small CCW vortex associated with the jet formation remains coherent and is advected above the shear layer. By \( t/T_{conv} = 0.44 \) following actuation (Figure 3f), the CCW vortex is almost out of the measurement domain. As the induced CW vortex is advected downstream, the upstream attached boundary layer continues to move along the surface. The front of this new boundary layer begins to move towards the trailing edge (Figures 3d–f), creating a region of attached flow above the airfoil (compare Figures 3a and f). The global effect of the single pulse is observed in Figures 4a–f, highlighting the transitory reattachment of the separated shear layer above the airfoil over a large streamwise extent of the chord.

Figure 5 shows an \( x-t \) diagram of evolution of the phase-averaged vorticity flux through vertical cross-stream sections of the measurement domain (\( 0.1 < x/c < 0.45 \)) following a single actuation pulse. This distribution clearly shows the appearance and advection of the CW and CCW jet vortices at \( t/T_{conv} = 0.2 \). The advection of the CCW jet vortices is apparent from patches of positive flux (marked in blue) having a characteristic propagation velocity of \( u/U_o = 0.99 \) (marked by a dashed line). At the same time, as noted in connection with Figure 3, the CW jet vortex merges with the surface boundary layer and has a characteristic propagation velocity of \( u/U_o = 0.75 \). Perhaps the most salient feature in the \( x-t \) diagram, is the appearance of a low-flux streak (having a characteristic propagation velocity of \( u/U_o = 0.55 \)) that is associated with the severing and rollup of the separated CW vorticity. Two vertical dash lines are plotted at \( t/T_{conv} = 0.36 \) and 0.8 to illustrate the flow structure that

Figure 4. Phase-averaged raster plots of spanwise vorticity and velocity fields showing the transitory reattachment of the separated shear layer following a single-pulse actuation at \( t/T_{conv} = 0 \) (a), 0.6 (b), 0.75 (c), 0.9 (d), 1.05 (e), and 1.5 (f). Normalized vorticity levels: -40, -31, -20, -15, -10, -5, 0, 5, 10, 15, 20, 31, 40.

Figure 5. \( x-t \) raster plots of phase-averaged vorticity flux for single-pulse actuation showing propagation velocities of the direct vortex pairs and the induced CW vorticity concentrations. Vorticity flux levels: -1.5, -0.5, 0.5.
corresponds to this flux map. The line at $u/T_{\text{conv}} = 0.36$ corresponds to Figure 3e, which shows that the severed domain of the separated shear layer between the separated vorticity concentration and the leading edge of the upstream attached boundary layer is much slower and moving downstream at $u/U_0 \approx 0.36$ (also corresponds to the propagation velocity of the “peak” adverse pressure gradient). It is owing to the differences in the characteristic propagation velocities that the severed region is stretched in the streamwise direction as indicated by its increasing width with $u/T_{\text{conv}}$ in Figure 5. The second vertical dash line, at $u/T_{\text{conv}} = 0.8$, corresponding to Figure 4c is where the flow domain includes the attached boundary layer and the severed region which undergoes significant streamwise growth.

III. Transitory Flow Attachment and Circulation Build-Up By Successive Actuation

The change in circulation relative to the baseline (unforced) flow, $\Delta \Gamma(t)/T_{\text{conv}}$ as computed by integration of the vorticity flux into the wake, $(T_{\text{conv}}$ is baseline circulation) for bursts of $N$ successive actuation pulses $T_{\text{conv}}$ apart are shown in Figure 6. For $N = 1$, the shedding of a starting CCW vortex results in a brief increase in circulation and is followed by a decrease when a CW vorticity concentration is shed as result of the collapse of the separated flow domain following actuation. The global circulation increases rapidly ($\Gamma_{\text{attachment}} = O(2T_{\text{conv}})$) to about 22% above baseline as a result of accumulation within the attaching boundary layer before the flow slowly relaxes ($\Gamma_{\text{attachment}} = O(9T_{\text{conv}})$) to the stalled state as the circulation gradually returns to the baseline level.

The changes in circulation for $N = 5$ and 10 demonstrate that the severing of the separated vorticity layer and the subsequent shedding of vorticity concentrations during successive actuation pulses significantly enhances the accumulation of circulation around the airfoil. The peak increase in circulation that is achieved by exploiting the transients for $N = 5$ and 10 is about 41% and 52% at, respectively. The circulation begins to decrease monotonically thereafter as the flow begins to relax following the shedding of the last CCW vortex. A further increase in $N$ leads to an extended flow attachment, however, the circulation ultimately saturates and become “quasi-steady” at reaching a saturation level of 58% above baseline for $N = 25$. This indicates that additional actuation only regulates the trapped vorticity and maintains attachment.

