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Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received  Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

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TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

An abstract has been submitted to the 2017 AHS conference in Fort Worth Texas in May, 2017. It has not yet been accepted, so it has not been uploaded.
Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

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(d) Manuscripts

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I have attached a 13 page report that documents the study in great detail. Sections in the report include: Introduction, Experimental Facility, Results, and Conclusions. It would be impossible for me to adequately summarize the work in this short block without being able to import the figures and tables. Please refer to the attachment.

**Technology Transfer**

Presented findings at ARO contractors meeting in July, 2016. Discussed preliminary findings with relevant parties at AHS 2016 in Palm Springs, FL.
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**Section II: Certification**

Certification by Contractor/Subcontractor:

I, the undersigned, certify to the contracting officer that the information contained herein is true and correct, and that the undersigned is properly authorized to execute this report.

[Signature]

Date: [Date]

**Section III: Additional Information**

[Additional Information]

[Signature]

Date: [Date]
Title: P1.1.2 Unsteady Aerodynamics - Synchronized Flow Control of Dynamic Stall under Coupled Pitch and Freestream Oscillations  
**PI:** Prof. Jeffrey P. Bons, The Ohio State University  
**Co-PI:** Prof. James W. Gregory, The Ohio State University  
**Duration:** 9 months, Short Term Innovative Research (STIR)  
**Budget:** $50k

### Project Abstract

This work presents results of an experimental investigation into synchronized active flow control of a Sikorsky SSC-A09 airfoil undergoing periodic pitching motion in an unsteady free stream using leading edge blowing. The airfoil was evaluated at reduced pitching frequencies up to \( k = 0.05 \) at steady Mach numbers of 0.2 and 0.4, and at \( k = 0.025 \) with phase-locked pitch and Mach oscillations at Mach 0.4±0.07 at Reynolds numbers from 1.5 to 3 million. A spanwise row of vortex generator jets (VGJs) located at 10% chord is fed by an oscillating valve that is phase-locked to the pitch oscillation of the airfoil. The oscillating valve can be set to produce a peak jet mass flux ratio \( (C_q) \) of 0.0022 or 0.0028 with a background \( C_q \) of half this value over the remainder of the period. The phase and duration of the peak \( C_q \) were varied to optimize the flow control benefits to both \( C_L \) and \( C_M \) hysteresis loops and reduce negative damping. Peak performance was observed with actuation initiated just after lift stall and continuing for 11% of the pitch cycle. Blowing beyond 11% resulted in no perceptible benefit. Compared to steady blowing flow control, the 11% synchronized control case delivers comparable (or better) performance with less than 50% of the massflow. The degree of stall control is a function of reduced frequency, mass flux ratio, and Mach number.
Synchronized Flow Control of Dynamic Stall under Coupled Pitch and Freestream Oscillations

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NOTATION

- \( c \): Airfoil chord
- \( C_L \): Lift coefficient
- \( C_M \): Moment coefficient
- \( C_p \): Pressure coefficient
- \( C_q \): Mass Flux Ratio
- \( f \): Physical frequency
- \( k \): Reduced frequency
- \( L_{act} \): Effective span of VGJs
- \( M \): Mach number
- \( \dot{m} \): Mass flow rate
- \( P \): Pressure
- \( U \): Velocity
- \( x \): Chordwise position
- \( \alpha \): Angle of attack
- \( \rho \): Density
- \( \Delta \Phi \): Phase difference between \( M \) and \( \alpha \)

Subscripts

- \( \text{avg} \): Average value
- \( \text{init} \): Jet initiation angle of attack
- \( j \): Jet
- \( \text{max} \): Maximum value
- \( \text{on} \): Jet on time as a % of pitching cycle
- \( \infty \): Freestream

INTRODUCTION

Dynamic stall (DS) is a performance-limiting phenomenon experienced by rotorcraft in forward flight and in maneuvers. The lift and moment stall due to the shed vortex can produce significant variations in pitching moment. The transient, very high pitch link loads resulting from dynamic stall force design choices that add to the weight of the vehicle, and limit the operational envelope of the rotorcraft.

