AERODYNAMIC CONTROL BY REGULATION OF SURFACE VORTICITY FLUX USING ACTIVE BLEED

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1 Introduction

The interaction between aerodynamic bleed that is engendered by the pressure differences across a lifting surface in a cross flow and the local boundary layer can result in significant changes in the vorticity flux and therefore in the global aerodynamic loads. While the use of passive bleed through porous surfaces for flow control has been investigated since the 1920s (e.g., Lachmann 1924), the utility of active distributed bleed by time-dependent regulation of surface flow passages for control of pre- and post-stall aerodynamic loads has only been demonstrated recently by Kearney & Glezer (2011, 2012, 2013). These authors have shown that active bleed can mitigate adverse aerodynamic effects on pitching airfoils including dynamic stall and pitch instabilities.

Pitch oscillations of airfoils near or beyond their static stall margin that are accompanied by alternating flow separation and attachment are dominated by the formation, advection, and ultimate shedding of large vorticity concentrations that can lead to structural vibrations, wing torsion, and flutter (e.g., Johnson & Ham 1972; Carta & Carlson 1973; McCroskey, Carr, & McAlister 1976; McCroskey 1981; Ericsson & Reding 1988). A number of earlier numerical and experimental investigations have focused on mitigation of lift variation and pitch instability (negative damping) associated with the formation and shedding of the dynamic stall vortex by active flow control approaches including steady and time-periodic blowing (Weaver, McAlister, & Tso 1996; Greenblatt & Wygnanski 2001), pulsed, transitory actuation (Woo & Glezer 2010), and plasma-based actuation (Post & Corke 2006). Several of these investigations indicated that time-periodic excitation of the separating shear layer can increase the steady and unsteady stall angles and the post-stall lift and mitigate unfavorable temporal variation in the induced pitching moment.

The present investigations build on the earlier findings of Kearney & Glezer and focus on the time-dependent mechanisms by which bleed affects vorticity concentrations over the airfoil and in the near wake during oscillatory pitching motions. The alteration of the vorticity flux near the surface can have significant effects on the evolution and timing of the dynamic stall vortex that is manifested by alteration of the lift hysteresis and pitch stability during the cycle.

2 Experimental Setup

The present investigation is conducted in a low-speed closed-return wind tunnel ($U_{in} = 15$ m/s, $Re_c = 190,000$) with a rectangular test section measuring 25 x 47 x 132 cm having optical access from all sides. The VR-7 airfoil model ($c = 20$ cm, $l_{max} = 0.12c$) spans nearly the entire width of the test section ($s = 24$ cm, with endplates). The model is mechanically isolated from the test section and is mounted on a shaft through $s/c = 0.25$. Dynamic pitch is driven by two synchronized, computer controlled servo motors, one on each side of the tunnel, that are each connected to the model through a load cell that measures lift and drag (to within 0.014 N) and pitching moment (to within 0.002 N-m), with frequency response of up to 500 Hz. The system can pitch the model time-harmonically at frequencies in excess of 25 Hz (corresponding to a reduced frequency of $k = \omega x/2U_{in} \approx 1$). High-resolution PIV measurements of the velocity field above the airfoil and in the near wake are obtained using a high-speed system at rates up to 2000 fps. Measurements are taken at mid span within the streamwise domain $0 < x < 0.6c$ and $0 < x < 1.25c$ (magnifications of 10 and 5 pixels/mm, respectively).

The airfoil model is fabricated using stereolithography (SLA) and includes several spanwise rows of low-resistance bleed ports through the pressure and suction surfaces that are open to the inner volume of the model. Each spanwise row is comprised of 16 10 mm-wide ports whose streamwise length increases with distance from the leading edge from 2 mm (at $x/c = 0$) to 2.5 mm (at $x/c = 0.95$). As shown schematically in Figure 1, the bleed configuration in the present work leverages the pressure difference upstream of the trailing edge (on the pressure side) and the low pressure domain on the suction surface near the leading edge (0.03 < $x/c$ < 0.04). An array of planar piezoelectric louvers embedded over the inlet ports along the airfoil’s span can be actuated at frequencies above 150 Hz. Time-dependent actuation waveforms synthesized using the laboratory computer and external DC amplifiers enable desirable time-varying bleed. As noted by Kearney and Glezer (2012), static displacement of the louvers (characterized by the fractional opening, $A$) varies nearly linearly with the applied voltage, and the effects of the louvers’ presence on the aerodynamic...
characteristics of the airfoil in the absence of bleed (i.e. when the bleed passages are sealed) results in minimal interference and changes in aerodynamic loads.