The corresponding $x$-$t$ diagram of the vorticity flux (cf. Figure 5 for a single pulse) is shown in Figure 7. The successive severing and rollup of the large-scale CW vortices, is depicted by the streaks of low-level vorticity flux following each actuation pulse that are preceded by fluxes of strong vorticity concentrations. The severing and the associated diminution in flux begin to vanish following the 5-6 pulses. It is also noteworthy that in immediately downstream of the actuator $x/c > 0.15$ the flux becomes vanishingly small with time because the attached boundary layer becomes considerably thinner and cannot be well resolved by the present magnification.

To further elucidate the effects of bursts of successive actuation pulses, the time-dependent vorticity flux and the corresponding change in circulation (relative to the stalled flow) are computed for two successive bursts of $N = 5$ pulses with $T_{\text{dwell}} = 4T_{\text{conv}}$ (Figures 8a and b, respectively). Figure 8a shows the phase-averaged vorticity flux from each of the airfoil’s surfaces and their sum (net flux). It is noteworthy that the magnitude of the oscillations (which correspond to the formation of vorticity concentrations that are associated with the pulses within each burst) are considerable higher in the suction surface flux. This is clearly attributable to the changes that are associated with the release and accumulation of CW vorticity within the stalled flow domain. The corresponding flux that is associated with shedding of CCW vorticity is considerably smaller indicating that the increase in circulation during the burst (Figure 8b) is connected with accumulation of CW vorticity on the suction surface. Time traces of the phase-averaged circulation (Figure 8b) show that the initial transients are similar to the circulation increment for a single burst ($N = 5$, included for reference in gray). As shown, once the actuation is terminated for a single (isolated) burst the flow begins to relax to the stalled state. However, when a second burst is applied, the circulation transients that are
increases in circulation. As the airfoil pitches up, Figure 11 is also accompanied by significant oscillation cycle (e.g., Woo et al., 2010). Figure 9 also shows the effects of pulsed actuation that is applied over that are associated with dissimilar shedding of vorticity concentrations during the up- and down-strokes of the lift and pitching moment of the model (measured by load cells and torque sensors) exhibit hysteretic effects C_{L} (\alpha). Figure 8. (a) Temporal variation of the normalized vorticity flux for two consecutive burst-modulated (N = 5) actuation with T_{burst} = 47T_{conv}: Suction surface (negative) flux (▼), pressure surface (positive) flux (▲), and the net flux (●). The corresponding incremental change in circulation (●). Circulation for a single N = 5 burst are shown for reference in grey (♦).
effected by the second burst are quite different. The start of the second burst is indicated by a (small) local circulation peak at t/T_{conv} = 8 (a similar peak is also visible for the first burst at t/T_{conv} = 0.8). It is important to recognize that the second burst begins when the global circulation level is about 60% of the maximum circulation attained by the first burst and the flow is not fully separated and therefore, the second burst continues to increase the circulation (and unsteady lift). The circulation change affected by the second burst second reaches a somewhat higher peak (49%) than the first burst (45%). More importantly, the characteristic relaxation time when the actuation is terminated (t/T_{conv} = 15) is considerably longer than for a single burst (16T_{conv} compared to 10T_{conv}).

IV. Control of Dynamic Stall using Stage Pulsed-Actuation

While the earlier Sections describe the effect of transitory actuation on a static airfoil, the present section considers the effects of the actuation when the airfoil is undergoing time-harmonic pitch oscillations beyond its static stall limit. The prescribed oscillation range is 10° < \alpha < 18°, and the cycle period is T_{p} = 625 ms (T_{p} = 25T_{conv}) corresponding to a reduced frequency k = \omega/2U_{c} = 0.115. Figures 9a and b show the variation of the phase-averaged C_{L}(t) and C_{MD}(t) with \alpha(t) during the oscillation cycle. Five instances during the cycle (i through v) are marked for reference in connection with the discussion of Figure 10. In the absence of actuation, the lift and pitching moment of the model (measured by load cells and torque sensors) exhibit hysteretic effects that are associated with dissimilar shedding of vorticity concentrations during the up- and down-strokes of the oscillation cycle (e.g., Woo et al., 2010). Figure 9 also shows the effects of pulsed actuation that is applied over the center 0.21S section of the airfoil using a burst of eight actuation pulses that is triggered as the airfoil pitches up through \alpha(t = t_{start}) = 14° such that successive pulses are T_{pulse} = 1.41T_{conv} apart. The actuation is terminated at \alpha(t = 0.36T_{p}) = 16.8° while pitching down.