Relevant studies of dynamic stall stretch over four decades, such that the basic phenomena of dynamic stall under static freestream conditions are thoroughly documented (McCroskey et al., Ref. 1, and Carr, Ref. 2). Contemporary investigations of the intricate details of dynamic stall are also currently underway (Geissler et al., Ref. 3; Mulleners and Raffel, Ref. 4; Raghav and Komeraath, Ref. 5; Pruski and Bowersox, Ref. 6; and Muller-Vahl et al., Ref. 7). Due to large amplitude pitching motions, compressibility effects can be important for onset Mach numbers as low as 0.2. The state of the boundary layer and its susceptibility to separation are in turn functions of Reynolds number. Thus, the two flow parameters are strongly coupled. Typical onset Mach and Reynolds number ranges are 0.2-0.3 and 2-6 million, respectively, for retreating blade stall.

The majority of helicopter rotor dynamic stall studies reported in the literature have been conducted in constant velocity wind tunnels with either a 2D airfoil pitching (or plunging) at the appropriate reduced frequency. In reality, since the rotor stall occurs during the retreating blade motion (at advance ratios approaching 0.3-0.4), the component of the vehicle advance velocity “seen” by the retreating airfoil also varies during the dynamic stall event. Thus, in a rotor-relative frame, both the approach flow angle (due to

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pitch/plunge) and magnitude are time-varying. This time-varying relative velocity has a direct influence on the severity of the local pressure gradient and thus, the formation of the dynamic stall process as shown by Ericsson (Ref. 8). Several researchers have investigated the combination of airfoil pitching and relative velocity oscillations (Pierce et al., Ref. 9; Favier et al., Ref. 10; and Furman et al., Ref. 11) and concluded that a strong coupling exists between the two modes of oscillation. Of note, all of these studies have been conducted at incompressible flow speeds below Mach 0.1. Recently, Hird et al. (Ref. 12) studied the combined effects of fluctuating pitch and freestream velocity at a mean Mach number of 0.4 and at reduced frequencies up to \( k=0.05 \) (conditions equivalent to a rotor advance ratio of 0.2). They found that the peak \( C_{L_{max}} \) was increased well beyond the peak value observed in steady freestream conditions. They also reported a more abrupt lift stall without a significant change in the stall angle. It is anticipated that these differences between steady and unsteady Mach will only be exacerbated at advance ratios closer to those experienced at typical dynamic stall onset (0.3-0.4).

Numerous attempts have been made to implement flow control on a dynamically pitching airfoil and limit the negative effects of dynamic stall. Chandrasekhar et al. (Ref. 13) implemented a dynamically deforming leading edge model (DDLE) that modified the leading edge radius to adapt to high vs. low flow Mach numbers. Though the authors indicated that the DDLE could be operated in dynamic mode, the report only includes static LE deformation. Other passive flow control strategies have also been implemented with some success (LE slat - Carr et al., Ref. 14, variable droop leading edge, Martin et al., Ref. 15, and trailing edge flaps, Gerontakas et al., Ref. 16). Active blowing has also been very effective as demonstrated by Greenblatt and Wygnanski (Ref. 17), Singh et al., (Ref. 18), Gardner et al. (Ref. 19), Naigle et al. (Ref. 20) and Matalanis et al. (Ref. 21). All of these blowing cases have either been steady or pulsed at a frequency much higher than the pitch oscillation frequency (so that phasing or synchronizing the control was not attempted). Though the continuous blowing strategies have shown considerable success at improving mean lift and muting the moment spike, virtually all of the researchers recognized the potential value of synchronizing the fluidic actuation with the pitch oscillation. This would allow the control to only be employed when it is beneficial to the airfoil performance as well as reducing the massflow requirement. Post and Corke (Ref. 22) did synchronize SDBD plasma actuators with the pitch oscillation and showed that this was more effective than continuous actuation through the complete pitch oscillation, though their flow Mach number was 0.03 (incompressible). Moreover, none of these flow control studies have included Mach oscillation.

More recently, Tran et al. (Ref. 23) modeled synchronized blowing from a synthetic jet on a pitching SC1095 airfoil using unsteady RANS. When comparing continuous actuation to partial actuation (for just 30% of the pitching cycle), they found that synchronized partial blowing actually outperformed continuous blowing. Though no optimization of the timing was presented, the jets were actuated at 17° on the upstroke (before lift stall) and terminated at 18.5° on the downstroke (pitch oscillation was from 10 to 20°). Finally, Matalanis et al. (Ref. 24) integrated a row of combustion actuators (COMPACT) into a VR-12 airfoil and varied the starting phase and duration over a wide range of parameters. Experimentally, they showed that actuation for more than 30% of the pitch cycle provided no additional benefit in terms of cycle-averaged lift. Optimum actuation occurred when initiating the \( F^2=0.4 \) pulsed forcing following the lift stall and just prior to moment stall. Experiments were run over relevant ranges of Mach number (0.2 to 0.4) and reduced frequency (0.05 < \( k < 0.1 \)).