3 Modification of Vorticity Flux using Repetitive Bleed Pulses

The earlier work of Kearney and Glezer (2011, 2012, 2013) demonstrated that the interaction of time-dependent bleed flow with the outer flow leads to temporal and spatial modulation of vorticity concentrations within the surface vorticity layer. In the present investigations, these effects are exploited to alter the dynamics of the formation and transport of vorticity concentrations associated with stall during upstroke segment of the pitch cycle and flow reattachment during the downstroke.

Distributions of instantaneous velocity vectors and spanwise vorticity concentrations in the cross stream (x-y) plane of the flow over the airfoil when it is pitching at $k = 0.17$ within $14^\circ < \alpha < 22^\circ$ (static stall occurs at $\alpha = 16^\circ$) are shown in Figures 2a-f and g-l in the absence and presence of bleed, respectively. Bleed actuation is applied time-periodically at $S_{act} = 1.1$, corresponding to approximately 20 bleed pulses per pitch cycle. In the absence of actuation, at $\alpha = 18.0^\circ$ (Figure 2a) the flow remains attached through $x/c = 0.55$, and the separating shear layer rolls up into a larger scale vortex over the trailing edge with an induced reversed flow domain (having a characteristic cross stream scale of $\Delta y/c = 0.12$). The flow at the same pitch angle is considerably different in the presence of bleed actuation (Figure 2g). To begin with, the interaction of the bleed ($x/c = 0.15$) with the outer flow leads to a local displacement of the CW vorticity layer over the surface with an attachment that is followed by separation at $x/c = 0.52$ and the rollup of a large-scale CW vortex further upstream of the trailing edge ($x/c = 0.9$) compared to the base flow. At $\alpha = 20.0^\circ$, the base flow (Figure 2b) exhibits the rollup of a large CW vortex at $x/c \approx 0.65$ along with a smaller CW vorticity concentration at $x/c \approx 0.35$ that begins to lift off the surface (ostensibly owing to the induced flow by the larger vortex downstream). In the presence of bleed (Figure 2h), the timing of the large CW vortex is altered, and it appears farther downstream ($x/c \approx 0.82$), indicating its formation earlier in the pitch cycle, based on the similar advection speeds of these vortices over the midchord in the presence and absence of actuation ($U_{vel,c}/U^\infty \approx 0.6$ and 0.7, respectively). Of particular note is the formation of concentrations of CCW vorticity (Figure 2h) near the surface as a result of the induced (upstream) flow by the CW vorticity concentrations indicating the upstream migration of separation towards the leading edge. Following shedding of the dynamic stall vortex ($\alpha = 22^\circ$, Figure 2c), the base flow separates at the leading edge, forming a large recirculation domain that extends to the trailing edge of the airfoil and is accompanied by
significant widening of the near wake. However, bleed actuation continues to modulate and segment the separating shear layer and leads to the formation of two successive (upstream and downstream) CW vorticity concentrations that are separated by a domain in which the outer flow is deflected towards the surface (Figure 2i, $0.30 < x/c < 0.40$). As the downstroke begins, the base flow remains stalled (Figure 2d) while the segmentation of the separating shear layer and the rollup of a new CW vortex near the leading edge (Figure 2j) results in partial attachment that continues to migrate downstream while the previous, large scale CW vortex is advected towards the trailing edge. These changes in the flow are remarkable because even though the momentum coefficient of the bleed is relatively low [$O(10^{-4})$, it can lead to large-scale, global effects by exploiting the apparent receptivity of the base flow to modulation of the vorticity flux from the leading edge. As the downstroke proceeds, the attachment induced by the bleed continues to progress towards the trailing edge ($x/c = 0.40$ in Figure 2k, and $x/c = 0.70$ in Figure 2l) while at the corresponding cycle phases the base flow remains stalled (Figures 2c and f) even though the cross stream extent of the separated flow diminishes with the changes in the direction of the outer flow.

The variations in aerodynamic loads measured phase-locked to the pitch cycle are shown in Figure 3. In the absence of actuation, the lift increases and the pitching moment decreases proportionally with $\alpha$ through the onset of moment stall at approximately $\alpha = 19.1^\circ$ (Figure 3a-b). The formation and advection of the dynamic stall vortex beginning at $\alpha = 20^\circ$ (cf. Figure 2b) results in a rapid increase in $C_L$ (up to 2.1 at $\alpha = 21^\circ$) that is accompanied by an abrupt (nose-up) increase in $C_M$ through $\alpha = 20.2^\circ$ followed by a steep decrease in $C_M$ that continues almost through the peak cycle pitch angle, $\alpha_{max} = 22^\circ$. As the airfoil becomes fully stalled at $\alpha_{max}$ (cf. Figure 2c), $C_L$ decreases rapidly ($\Delta C_L = -0.46$) and then continues to decrease through the downstroke to $C_{L,min} = 0.63$ near $\alpha = 14.6^\circ$ when the flow begins to reattach and lift is restored. The onset of the downstroke and shedding of the dynamic stall vortex produces a rapid recovery of $C_M$, which increases throughout the downstroke segment of the pitch cycle to slightly nose-up (CW) $C_M = 0.03$ at $\alpha = 14.1^\circ$.