In the absence of actuation, as the (baseline) airfoil begins to pitch up at \alpha = 10°, the lift (Figure 9a) is the same as for the static model indicating that the dynamic effects associated with the pitching cycle have subsided and as the pitch continues at \alpha = 12°, the lift increases above the static level. The dynamic lift, C_{L}(t), continues to increase beyond the static stall angle (13.5°) and, as shown by Woo et al. (2011), there is a significant increase in suction pressure of the baseline airfoil. The earlier work also showed that as \alpha increases beyond 13.5°, a recirculation domain is formed upstream of the trailing edge and is indicative of accumulation and regulation of trapped CW vorticity. This recirculation domain continues to increase with angle of attack, and the separation moves upstream (Woo et al. 2011). The accumulation of (trapped) vorticity is manifested by the increased C_{L} relative to the static levels (15%, 29%, and 36% above static values at 14°, 16°, and 18°, respectively), and, as shown in Figure 11 is also accompanied by significant increases in circulation. As the airfoil pitches up from \alpha = 18° to 18.5° and then down to 18°, the lift decreases significantly indicating the onset of stall. Figure 9b shows that C_{MD}(t) is almost invariant within the range 12° < \alpha < 17.5° while the lift increases monotonically, but at the onset

Figure 9. Phase-averaged dynamic lift, C_{L}(t), (a) and pitching moment, C_{MD}(t), (b) in the absence (.) and presence of an 8-pulse actuation sequence (•). The phases of the actuation pulses are marked (●). The corresponding static values of C_{L}(\alpha) and C_{MD}(\alpha) are shown using for reference (dashed lines). Five instances during the cycle (i through v) are marked for reference in connection with the discussion of Figure 10.
of stall $C_M(t)$ decreases abruptly as the separation moves upstream and the center of pressure changes. While the change in lift (and circulation) may be thought of as shedding of the recirculating flow domain, it is also accompanied by changes in the accumulation of vorticity over the airfoil as discussed in connection with Figure 10 and 11. Finally, the lift begins to recover slowly as $\alpha$ drops below 12°, and the accumulation of vorticity commences, and eventually, the flow returns to the fully attached state as the airfoil pitches through $\alpha = 10^\circ$ and the cycle repeats.

Woo et al. (2010 and 2011) showed that pulsed actuation can be used to mitigate some of the undesirable aerodynamic effects that are associated with dynamic stall on an oscillating airfoil. Specifically, the actuation reduces the magnitude of lift reduction during the downstroke, and the effects of “negative damping” in the pitching moment. In the present experiments, the response of the flow to staged, 8-pulse actuation sequence (1.4f<sub>conv</sub> apart) that is triggered when $\alpha(t) = 14^\circ$, is investigated in detail (the pulse timing is marked in Figure 9). The actuation has two primary effects, namely reduction of the loss in lift and of the pitching moment during the downstroke segment of the pitch cycle following stall. These results indicate that even in the presence of strong 3D effects, tuning the timing of the actuation pulses can lead to an “optimal” pulsed actuation sequence that can effectively control and trap the vorticity concentrations that are associated with dynamic stall while minimizing actuation power. The data in Figure 9 show that in the presence of actuation, the cyclic hysteresis of the dynamic lift $\Delta C_L$ decreases by 20% (from 1.02 to 0.82) and the extent of “negative damping” of the pitching moment $\Delta C_M$ decreases by 71% (from 0.014 to 0.004).