The aforementioned flow control studies were all done on oscillating airfoils in a steady freestream. Herein lies the motivation for this study; to expand active flow control using VGJs with synchronized oscillations of both airfoil pitch and freestream Mach number, at reduced frequencies and Reynolds numbers representative of realistic helicopter operating conditions.

**EXPERIMENTAL METHODOLOGY**

Data collection was conducted in the 6"x22" blowdown transonic wind tunnel at The Ohio State University, the design and capabilities of which are detailed by Gompertz et al. (Ref. 25). The tunnel has electrically operated rotating mechanisms to oscillate the airfoil pitch and the freestream Mach number synchronously. Figure 1 is a schematic of the tunnel and Fig. 2 shows the range of possible operating conditions for the tunnel. The freestream flow is supplied to the test section through a 20 cm (8 in.) supply line from two 42.5 m³ (1500 ft³) air storage tanks pressurized up to 17 MPa (2500 psi) with in-line air dryers to control condensation. The high pressure air flow is controlled by two valves. The first is a control valve which sets the total pressure. The flow density and Reynolds number for the experiment are established by the total pressure combined with the flow temperature. The second valve is a fast acting valve used to start and stop the flow. The maximum limiting pressure of the wind tunnel is 350 kPa (50 psia). The settling chamber is equipped with a perforated plate, a honeycomb section, and eight screens (60-mesh) to condition the flow and lower the test-section turbulence intensity to less than 0.5% under steady flow conditions. A subsonic nozzle with a contraction ratio of 15:1 further establishes flow uniformity in the 15.2 cm x 55.9 cm test section, which is 1.1 m long. The solid sidewalls have clear and opaque windows to hold the airfoil, while the spanwise floor and ceiling walls are perforated with 3.2-mm straight holes yielding an effective porosity of 6 percent. These isolation cavities are open to the flow only downstream of the test section and aid in producing a high quality flow in the test section by reducing Mach wave reflections in transonic flow.
Mach oscillations are produced by a set of four elliptical choke vanes driven by a stepper motor slaved to the pitch oscillation motor. The choke vane stepper motor is slaved such that the Mach oscillation frequency is synchronized to the pitch oscillation frequency at a desired phase delay through a predetermined phase offset ($\Delta\Phi$). For this study, $\Delta\Phi$ was set to 180°, which is the realistic flow condition for a rotor in forward flight. As the blowdown tunnel is operated at a sufficiently high pressure ratio to choke the flow at the downstream throat, the throat area produced by the choke vanes uniquely modulates the test section Mach number. Gompertz et al. (Ref. 25) characterized these details of the wind tunnel and calculated pressure wave propagation through the tunnel. Due to the oscillating frequencies of the elliptical choke vanes and the pressure translation through the tunnel, the resultant Mach amplitude varies slightly at higher reduced frequencies from an ideal sinusoidal pattern of $M = 0.4 \pm 0.07$ as depicted in Fig. 3. At low reduced frequencies, the variation in Mach number matches the predicted sinusoid well, but at the highest reduced frequencies, there is some distortion of the waveform as well as a phase lag. However, in all cases, the mean Mach remains at 0.4.

**Instrumentation and Test Article**

The airfoil used for this study was a milled aluminum SSC-A09 model with span and chord of 15.2 cm (6 in.) resulting in an aspect ratio of 1 (Fig. 4). The model was fitted with 30 pressure taps on the suction surface and 23 taps on the pressure surface. The pressure taps were connected to two ESP 32HD pressure scanners via flexible tubing of 1 mm in diameter and approximately 20 cm long. A hardware-triggered DTC Initium interface read in the multiplexed analog output of the scanners at 1000 Hz and streamed the data to a dedicated hard disk. The scanner...
Figure 3: Empty Tunnel Mach Variation with Reduced Frequency.

Figure 4: SSC-A09 Airfoil with Spanwise VGJs and Surface Pressure Taps.

The measurements of the unsteady pressures. All results in this paper have been appropriately compensated based on this combined analytical/experimental model.