The corresponding cycle-averaged aerodynamic damping coefficient, $E_\alpha = \frac{\int C_M c d\alpha}{\pi \alpha^2}$, is 0.05 (recall that $E_\alpha > 0$ indicates suppressive or stable damping; Carta 1967; McCroskey 1982). However, even though the cycle damping is slightly positive, the pitching cycle includes a CW loop ($19.4^\circ < \alpha < 20.8^\circ$) which is indicative of negative or unstable damping.

As shown in Figure 3a-b, the influence of the time-periodic bleed ($St_{act} = 1.1$) is quite profound. Although there is a reduction in $C_L$ during the upstroke compared to the base flow ($\Delta C_L \approx 0.25$), the rapid increase in $C_L$ during the formation of the dynamic stall vortex is significantly muted, and the magnitude and rate of the decrease in $C_L$ following its shedding are considerably lower. Furthermore, the earlier flow attachment during the downstroke (cf. Figure 2k-l) is associated with higher $C_D$ for $14^\circ < \alpha < 20^\circ$. Therefore, the actuation results in a significant reduction in cycle hysteresis. Despite reduction in lift during the upstroke, the cycle-averaged lift is nearly the same in the presence and absence of bleed ($C_L = 1.26$ and 1.31, respectively). Similar to the changes in lift, the corresponding variations in $C_M$ during and following the shedding of the dynamic stall vortex are suppressed, and the increase in the nose-down rate during the upstroke is smaller than in the base flow. The maximum nose-down moment ($C_M = -0.30$) is lower than for the baseline ($C_M = -0.35$) and occurs earlier during the pitch cycle ($\alpha = 21.0^\circ$ compared to $21.7^\circ$ for the base flow). Furthermore, $C_M(\alpha)$ is CCW throughout the entire pitch cycle indicating that the cycle is positively damped, and, in fact, $E_\alpha = 0.72$ which is significantly higher than in the base flow. In the presence of bleed, the drag is somewhat higher during the upstroke, but is lower near $\alpha_{max} (C_{D,max} = 0.68$ at
The effect of distributed bleed on the spatial and temporal characteristics of the vortical structures during the pitch cycle and therefore on the pitch stability is gained by proper orthogonal decomposition (POD) analysis of the time-resolved velocity field in the near wake of the pitching airfoil. The pitch oscillation cycle is analyzed using 2,500 instantaneous images from five consecutive pitching cycles \((k = 0.17)\) by adapting the formulations of Sirovich (1987) and Adrian & Westerweel (2011). The velocity field measured in \(N\) time-resolved PIV snapshots is represented as

\[
\mathbf{u}(x, y, t) = \sum_{i=1}^{N} c_i(t) \mathbf{\phi}_i(x, y)
\]  

where \(\mathbf{\phi}_i(x, y)\) are the orthogonal basis functions or spatial modes, and \(c_i(t)\) are the temporal coefficients. The fluctuating components of the velocity field are concatenated into a single matrix and its autocovariance matrix and eigenvalues \(\lambda_i\) (having dimensions \([\text{length}/\text{time}]^2\)) are computed. This method yields \(N\) temporal coefficients that each scale the contribution of the modes to the velocity vector field where the most energetic modes are arranged in descending order by the eigenvalues. In this way, the velocity field of any snapshot may be partially reconstructed using an arbitrary number of modes and their associated coefficients.

