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Effects of Synthetic Jets on Large-Amplitude Sinusoidal Pitch Motions

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Nomenclature

Cl = sectional lift coefficient
Cm = sectional quarter-chord pitching-moment coefficient
$C\mu$ = jet-momentum coefficient
c = airfoil chord
$F+$ = nondimensional actuator frequency
f = angular pitch rate
k = nondimensional pitch rate
sw = slot width, mm
U = freestream velocity
V = jet velocity

Subscripts

max = maximum
rms = root mean square

Introduction

RAPID airfoil motions, caused by either rapid pitching during maneuvering or the cyclic pitching of a rotorcraft blade, can cause significant changes in the aerodynamic characteristics compared to the static (equivalent incidence) case. The linear region of the lift curve can be significantly extended beyond the static stall, which might be caused by boundary-layer improvement effects (i.e., leading-edge jet and moving wall effects[1]). Depending on the pitch rate, this linear extension can either terminate in a conventional quasi-static-type stall or a significant nonlinear lift overshoot, caused by the formation of a dynamic stall vortex (DSV).[2] This vortex is a large-scale coherent vortical structure that typically forms near the quarterchord of the wing. After formation, this structure advects rearwards.[3,4] Vortex passage is indicated by large moment excursions, reaching a maximum with vortex location over the trailing edge. The effects of DSV formation are seen as undesirable as a result of these moment excursions and possible fatigue of oscillatory loaded surfaces. The DSV affects the performance of helicopter rotors (causing fatigue and limiting the cruise speed), wind turbines, and turbomachinery. Methods to attenuate their impact include active flow control methodologies such as pulsed vortex generators,[5] slot suction,[6] and blowing.[7] Structural modifications include slats,[8] leading-edge droop,[9] as well as shape variable airfoils.[10] Effects of synthetic jet actuators (SJAs), both with[11] and without[2] passive vortex generators, have been explored on a ramp and hold NACA 0015 wing. Greenblatt and Wygnanski[12] have performed experiments showing the effect of fluidic actuation on a NACA 0015 airfoil performing oscillations. The airfoil excursion angle was 5 deg around the mean. Their data showed that for the test parameters, fluidic actuation attenuated the moment excursions and increased the lift-to-drag ratio.

Oscillatory fluidic actuators, exemplified by the SJA, have been shown to be a highly effective means for viscous fluid control. Studies have shown synthetic jets to be effective and efficient in controlling flow separation under both static[13,14] and dynamic[2,11,12] conditions. The SJA actuator consists of a cavity, which is bounded by a moving wall on one side and an inlet/exit slot on another. Oscillation of the wall (or piston—depending on the particular method of implementing the jet) causes a periodic inflow and outflow of fluid, such that no net mass is transferred; however, momentum transfer is finite, as the inflow area greatly exceeds that of outflow. The jet can be exhausted tangentially or obliquely to the surface, depending on the desired effect, or tangentially for separation control and obliquely for so called "virtual shaping," such that the potential pressure distribution around the wing is altered. The compact nature of the SJA design can also allow the device to be placed locally where required without the need for pneumatic ducting.

The mechanism for synthetic jet operation is well documented.[15] Shear layers are generally, highly receptive to disturbances. The SJA, when pulsed in the correct frequency range, can cause the shear layer to resonate, which is associated with the formation of coherent structures. The shear layer generally locks into the driving frequency or one of its harmonics. As a result, the shear layer forms discrete vortices, which then pair or merge, ultimately forming larger, stronger coherent structures with a lower frequency. As they advect downstream, these vortices behave in a similar fashion to those injected by conventional vortex generators. They mix high-momentum freestream fluid into the boundary layer, energizing it. Increasing the forcing frequency causes the formation of smaller, more closely spaced discrete vortices.

In this Note, an experimental investigation into the effects of large-amplitude sinusoidal pitching on calculated lift and pitching moment is presented.