The airfoil was fabricated with a row of spanwise vortex generating jets near the leading edge. The VGJ diameter and spacing are 1% and 5.6% of airfoil chord, respectively (see Fig. 4). For all of the results in this study, every other hole was filled and sanded smooth creating a new spacing of 11.2% of airfoil chord and spread over the center 10 cm (4 in) of span (Lact). The VGJs are located at 10% chord as this was the typical release point for the dynamic stall vortex on the SSC-A09 airfoil, as determined by Lorber and Carta (Ref. 27) at comparable reduced frequencies and Mach number. The VGJs are oriented normal to the surface, which is similar to the configuration determined by Gardner et al. (Ref. 19) to be optimal for dynamic stall control at higher maximum angles of attack. An internal uniform cavity with a diameter of 3mm (0.125 in.) at 10% chord served as a VGJ manifold and connected the airfoil to the high pressure air source through a threaded steel tube.

High pressure air was stepped down from greater than 10.3 MPa (1500 psi) to a maximum of 2 MPa (300 psi) before entering the oscillating valve shown in Fig. 5. The valve consists of a cylindrical plenum with an entrance and exit port. The exit port is covered by a circular disk that seals to the plenum walls. The disk is connected to a shaft that enters the plenum through the opposing wall. The shaft, in turn, is connected to a belt pulley that is driven by the same linkage that drives the airfoil pitch oscillation. The disk has a cutout that lines up with the plenum exit port to produce the pulsed jet. Cutouts of 15, 40, and 60 degree width were used to create high pressure pulses of 4.2%, 11.1%, and 16.7% of the pitching period. The initiation of the high pressure release is controlled by adjusting the alignment of the cutout with the exit port. In this study, alignments were chosen to trigger the high pressure pulse just after lift stall (α = 17°, 18°, and 19°), based on the findings of Matalanis et al. (Ref. 24).

Figure 5: Oscillating valve used for synchronized blowing. 40° disk shown in inset.
A pressure transducer and thermocouple were installed on the piping upstream of the flexible tubing that connects the oscillating valve to the airfoil. The instrumental uncertainty for the pressure gauge and thermocouple are ±5 psig and ±0.1K, respectively. The time history of exiting massflux from the VGJs during unsteady wind tunnel operation was estimated as follows. With the wind tunnel off and steady flow through the VGJs, the massflux was measured with an Alicat MCR Series 3000 SLPM mass flow controller and correlated to the measured pressure difference between the tubing just outside the airfoil to the static pressure at the VGJ exit. This correlation was then used to estimate the massflux during unsteady operation using the same delta pressure measurement with the airfoil pitching in the unsteady freestream. It is acknowledged that during unsteady operation there is likely to be some modulation of the pulse amplitude from the pressure measurement location to the VGJ exit, but this was not accounted for.

The calculation of jet mass flux ratio ($C_q$) is defined below where $m_j$ is the mass flow rate of the jets, $\rho_\infty$ and $U_\infty$ are freestream density and velocity, respectively, and the effective span with VGJs fitted is $L_e$. 

$$C_q = \frac{m_j}{\rho_\infty U_\infty e L_e}$$

Samples of $C_q(\alpha)$ histories are provided in Fig. 6 for the “High” supply pressure and all 3 cutout disks at Mach=0.2 and $k=0.05$ (the trends are similar for the other cases studied). In this figure, actuation was initiated at $\alpha=18^\circ$.

As is evident from Fig. 6, the massflux from the VGJs is not uniform over the pulse duration, instead exhibiting a sharp peak immediately following the disk cutout alignment with the output port of the oscillating valve plenum. Due to compressibility of the air in the valve plenum, the flexible tubing, and the airfoil plenum, the sharp peak is followed by a gradual drop as shown. The shape of this drop off varies with the duration of the pulse (4.2%, 11.1%, or 16.7%). The figure also shows that due to leakage around the rotating disk in the plenum, the massflow does not drop to zero, instead holding at some constant value throughout most of the upstroke. To facilitate comparison between synchronized and continuous (steady) actuation, several tests were conducted with constant blowing levels (bypassing the oscillating valve altogether). These steady $C_q$ levels are indicated on Fig. 6 as well. An attempt was made to test at steady blowing values corresponding to the peak jet velocity and a lower value for both operating pressures. These steady comparisons are identified as “Peak” and “Mean” in the plot and will be referred to later. It should be noted that the 11.1% $C_q$ time history differs noticeably from the others at both Low and High pressure settings. This is thought to be due to a better sealing of the 40° disk during rotation.

**DATA ANALYSIS**

As this is a transient tunnel, the tunnel conditions are constant for a period of 6 seconds during which time surface and tunnel pressure data are acquired at 1000 Hz. The data are analyzed and truncated as necessary to eliminate tunnel acceleration or deceleration transients. The resultant sample for steady data is time-averaged over 4.5 seconds. The unsteady data are phase-averaged over 14 to 56 cycles depending on the pitching frequency with higher frequency associated with more averaged cycles. Calculations for lift and moment coefficients were obtained by trapezoidal integration of the measured pressure distributions.