The global aerodynamic performance of the moving airfoil is quantified by considering the time-evolution of the phase-averaged cross-stream distributions of the vorticity flux $\omega_y u$ (CW and CCW from the suction and pressure surfaces) downstream of the trailing edge (at $x/c = 1.25$) as shown in Figures 10a and b. Time instances $i$ through $v$ in Figure 9 are also marked for reference. In the absence of actuation (Figure 10a), the changes in the cross stream width of the wake for $t < 0.18 t_p$ are relatively small indicating a reasonably attached flow during this part of the upstroke. However, when the flow begins to separate the cross-stream extent of the wake increases rapidly along with the magnitude of the flux of CW vorticity which is associated with the shedding of the vorticity concentration that is associated with the dynamic stall (at about $t/T_p = 0.18$ $\alpha \approx 17^\circ$ during the downstroke, cf., Figure 9). The maximum broadening of the wake occurs at $0.36 \leq c \leq 0.38 T_p$ corresponding to full stall. Thereafter, the flow slowly reattaches as the airfoil continues to pitch down. The corresponding cross stream distributions of the vorticity flux in the presence of actuation (Figure 10b) exhibit two striking differences compared to the baseline flow. First, the sequence of eight actuation pulses clearly modulates the vorticity fluxes from both the suction and pressure surfaces of the airfoil. This indicates that the actuation regulates the vorticity distribution about the airfoil through trapping and shedding. Second, and perhaps more striking, is the absence of massive stall as indicated by the widening of the wake. The time rate of change of the airfoil’s circulation for the baseline and actuated flows is computed by integration of vorticity flux across the wake $d\Gamma/dt = -\int \omega_y u dy$, and traces of normalized $(d\Gamma/dt)_{CW}$ and $(d\Gamma/dt)_{CCW}$ are also shown in Figures 10a and b. It is interesting to note that in the absence of actuation, the magnitudes of $(d\Gamma/dt)_{CW}$ and $(d\Gamma/dt)_{CCW}$ are similar and that the vorticity flux from the suction side intensifies during the downstroke. It is evident that the sum $(d\Gamma/dt)$ is associated with a net increase in circulation as shown in Figure 11. As noted above, the vorticity flux into the wake is altered significantly in the presence of actuation. The time rate of change of the circulation that is associated with the shedding of the discrete vortices induced by the actuation pulses increases as the actuation progresses and appears to reach a maximum level around $t/T_p = 25$ when the airfoil attains its largest angle of attack before the beginning of the downstroke. The reason for the successive increases in the peaks of $(d\Gamma/dt)_{CW}$ is connected with the increased thickness of the boundary layer on the suction surface and therefore the stronger shed vorticity concentrations.

![Figure 10. Raster plots of the phase-averaged cross-stream distribution of vorticity flux (CW and CCW) during the pitching cycle of the airfoil measured at $x/c = 0.25$ downstream of the trailing edge in the absence (a) and presence (b) of actuation. Included is the corresponding time-rate change of circulation. Line traces show $(d\Gamma/dt)_{CW}$ and $(d\Gamma/dt)_{CCW}$. Also included for reference are the five instances during the cycle (i through v) that are marked in Figure 8.](image-url)
as a result of the actuation. Each of the shed vortices is followed by a significant reduction (or deficit) in CW vorticity concentration that is associated with the severing the vorticity layer by the actuation on the airfoil and the buildup of vorticity in the upstream boundary layer indicating a concomitant increase in CW vorticity (or positive $\frac{d\Gamma}{dt}$) on the airfoil that contribute to the increases in circulation as shown in Figure 11. It is remarkable that the strength of the shed CW vortices (which is clearly coupled to the motion of the airfoil) is nearly invariant during the downstroke. The data in Figure 10 also show that the corresponding flux of CCW vorticity from pressure side of the airfoil has similar (but opposite) effects on $\frac{d\Gamma}{dt}$._{CCW}. Finally, the raster plots of vorticity flux and the traces of $\frac{d\Gamma}{dt}$._{CW} and $\frac{d\Gamma}{dt}$._{CCW} also show an intricate effect that is associated with the severing of the CW vorticity layer on the airfoil. Following the reduction in flux of CW vorticity the flux resumes before the next actuation pulse and as a result the shed vorticity concentrations (CW and CCW) exhibit two adjacent vortices.