Experimental Equipment and Procedure

The wind-tunnel model used in this investigation is well documented (see Ref. 16). The wing's profile was that of a NACA 0015 with a chord of 420 mm. Tests were undertaken in Texas A&M Universities 3 × 4 ft closed return wind tunnel at a freestream

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velocity of 20 m/s (Mach number = 0.06), giving a chord-based Reynolds number of 0.57×10^6. No wind-tunnel wall interference or blockage corrections were applied to the data, as their application for dynamic motions is uncertain at best. All instrumentation was self-contained in the wing. The SJA exit slot was located at 12% of the chord. A study[17] has shown successful implementation of SJA control with the exit port in this location for NACA 4 series profiles, and the size of the employed SJA necessitated that it be positioned in the thickest part of the wing, which resulted in an exit slot at 12% chord. For details of the SJA, see Ref. 16. A slot width of 1.2 mm was used in all data reported herein. The length of slot over each piston chamber was 41 mm.

Surface pressures were measured over the wing using a 32-channel electronic scanning pressure (ESP) pressure scanner. The scan rate for this instrument is given by the manufacturer as 20 kHz. The ranges of the 32 embedded transducers is $\pm 10 \text{inH}_2\text{O}$ (± 2.49 kPa). Location of the ports is given in Ref. 16. Prior to use, the ESP was calibrated using an Edwards's barocel as a reference. Sequential checks of the validity of the calibration indicated pressure deviations of no more then 0.3% of the calibration values. To account for acoustic effects, the instantaneous pressures were corrected using the method of Wildhack.[18] To ensure quasi-two-dimensional behavior, side plates were mounted on the wing. Forces and moments were calculated through integration of the pressure distribution around the wing. The upper and lower surface-pressure traces were fitted using cubic splines. The splines were then integrated to yield forces and moments. Presented moment coefficients are about the quarter-chord.

The wing was pitched using a maxon dc motor connected to the wing's pitch strut through a 43:1 maxon reduction gearbox. During a pitch test, wing position was recorded using an encoder mounted on the motor shaft. The pitch axis was located at 45% of the chord. Data from the ESP were digitized using a 12-bit A/D chip incorporated into the electronic hardware. Each presented data set is comprised of 10 ensemble averages runs. Comparison of similar data runs containing 5, 10, and 30 ensemble averages indicated that the instantaneous pressure distributions had low noise and were highly repeatable.

Results and Discussion

In all experiments, the wing was pitched in a sinusoidal fashion through a target amplitude of 12.5 deg. The mean setting incidence was 12.5 deg, yielding a motion encompassing an incidence range from 0 to 25 deg. As the SJA frequency was much larger then the pitch rate, a phase relationship was unecessary.[12] For the experimental data presented, the jet-momentum coefficient, defined as

$$C\mu = 2V_{\text{rms}}^2 sw \big/ U^2 c \tag{1}$$

has a value of 0.009. The uncertainty in $C\mu$ is estimated as approximately 2%. The rms of the jet-exit velocity was calculated using data from a hot-wire anemometer survey of the jet exit. The SJA actuator nondimensional frequency $F+$ was set to 1. Prior studies[19] have suggested that depending on the SJA configuration and requirement a value of $F+ \approx 1$ is optimal as it corresponds to the presence of approximately 2–4 convecting vortical structures over the upper surface. Measurements of the lift-curve slopes of the data to be presented give values of $\approx 0.9\pi$ (which is approximately half what would be expected). This low value is caused by the limited size of the end plates as well as the trailing vortices from the stub panels' outboard of the end plates. However, this is not significant because of the comparative nature of this investigation.