![Figure 6: $C_q$ vs. $\alpha$ time history for 15° (4.2%), 40° (11.1%), and 60° (16.7%) cutout disks at Mach=0.2 and $k=0.05$ for the “High” pressure level. Steady blowing $C_q$ values for peak and mean pressure also indicated. Arrows indicate direction of pitching motion in time.](image)

Temperature, pitch, and Mach phase revolutions were acquired at 100 kHz for 10 seconds such that temperature and phase data overlapped the duration of pressure acquisition. Lift and moment coefficient calculations were synchronized with the corresponding angle of attack (from an optical encoder) to generate lift and moment loops.

An analysis was conducted in the manner outlined by Coleman and Steele (Ref. 28) to estimate the relevant calibration uncertainties with the wind tunnel in steady-flow mode. Gompertz et al. (Ref. 25) showed tunnel-relevant dominant uncertainty estimates based on pressure instrumentation to be: Mach number, ±0.005; Reynolds number, ±5,000; angle of attack, ±0.05°; $C_p$, ±0.05; $C_L$, ±0.05; and $C_M$, ±0.02. The uncertainty of the jet mass flux ratio ($C_q$) is ±0.00005, though this does not account for differences between the pressure measured at the inlet to the VGJ plenum and pressure at the inlet to each VGJ (as discussed above).
RESULTS AND DISCUSSION

Baseline, No Control, Steady Freestream:

Figure 7 show the uncontrolled pitching airfoil $c_L$ and $c_M$ hysteresis loops for the case of steady flow at $M=0.2$. Results are included for $k=0.025$ and 0.05 to show the effect of reduced frequency. Arrows are added to the plots to indicate the direction of the pitching motion in time. The $k=0.025$ case shows greater unsteadiness only because it represents an average of half as many pitch oscillations.

Figure 7: $C_L$ and $C_M$ vs. $\alpha$ for Mach=0.2 and $k=0.025$ & 0.05. Baseline case with no blowing. ($\alpha=9^\circ \pm 11^\circ$). Arrows indicate direction of pitching motion in time.

From Fig. 7 it is clear that the increase in reduced frequency results in larger hysteresis in both $c_L$ and $c_M$. The lift recovery moves from $12^\circ$ at $k=0.025$ to below $8^\circ$ for $k=0.05$. The negative damping region in the $c_M$ loop (region of clockwise rotation) also changes with reduced frequency as does the peak negative moment spike.

As the steady flow Mach number is increased from 0.2 to 0.4, the lift slope increases slightly and the stall is earlier and less abrupt (all as expected) with a lower peak $c_L$ (Figs. 8a&b). The moment stall is also less severe and the negative pitching spike is muted somewhat. The results with $k$ and $M$ in Figs. 7 and 8 are consistent with dynamic stall trends documented by numerous researchers.

Synchronized Control, Steady Freestream:

Synchronized VGJ control was studied for a variety of test conditions with a steady freestream before application in an unsteady freestream. Flow control variables include: (1) High or Low pressure (2) actuation initiation ($\alpha_{init}$) of $17^\circ$, $18^\circ$, or $19^\circ$ and (3) actuation duration ($\alpha_{dur}$) of 4.2%, 11.1%,
and 16.7% of the pitching period. Figure 9 shows the $c_L$ loop only for $\alpha_{\text{init}} = 19^\circ$ and $\alpha_{\text{on}} = 11.1\%$ at $M=0.2$ and $k=0.05$. Data for both the low and high pressure actuation are shown. In this case, and all other cases, the high pressure case was notably superior to the low pressure case. The low pressure actuation did not sustain the lift enhancement during the downstroke following stall and the lift recovery is essentially equivalent to the baseline case ($8^\circ$). The high pressure actuation case also delays the lift stall slightly (by 1 degree) while the low pressure case does not. Though not shown, the maximum negative $c_M$ (moment spike) is reduced for the high pressure actuation case and the negative damping is slightly lower. Accordingly, all remaining plots will be for the high pressure case only. By way of comparison, Fig. 9 also includes the $c_L$ loop for steady actuation at both the “Peak” and “High” levels introduced in Fig. 6. Already we see that the synchronized actuation is at least as effective as the steady “High Blowing Peak” case, of course with lower net massflow required.