Figure 4 shows color raster plots of the three most energetic POD modes of the streamwise flux of spanwise vorticity concentrations \(u(x, y, t)\) of the pitching airfoil \((k = 0.17)\) in the absence (Figure 4a, c, and e) and presence (Figure 4b, d, and f) of bleed \((St_{act} = 1.1)\). The data are shown within the domain \(0.25 < x/c < 0.80\) relative to the trailing edge, and the excursion of the trailing edge of the airfoil about \(\alpha = 18^\circ\) is marked for reference on the ordinate. The first mode of the base flow (Figure 4a, 9.6% of the energy) exhibits fluxes of opposite sense that are associated with the CW vorticity of the separating shear layer (centered about \(y/c = 0.95\)) and the CCW vorticity layers over the suction and pressure surfaces (centered about \(y/c = 0.50\)). The bleed actuation alters the first flux mode significantly (Figure 4b, 7.3% of the energy), where the magnitude of the flux of the separating shear layer is diminished, and alternating layers of flux of opposite sense are adjacent to the CCW flux from the pressure surface as a result of the continuous regulation of vorticity concentrations through the separated flow domain. These changes in the flow above the suction surface are also apparent from the cross-stream distributions of the velocity. The breakup of the vorticity layers from the suction and pressure surfaces are apparent in the second POD mode. While the mode of the base flow exhibits nearly-continuous opposite-sense layers of flux across the entire streamwise domain (Figure 4c, 5.0% of the energy), the bleed gives rise to spatial segmentation of the flux from the suction (CW) and pressure (CCW) surfaces (Figure 4d, 3.9% of the energy) indicating that the temporal modulation that is effected by the bleed affects the global circulation about the entire airfoil and therefore the flux from the pressure surface. This mode is accompanied by changes in the direction of the velocity modes as is evidenced by the upward vectoring of the flow past \(x/c > 0.45\). The third mode of the base flow (Figure 4e, 3.1% of the energy) and in the presence of bleed (Figure 4f, 3.6% of the energy) already exhibit higher order structure.

**Figure 4:** Color raster plots of POD modes of the vorticity flux across the near wake of the pitching airfoil \((k = 0.17)\) superposed with cross-stream distributions of vectors of the velocity modes \(\mathbf{\phi}_i, \mathbf{\phi}_j\) in the near wake of the pitching airfoil \((k = 0.17)\) in the absence (Figure 4a, c, e) and presence (Figure 4b, d, f) of bleed \((St_{act} = 1.1)\). The vertical excursion of the trailing edge of the airfoil is shown on the ordinate.
in the near wake, indicating fluxes of alternating sense (of CW and CCW vorticity concentrations) and with them alternating sense of the cross-stream velocity component. However, it is noteworthy that in the presence of the bleed the spatial distribution of these concentrations is altered, indicating that the bleed actuation leads to spatial modulation of the vorticity accumulation and shedding from the airfoil. It should also be noted that the first three modes of the base flow and in the presence of actuation account for 17.7% and 14.8% of the total energy, respectively. This is not surprising since the bleed leads to temporal and spatial modulation of the vorticity flux from the airfoil (which mitigates some of the adverse effects of dynamic stall).

It is instructive to consider the time coefficients of the vorticity flux POD modes during the pitch cycles, which are plotted in terms of the pitch angle in Figure 5a-f. The time coefficient of the first mode of the base flow (c₁, Figure 5a) indicates that the first mode is nearly temporally-invariant during the upstroke (even though the lift is increasing), and aside from sharp transitions at α₂₅₅ and α₃₅₅, the variation during the downstroke is also somewhat low. However, in the presence of bleed (Figure 5b), c₁ exhibits nearly linear increase punctuated by oscillations that are clearly associated with the actuation (although not at the actuation frequency) followed by a similar decrease during the downstroke with some hysteresis. It is remarkable the time coefficient of the second mode of the base flow (c₂, Figure 5c) is reminiscent of c₁ in the presence of bleed although the oscillations are not as pronounced and the traces that correspond to the upstroke and downstroke motions intersect at α = 18°. The time coefficient c₂ with bleed (Figure 5d) is similar to c₁ for the base flow (Figure 5e), and also to c₁ with bleed (Figure 5f). These findings underscore the observation that the bleed predominantly modulates the vorticity flux over the airfoil and into the near wake, and thereby affects the aerodynamic forces and moments as the pitch rate and the excursion in pitch angle increase.

The overall effects of bleed actuation on the pitch stability of the airfoil over a range of reduced frequencies k < 0.42 (f_cycle < 10 Hz) for 14° < α < 22° are demonstrated by considering the cycle damping coefficient and the cycle-averaged lift (Figures 7a and b). The variation of Eₙ with reduced frequency in the absence and presence of bleed (Figure 7a) shows that the base flow is most stable at k = 0.08 within the quasi-steady regime (Eₙ = 0.29), and thereafter the stability diminishes with increasing k, changing sign at k = 0.18. However, bleed actuation significantly enhances the pitch stability with increasing k with a peak at k = 0.17 (Eₙ = 0.72), and changes sign at k = 0.31 (maintaining an average increment of Eₙ = 0.88 above the baseline for k > 0.21). Furthermore, as shown in Figure 7b, bleed actuation is accompanied by small changes in the cycle-averaged lift compared to the baseline flow (with maximum increase and decrease of +4% and -5%, respectively).