Figure 1 shows the effect of pitch rate for $F+ = 0$ (no blowing) and $F+ = 1$. As can be seen, zero angle of attack does not correspond to zero lift coefficients. This might be because of the wing experiencing an effective incidence at zero angle of attack (tunnel flow angularity) or the effect of the support bayonet on the lower surface-pressure taps. The data show that increasing the pitch rate delays the onset of stall, until the stall coincides with the maximum pitch angle, that is, 25 deg, for $k = 0.066$ ($f = 1$ Hz). The delay of stall is affected as a linear extension of the lift curve, until boundary-layer flow reversal manifests. Because of the comparatively low

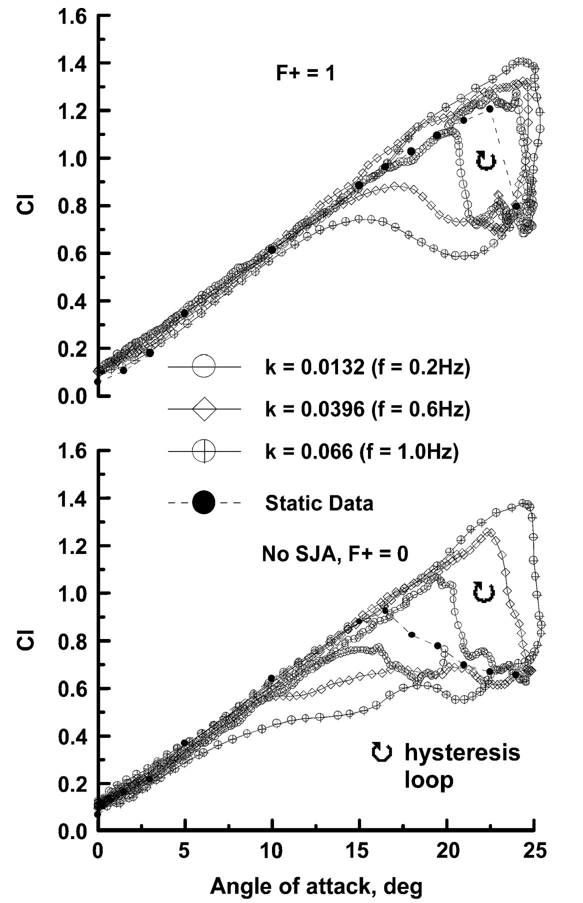

Fig. 1 Effect of k on calculated lift coefficient, with and without actuation.

pitch rates, a dynamic stall vortex does not form. As the pitch rate increases, the hysterisis effects seen during the downstroke increase, indicating that boundary-layer reattachment is delayed; thus, larger pitch rates lead to larger hysterisis loops.

For $F+ = 1$, the data show that the systematic delay in stall onset shown for $F+ = 0$ as k increases is not as apparent. For $k > 0.0132$, increasing the pitch rate has little effect on the presented data, that is, it becomes somewhat independent of the dynamic motion. This indicates that for these experimental conditions the SJA maintains attached flow over the upper wing surface essentially up until the termination of the upstroke. Similarly, the size and dispersion of the downstroke's hysterisis loops are also decreased.

Figure 2 presents the lift and pitching-moment coefficient as a function of incidence for $k = 0.066$ ($f = 1$ Hz) and $k = 0.1319$ ($f = 2$ Hz) with and without actuation. Setting $k = 0.066$ ($f = 1$ Hz) shows the dynamic pitching motion delaying stall comparably to that achieved using forced flow control at lower pitch rates. Although increasing the pitch rate steadily delays the upper surface reattachment for $F+ = 0$ (Fig. 1), fluidic forcing reduces the dependency of the reattachment process during the downstroke on the frequency of the motion, as the SJA itself reattached the flow. For this frequency, a significant negative moment associated with stall (in concert with the termination of the upstroke) is seen ($F+ = 0$).

Increasing k to 0.0792 ($f = 1.2$ Hz—plots omitted as a result of space limitations) and greater shows the formation of a DSV at the termination of the upstroke, indicated by the nonlinear lift augmentation. The data (some not presented) showed that the size of the actuated case hysteresis loop increases to a maximum for $k = 0.1056$ ($f = 1.6$ Hz). However increasing the pitch frequency then shows a reduction in the hysterisis loop size until it is eliminated for $k = 0.1319$ ($f = 2$ Hz), Fig. 2. For the present test conditions and a nondimensional pitch frequency of 0.1319, the negative damping loop is eliminated from the SJA active moment coefficient plot data.