For $\alpha_{\text{init}} = 18^\circ$, lift stall is delayed to a higher angle of attack, whereas pulsing at $\alpha_{\text{init}} = 19^\circ$ has a higher average $c_L$ during the downstroke. Due to the later lift stall for $\alpha_{\text{init}} = 18^\circ$, the moment stall is also delayed, reducing the moment spike. At the same time, with $\alpha_{\text{init}} = 19^\circ$ the negative damping is nearly eliminated from the $c_M$ loop. Since initiating actuation beyond lift stall misses the opportunity to influence the moment spike, $\alpha_{\text{init}}$ values greater than $19^\circ$ were not attempted in this study.

The next variable studied was the actuation initiation angle, $\alpha_{\text{init}}$. Figure 10 includes the $c_L$ and $c_M$ hysteresis loops for the case of steady flow at $M=0.2$ ($k=0.05$) with $\alpha_{\text{init}} = 17^\circ$, $18^\circ$, and $19^\circ$. Data are shown for the high pressure setting (as indicated earlier) with the 40° cutout disk (11.1% of the full pitching period). For this case, the $18^\circ$ and $19^\circ$ initiation angles yielded very similar results, while the $17^\circ$ case was definitely inferior. This was generally true for all test conditions and corroborates the findings reported by Matalanis et al. (Ref. 24) given that the baseline stall angle is approximately $18^\circ$.

With the focus now turned to the pulse duration, Fig. 11 includes all 3 cutout disks (4.2%, 11.1%, & 16.7%) with $\alpha_{\text{init}} = 19^\circ$ for the same conditions in Fig. 10 ($M=0.2$, $k=0.05$).
The lift stall is delayed and the recovery $C_L$ has the highest average value. At the same time, the $\alpha_{on} = 11.1\%$ case virtually eliminates the negative damping in the $c_M$ loop and has a less severe moment spike compared to the $16.7\%$ case. Since the pulse waveforms differ substantially for the $\alpha_{on} = 11.1\%$ and $16.7\%$ cases (as shown in Fig. 6) there is some uncertainty as to which attributes of the pulse waveform are responsible for the improvements at $11.1\%$ and $16.7\%$: the duration of the peak actuation, the lower level of blowing during the “off” cycle, or the “flat” vs. “double-hump” waveform shape. Further study is clearly warranted with a more precise actuation waveform.

To better understand the interaction of the VGJs with the DS vortex it is helpful to look at the unsteady pressure distribution on the suction surface of the airfoil. Figure 12 contains $c_p$ contour plots for 3 cases in an x-$\phi$ format. Chordwise position is plotted on the x-axis while the y-axis is the phase position in the pitching cycle. Data are shown for the baseline case and both steady and synchronized actuation ($\alpha_{init} = 19^\circ$) at M=0.2 & k=0.05. In the baseline case, evidence of stall occurs near $\phi = 150^\circ$ as the suction peak near the leading edge drops off abruptly. The low pressure zone associated with the DS leading edge vortex can then be seen convecting downstream, reaching the trailing edge near $\phi = 170^\circ$. There is some evidence of a secondary vortex shed near $\phi = 200^\circ$ before full lift recovery occurs for $\phi > 240^\circ$. With synchronized blowing, the footprint of the DS vortex is not as severe, attenuating earlier during the convection process. Also, the secondary vortex is not apparent and lift recovery is earlier and more stable. While many of the same observations can be made for the steady blowing case (High Blowing Peak), the synchronized actuation is definitely superior. This is all the more remarkable since the synchronized actuation case uses less net massflow.

At the higher Mach number (M=0.4), testing was conducted over a more limited range: $\alpha_{on} = 11.1\%$ & $16.7\%$, $\alpha_{init} = 18^\circ$ & $19^\circ$ with “High” pressure only. Figure 13 includes the $c_L$ and $c_M$ hysteresis loops for the case of M=0.4 (k=0.025) with $\alpha_{init} = 18^\circ$ and $19^\circ$. Data are shown for the high pressure setting with the 40° cutout disk (11.1% of the full pitching period). Many of the features evident at the lower Mach number are evident here as well. Since peak $c_L$ happens earlier at M=0.4 (just past $\alpha = 15^\circ$ vs. $18^\circ$ at M=0.2), VGJ actuation is initiated during lift stall, which is much more gradual at this Mach number and reduced frequency. Synchronized blowing very nearly matches the performance of the steady “High Blowing Peak” case, which is also shown in Fig. 13. There is very little distinction between the results for actuation at $\alpha_{init} = 18^\circ$ & $19^\circ$, the latter case exhibiting a slightly reduced negative damping with an earlier moment (lift) recovery.