The effect of the variations in vorticity flux in the presence of bleed on the global aerodynamic loads on the pitching airfoil is investigated by evaluating the phase-locked circulation about the airfoil using PIV measurements in the near wake. The circulation is computed by integration of the phase-locked vorticity flux through x = 0.3c downstream.
from the trailing edge:

\[ \Gamma(t) = - \int_0^t \int_{-\infty}^0 u \cdot \omega_z \, dy \, dt \]  

(2)

where \( u \) is the streamwise component of velocity, \( y \) is in the cross-stream coordinate, and \( \omega_z \) is the spanwise vorticity. Figures 6a, b, and c show the normalized circulation offset by the circulation computed from the cycle-averaged lift for the base airfoil and with time-periodic bleed for \( k = 0.08, 0.17, \) and \( 0.34 \) respectively (\( t = 0 \) corresponds to \( \alpha = 18^\circ \) during upstroke) along with the corresponding \( C_L \) (shown using dotted lines). When \( k = 0.08 \) (Figure 6a) in the absence of bleed (gray), both \( C_L \) and the circulation increase through \( t/T_{cyc} = 0.12 \) and 0.15 respectively as CW vorticity accumulates and is advected along the surface of the airfoil. The shedding of the vortex into the near wake is accompanied by sharp decreases in \( C_L \) and circulation that persist through \( t/T_{cyc} = 0.65 \), when the flow reattaches and circulation begins to increase. The phase difference between the lift and circulation measurements arises due to the advection time in the wake. The time-periodic bleed actuation (red) alters both the phase and magnitude of circulation of the base flow with a diminished peak during dynamic stall and faster recovery on the downstroke. While the magnitude of \( C_L \) in the presence of bleed exceeds that of the baseline airfoil for nearly \( 0.2 < t/T_{cyc} < 0.7 \), the cycle-averaged lift is virtually unchanged. Towards the end of the pitch cycle, the circulation becomes nearly invariant \((t/T_{cyc} > 0.55)\) until dynamic stall occurs during the upstroke of the following pitch cycle. The phase change in vorticity transport in the presence of bleed is even more pronounced at \( k = 0.17 \) (Figure 6b), where \( \Gamma_{max} \) and \( C_L \) with bleed precede the corresponding peaks on the base flow by \( t/T_{cyc} = 0.12 \) and 0.05, respectively. The bleed leads to an overall reduction in the variation of circulation during the pitch cycle including the abrupt loss in circulation following the shedding of the dynamic stall vortex.
(\dd T_{cy} > 0.1). On the downstroke, the bleed improves in circulation and lift recovery (0.35 < \dd T_{cy} < 0.85). Finally, as the reduced frequency is increased further to k = 0.34 (Figure 6c), the effects of the actuation on the lift and circulation are more muted. Although the circulation and lift in the absence and presence of bleed are similar throughout the pitch cycle, there is still a strong effect on the pitching moment and pitch stability as is evident from change in the timing of the shedding of the dynamic stall vortex in the presence of bleed which occurs earlier in the pitch cycle.

3 Conclusions

Aero-effected bleed actuation is used to regulate the production, accumulation, and advection of vorticity concentrations over the suction surface of an airfoil that is dynamically-pitching beyond its static stall angle at pitch rates that exceed the quasi-steady regime (k ≤ 0.42). The present investigation builds on the earlier work of Kearney & Glezer that demonstrated the efficacy of active bleed for tailoring the airfoil’s apparent aerodynamic shape without using external control surfaces. The interaction between time-periodic bleed and the cross flow over the surface is investigated using high-speed PIV coupled with measurements of bleed-effected alteration of the aerodynamic loads. The spatial and temporal structure of the vorticity flux that is associated with the formation and shedding of vorticity concentrations during the pitch cycle are explored using proper orthogonal decomposition (POD). The POD modes and their time coefficients as well as integral measures of the time-dependent bound circulation show that the bleed actuation leads to a shift in the timing of shed vorticity concentrations relative to the base flow. These changes in timing result in significant alteration of the aerodynamic loads that are manifested in a reduction in lift hysteresis during the pitching downstroke with minimal effect on the cycle-averaged lift. In addition, it is demonstrated that bleed actuation leads to a significant improvement in the pitch stability of the airfoil that is accompanied by a substantial reduction in “negative damping” over a wide range of pitch rates (or reduced frequencies). These findings indicate that time-varying bleed actuation can be used to control aero-structural characteristics of the airfoil and therefore mitigate its receptivity to vibrations and flutter.

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References