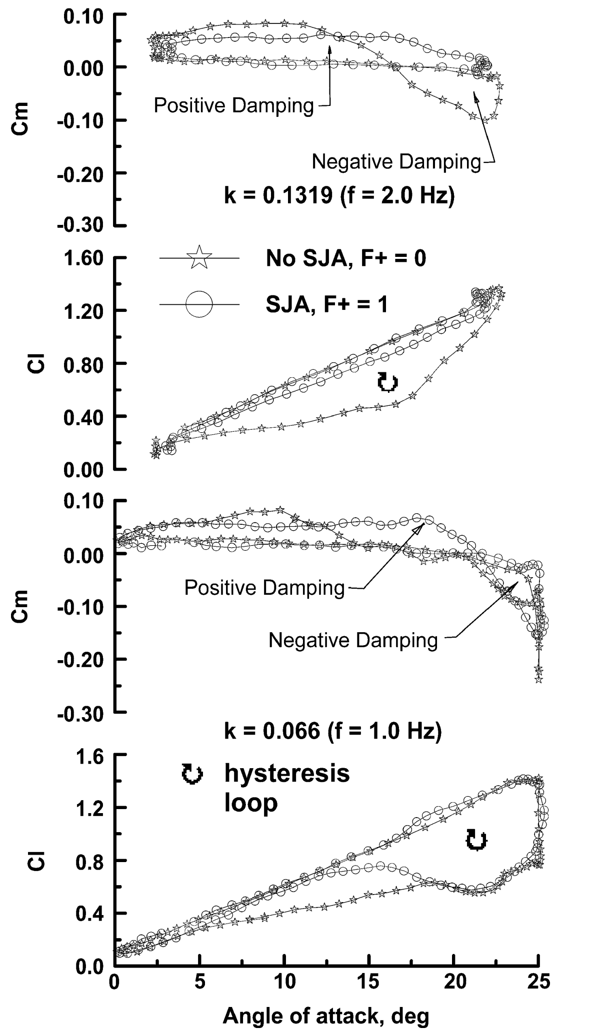

Fig. 2 Effect of fluidic actuation on calculated lift and pitching-moment coefficient; $k = 0.066$ and 0.1319.