Figure 14 shows the $c_L$ and $c_M$ hysteresis loops for the case of M=0.4 (k=0.025) with $\alpha_{on} = 11.1\%$ & $16.7\%$. Data are shown for the high pressure setting with $\alpha_{init} = 19^\circ$. The only significant difference noted is in the $c_M$ loop, where the added massflow ($16.7\%$) exacerbates the secondary spike during moment stall.
Figure 12: $C_p$ contour plots ($x/c$ vs. $\phi$) for Mach=0.2 and $k=0.05$. Baseline case with no blowing compared to steady blowing at “Peak” pressure and synchronized blowing at $\alpha_{on} = 11.1\%$, $\alpha_{init} = 19^\circ$, and “High” pressure. ($\alpha=9^\circ \pm 11^\circ$).

Figure 13: $C_L$ and $C_M$ vs. $\alpha$ for Mach=0.4 and $k=0.025$. Baseline case with no blowing compared to synchronized blowing with 2 initiation angles, $\alpha_{init} = 18^\circ$ & $19^\circ$ for $\alpha_{on} = 11.1\%$, and “High” pressure. Steady actuation at “Peak” and “Mean” settings also included. ($\alpha=9^\circ \pm 11^\circ$).
Figure 14: $C_L$ and $C_M$ vs. $\alpha$ for $M=0.4$ and $k=0.025$. Baseline case with no blowing compared to synchronized blowing with 2 actuation durations, $\alpha_{on}=11.1\%$ & 16.7\%, for $\alpha_{init}=19^\circ$ and “High” pressure. Steady actuation at “Peak” and “Mean” settings also included. ($\alpha=9^\circ \pm 11^\circ$).

Figure 15: $C_p$ contour plots ($x/c$ vs. $\phi$) for $M=0.4$ and $k=0.025$. Baseline case with no blowing compared to steady blowing at “Peak” pressure and synchronized blowing at $\alpha_{on}=11.1\%$, $\alpha_{init}=19^\circ$, and “High” pressure. ($\alpha=9^\circ \pm 11^\circ$).

The pressure coefficient contour maps for $M=0.4$ and $k=0.025$ are shown in Fig. 15 for the baseline, steady (peak) blowing, and synchronized blowing cases ($\alpha_{on}=11.1\%$ at $\alpha_{init}=19^\circ$). The lift stall phenomenon occurs earlier than in Fig. 12 and is unaffected by the actuation due to the later $\alpha_{init}$. In fact, the lift stall for all 3 contour maps looks identical, even for the case of steady blowing throughout the entire pitch cycle. Again, the sharp peak of the synchronized blowing case appears to mute the secondary stall event at $\phi=145^\circ$. The lift recovery from $225^\circ < \phi < 300^\circ$ is more pronounced and sustained for the 2 actuation cases compared to the baseline $c_p$. Since the steady (peak) actuation case delivers the same massflow as the maximum value attained by the synchronized blowing (see Fig. 6), it is
clear that the impulsive opening of the oscillatory valve creates a dynamic that is singularly beneficial for effective flow control.

Figure 16: $C_L$ and $C_M$ vs. $\alpha$ for steady $M=0.4$ vs. oscillating Mach = 0.4±0.07 at $k=0.025$. Baseline case with no blowing. ($\alpha=9^\circ \pm 11^\circ$).

Baseline, No Control, Unsteady Freestream:
Figure 16 shows the uncontrolled pitching airfoil $C_L$ and $C_M$ hysteresis loops for the case of steady $M=0.4$ vs. oscillating Mach = 0.4±0.07 at $k=0.025$. For the unsteady freestream case, the Mach oscillation is 180° out of phase with the pitch oscillation such that at the peak $\alpha$ the Mach number is at its minimum value, as would be the case for a helicopter rotor in forward flight (Fig. 17).