The time-dependent circulation increment that is computed relative to the circulation when the airfoil pitches up through $\alpha = \alpha_o$, $-\Delta \Gamma(t)$ is shown in Figure 11 in the absence and presence of actuation. The initial rise in circulation (0 $\leq t \leq 0.16T_p$) for the baseline (unactuated) motion corresponds to the accumulation of CW vorticity during the formation of the dynamic stall vortex ($-\Delta \Gamma_{max}/\Gamma_o \approx 0.09$ at $t \approx 0.12T_p$). The subsequent reduction in circulation (0.16 $\leq t \leq 0.56T_p$) is due to the shedding of accumulated dynamic stall vorticity and the onset of stall over the airfoil at $t \approx 0.56T_p$ before the flow reattaches again ($-\Delta \Gamma$ vanishes) as the pitching cycle continues. In the presence of actuation, the circulation exhibits oscillations that are induced by the actuation pulses as the circulation level increases relative to $\alpha = \alpha_o$, $t = 0$, but the increase is significantly larger compared to the baseline ($-\Delta \Gamma_{max}/\Gamma_o \approx 0.25$ at $t \approx 0.37T_p$) and lasts for the duration of the actuation through $t \approx 0.52T_p$. Following the termination of the actuation as the airfoil continues to pitch, there is a reduction in circulation $(-\Delta \Gamma_{max}/\Gamma_o \approx -0.13$ at $t \approx 0.64T_p$), but this reduction is significantly smaller than the corresponding reduction of the baseline pitch indicating that the effects of the actuation lasts beyond its termination and consequently a cycle-averaged increase in circulation owing to the actuation. In addition, the control authority of the actuation is evident in Figure 11 that shows the phase-averaged net change in global circulation relative to the baseline during the pitching cycle. Even though the circulation is only computed at center span and the effect of the actuation clearly varies across the span owing to three-dimensional effects, it is remarkable that an eight-pulse sequence that is applied during the upstroke and lasts for about 40% of the cycle period leads to an increase in circulation through almost the entire cycle. The net circulation build-up during actuation is rapid, reaching a maximum level (at $t \approx 0.3T_p$) which is equivalent to an increase of 33% when normalized by $\Gamma_o$($t_0$), before decreasing upon termination of actuation and the end of the pitch cycle.

V. Conclusions

Transitory control of the stalled flow over a 2-D airfoil is investigated in wind tunnel experiments using pulsed actuation that is effected by a spanwise array of momentary, combustion-based actuator jet array that covers a 21% center segment of the airfoil’s span. The characteristic time scale of the actuation is an order of magnitude shorter than the convective time scale of the flow.

On a statically stalled airfoil, pulse actuation results in momentary attachment of the flow with characteristic rise time of $2-3T_{conv}$, followed by detachment that is considerably slower (up to $10T_{conv}$) before the flow becomes fully stalled again. The attachment is manifested by rapid changes in the global circulation and aerodynamic forces. The flow transients associated with the onset of single actuation pulse are exploited by using successive pulse actuation to enhance the actuation effectiveness and hence the aerodynamic performance of the airfoil to induce large-scale changes in vorticity accumulation for significant “progressive” extension of the attached flow. Detailed phase-locked PIV measurements of the flow field at center-span over the airfoil and in the near wake show that the dynamically separated flow is controlled by effective trapping of vorticity over the airfoil. The successive
severing of the separating CW shear layer by the actuation increases accumulation of vorticity upstream of the severed layer, and regulates the shedding of CW and (indirectly) CCW vorticity. The results indicate that even in the presence of strong 3-D effects, tuning the timing of the actuation pulses during the cycle can lead to optimal actuation sequence that can effectively control and trap the vorticity concentrations that are associated with dynamic stall while minimizing actuation power. The prevention of massive stall by the actuation also reduces the degree of “negative damping” of the pitching moment by avoiding the large and abrupt changes in the location of the airfoil’s center of pressure that are caused by massive shedding of vorticity as observed in the baseline flow. Finally, it is also shown that in the presence of the actuation, the circulation (in the center cross stream plane \( z = 0 \) builds up around the airfoil for almost the entire pitching cycle by as much as 33% over the (unactuated) baseline flow.

**Acknowledgments**

This work has been supported in part by NASA's Subsonic Rotary Wing Program, and by the Georgia Institute of Technology.

**References**

Brzozowski, D., and Glezer, A., “Transient Separation Control Using Pulse-Combustion Actuation”, AIAA Paper, 3rd AIAA Flow Control Conference, 2006-3024, 2006.

Brzozowski, D., Woo., G. T. K., Culp, J., and Glezer, A., “Transient Separation Control using Pulse-Combustion Actuation,” *AIAA J.*, **48**, 2482-2490, 2010.

Woo, G. T. K., Crittenden, T., and Glezer, A., “Transitory Control of a Pitching Airfoil using Pulse Combustion Actuation,” AIAA Paper 08-4324, 2008.

Woo, G. T. K., Crittenden, T., and Glezer, A., “Transitory Separation Control over a Stalled Airfoil,” AIAA Paper 09-4281, 2009.

Woo, G. T. K., and Glezer, A., “Transient Control of Separating Flow over a Dynamically-Pitching Airfoil,” AIAA Paper 2010-861, 2010.

Woo, G. T. K., Crittenden, T., and Glezer, A., “Transitory Control of Dynamic Stall on a Moving Airfoil,” AIAA Paper 2011-0489, 2011.