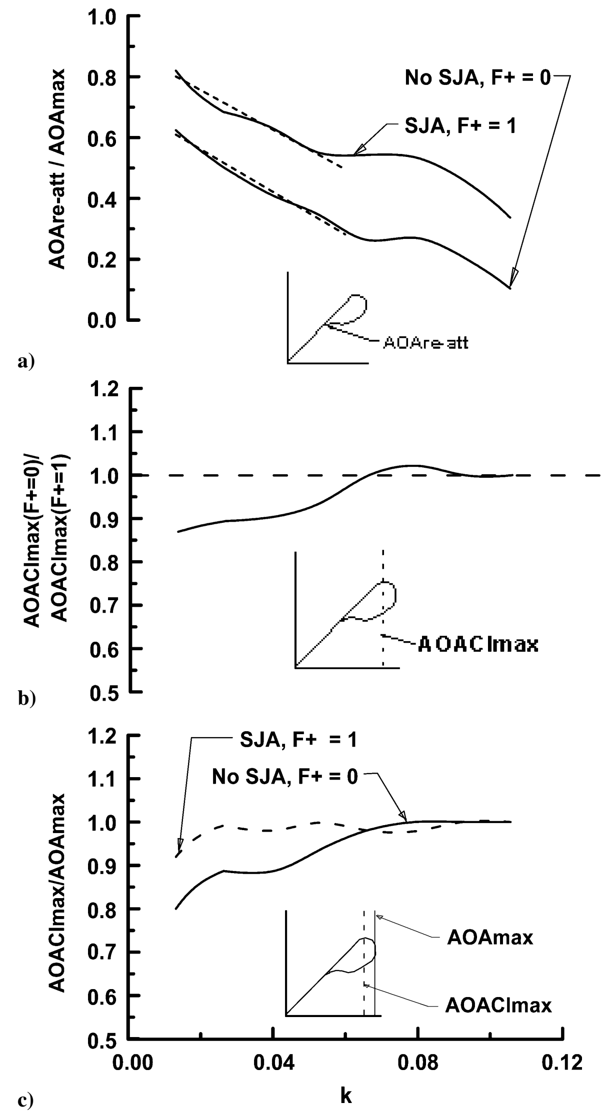

Fig. 3 Summary of measured data: a) effect of fluidic actuation and pitch frequency on downstroke boundary-layer reattachment incidence, b) ratio of the incidence at which the Cl_{max} occurs with and without SJA actuation, and c) effect of forcing on the incidence at which the maximum lift coefficient occurs.

Salient features of the measured data are summarized in Figs. 3a–3c. Figure 3a presents the angle of attack of the projected flow reattachment angle as a fraction of the maximum angle. Presenting the data in this format eliminates effects caused by small variations in the pitch amplitude angle. Boundary-layer reattachment was presumed to have occurred at the termination of the hysterisis loop on the downstroke.[7] The data in Fig. 3a show that the effect of flow control is essentially to promote earlier reattachment during the downstroke, effected as an approximately constant offset for all tested pitch frequencies. Actuation reduces the angle-of-attack decrement required for reattachment by about 20%. The data show that the delay in reattachment with increasing k is approximately linear for $k < 0.055$. This appears to be followed by a localized plateau for $0.06 < k < 0.08$ (within the density of presented data) and then a resumption of the pseudolinear delay in reattachment angle as k increases further. The cause for this behavior was not clearly established.

Figure 3b shows the angle of attack at which the maximum lift coefficient was recorded for the unforced case reduced by the forced case. This is essentially a quantification of the effect of the dynamic motion to the forced actuation as means to suppress upper-surface flow separation. As can be seen, the effect of the dynamic motion becomes comparable to the fluidic forcing for $k > 0.06$. Generally, increasing the pitch rate has an analogous effect to that of forcing, although the mechanisms through which flow separation is prevented are vastly different. Figure 3c shows the angle of attack for the maximum lift coefficient reduced by the angle of attack of the excursion. As can be seen, for the frequency range of pitch motions these two angles are coincident for $F+ = 1$, indicating that maximum lift was achieved at the termination of the upstroke and that the flow was still attached. For the unforced case, the airfoil stalls prior to the maximum angle of attack for $k < 0.06$. As the nondimensional frequency of the oscillations reaches 0.066 ($f = 1$ Hz), the dynamic effects of the motion (leading-edge jet effect[1] with concomitant boundary-layer energizing/improvement) delay stall such that the maximum measured lift is coincident with the angle of attack of the motion.

Summary

An investigation was conducted to determine the effects of synthetic jet actuators on a sinusoidally pitching wing. Experiments were performed in a low-speed 3×4 ft wind tunnel at a chord Reynolds number of 0.57×10^6. The pitch motion consisted of a 12.5-deg amplitude centered around a 12.5-deg mean, yielding a sinusoidal pitch with a 25-deg peak to trough excursion angle. Nondimensional pitch frequencies from 0.0132 ($f = 0.2$ Hz) to 0.1319 ($f = 2.0$ Hz) were tested. During the dynamic motion, pressures were recorded around the wing using a high-speed pressure scanner connected to 32 tappings. Integration of these pressures yielded instantaneous lift and pitching moment. From the experimental data, the following conclusions are drawn.

During the upstroke, at low pitch frequencies the SJA delayed stall. As the frequency increased, the effect of the SJA compared to the unforced case diminished as the dynamic motion itself delayed the onset of stall. During the downstroke, the SJA significantly increased the angle of attack at which flow reattachment was indicated, resulting in considerably smaller hysterisis loops. For the highest pitch frequency evaluated, the hysterisis loop was eliminated. Actuation reduced the magnitude of the pitching-moment coefficient excursions and reduced the size of the negative damping loops.

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