As shown previously by Hird et al. (Ref. 12), the decelerating freestream combined with the aggressive pitch up motion exacerbate the hysteresis producing a higher $C_L$ max and a depressed post-stall recovery. The remainder of the $C_L$ loop (the lift slope and the increased lift during the attached part of the pitch down motion) is virtually unchanged. The effect of the freestream deceleration on $C_L$ max is partly obfuscated by the lower freestream velocity in the denominator of the lift coefficient normalization. Figure 17 shows the phase history of angle of attack and Mach number for the unsteady Mach case. The 12.5% drop in $M$ (from the mean value of 0.4 to 0.35 at $\alpha = 16^\circ$) translates to a 23% drop in dynamic pressure (and thus a commensurate increase in $C_L$). So, if the physical lift force on the pitching airfoil at $C_L$ max was the same in the steady and unsteady Mach cases, the peak $C_L$ would increase from 1.4 to 1.82 from the normalization alone. The fact that the peak $C_L$ only reaches 1.5 indicates a much weaker suction peak due to the decelerating freestream. Accordingly, the moment spike in the $C_M$ plot is also muted in the oscillating Mach case.

Similarly, in the post-stall recovery during the downstroke from $\alpha = 20^\circ$ to $10^\circ$, the unsteady Mach number (and normalizing dynamic pressure) is still below the mean value, which should artificially raise the lift coefficient. Yet, $C_L$ with the oscillating freestream is lower than the steady Mach case during this recovery. Though the freestream Mach is accelerating, the vestiges of the flow deceleration up to $\alpha = 20^\circ$ must continue to have a destabilizing effect on the recovery of the separated boundary layer.

Synchronized Control, Steady Freestream:
Since the simultaneously oscillating pitch and freestream case is the most challenging to execute, an even more abbreviated test series was conducted in this case: $\alpha_{init} = 17^\circ$. 

Figure 17: Phase history of $\alpha$ and Mach number for the oscillating Mach = 0.4±0.07 case at $k=0.025$. Location of max $C_L$ noted with dashed lines.
18°, & 19° at \( \alpha_{\text{init}} = 11.1\% \) and “High” pressure only. Figure 18 includes the \( c_L \) and \( c_M \) hysteresis loops for these three cases with Mach = 0.4±0.07 at \( k=0.025 \). Many of the features evident in the corresponding steady Mach number case (Fig. 13) are evident here as well. In all 3 cases, VGJ actuation is initiated during lift stall, and thus no effect is obvious until the lift recovery phase on the downstroke. During this time, lift is augmented, the lift performance is recovered earlier, and the negative damping is reduced substantially. There is however very little distinction between the results for different actuator initiation angles; \( \alpha_{\text{init}} = 19° \) exhibits the smallest negative damping and moment spike while 18° has the best moment (lift) recovery. Though the steady “Peak” and “Mean” blowing cases were not tested in this case, it is anticipated that the synchronized result would be comparable to the steady “Peak” case and superior to the steady “Mean” case, as has been demonstrated repeatedly. Thus, the added freestream dynamic does not impair the ability of synchronized blowing to effectively recover 10-15% of the lift (compared to the baseline) and reduce negative damping by 60-70% in the post-stall regime.

CONCLUSION

Synchronized dynamic stall control with unsteady blowing on a SSC-A09 airfoil was investigated with dynamic pitching motion at steady Mach 0.2 and 0.4 as well as dynamic pitching phase-locked with an oscillating freestream at Mach 0.4±0.07. The Reynolds numbers for the experiments were 1.5M and 2.9M at each Mach number. Flow control variables included: (1) High or Low pressure (2) actuation initiation (\( \alpha_{\text{init}} \)) of 17°, 18°, or 19° and (3) actuation duration (\( \alpha_{\text{on}} \)) of 4.2%, 11.1%, and 16.7% of the pitching period. Actuation was found to be most effective when initiated just after lift stall and maintained for at least 11% of the pitching cycle. Blowing beyond 11% provided no appreciable benefit. With actuation, post-stall lift was enhanced, lift recovery occurred sooner, and negative damping was reduced substantially. For select cases, a very modest benefit was seen in the lift stall delay and the moment spike amplitude as well. Pressure contours clearly show that the unsteady nature of the synchronized blowing serves to damp out the secondary stall event and produce a stronger, earlier lift recovery. When compared with steady blowing at the same maximum VGJ amplitude, synchronized blowing at an optimized start time and duration produces equivalent stall suppression while requiring up to 50% less massflow.

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REFERENCE


Figure 18: \( C_L \) and \( C_M \) vs. \( \alpha \) for Mach = 0.4±0.07 case at \( k=0.025 \). Baseline case with no blowing compared to synchronized blowing with 3 initiation angles, \( \alpha_{\text{init}} = 17°, 18°, \) & 19° for \( \alpha_{\text{on}} = 11.1\% \), and “High” pressure. (\( \alpha=9° \pm 11° \)).


