[11]Ericsson, L. E., "Circular Cylinder Response to Karman Vortex Shedding," *Journal of Aircraft,* Vol. 25, No. 9, 1988, pp. 769-775.

[12]Ericsson, L. E., "Prediction of Slender Body Coning Characteristics," *Journal of Spacecraft and Rockets,* Vol. 28, No. 1, 1991, pp. 43-49.

[13]Swanson, W. M., "The Magnus Effect: A Summary of Investigations to Date," *Journal of Basic Engineering,* Vol. 83, No. 9, 1961, pp. 461-470.

[14]Ericsson, L. E., "Control of Forebody Flow Asymmetry, a Critical Review," AIAA Paper 90-2833, Aug. 1990.

Poststall Airfoil Response to a Periodic Freestream

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I. Introduction

THE maintenance of air superiority in the future will depend on an ability to perform rapid transient maneuvers at high angles of attack, often into the poststall flight regime. This new class of flight maneuvers will require a more complete understanding of high-alpha unsteady flight dynamics and aerodynamics. During a high angle-of-attack maneuver, any sudden unintentional asymmetry induced in the flow over the lifting surfaces could adversely affect the control of the aircraft. A change in the wing-boundary-layer behavior for an aircraft operating near stall or in the poststall regime may potentially affect the ability of the flow to remain attached during the maneuver—or to remain separated. This situation may arise when the lifting surface of a maneuvering aircraft penetrates the wake of a second aircraft, is disturbed by the blast from a launched missile, or receives adverse interference from the wake of a canard during an agressive maneuver.

The effects of steady disturbances on airfoil boundary-layer behavior have been studied extensively; unsteady effects have been treated to a much lesser degree. Most research of an unsteady flowfield has involved either a pitching airfoil, related to dynamic stall,[1] or a streamwise velocity variation, usually sinusoidal, over a stationary wing section.[2] Bar-Sever[3] introduced transverse velocity fluctuations upstream of an airfoil leading edge using an oscillating-wire technique; periodic forcing of the velocity field was shown to increase the static poststall lift coefficient by 38%. Howard and Miley[4] observed the periodic response in a wing boundary layer immersed in a propeller slipstream and found a stabilizing mechanism to provide a time-dependent relaminarization over the airfoil. Renoud and Howard[5] considered the case of the wing-boundary-layer response behind a spinning rod for attached flows and found the same mechanism to exist without any propeller thrusting. The current effort looks at the features of the two previous studies that involved the superposition of a periodic wake flow on a mean flowfield, but for a poststall flow regime. It was desired to determine if there exists a stabilizing influence on the separating flow. Understanding the response of such a flowfield may lead to unusual methods of control in the maneuvering high angle-of-attack flight regime.

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II. Experimental Investigation

Tests were performed in the low-speed wind tunnel at the Naval Postgraduate School. This wind tunnel is of the closed-return type with a 32- × 45-in. test section. A 2-ft wide, 10-in.-chord airfoil model was supported between vertical plates running from the floor to the ceiling. The wing section used was from a helicopter tail rotor, filled to contour and refinished. A 3/8-in.-diam polished steel rod 16 in. long was rotated 10% chord distance upstream of the wing leading edge, with the axis of rotation 25% chord distance below the chordline. The nominal test-section velocity U_∞ was maintained at 95 ft/s for a Reynolds number based on chord c of 5×10^5. The ambient turbulence intensity at the test dynamic pressure was 0.18%.

To sense the flow reversal expected with the separated flowfield, a split-film probe was used. The split-film probe consists of two electrically independent nickel-film sensors placed on a quartz fiber yielding flow velocity and flow angle in the streamwise plane. Only one case studied will be presented here; complete results can be found in Ref. 6. Data were gathered at 3.53 kHz at a turbulent-pulse frequency ω (two pulses per rotation) of 3 Hz and a sampling time of 5.67 s for a reduced frequency $k = \omega \cdot c/(2 \cdot U_\infty)$ of 0.09. Seventeen turbulent pulses were recorded for ensemble averaging of phase-locked velocity profiles. A low-pass digital filter was applied by frequency-domain smoothing.

III. Results

Measurements were made at 22-deg angle of attack at the 70% chord position. Ensemble-averaged values of the total velocity V and the streamwise component u for the undisturbed case (no spinning rod) are shown in Fig. 1. The total velocity across the vertical dimension might be interpreted to be a boundary-layer profile, with a velocity level of 40–50% of U_∞. The streamwise component, though, indicates that the profile is actually one of incipient separation, with little forward or reversed flow in this region near the surface.

Figure 2 shows ensemble time histories for the streamwise velocity component across the separated layer. The time t is

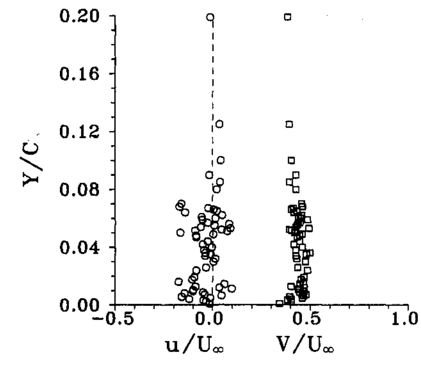

Fig. 1 Total and streamwise velocity profiles, 70% chord, α = 22 deg, no disturbance input.

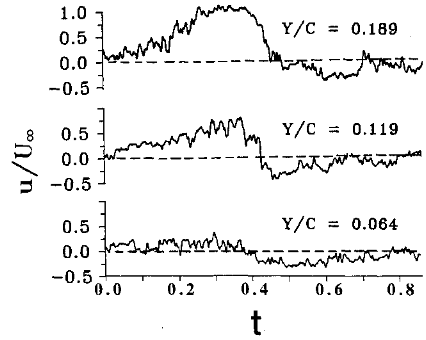

Fig. 2 Streamwise velocity time histories, 70% chord, α = 22 deg, k = 0.09.

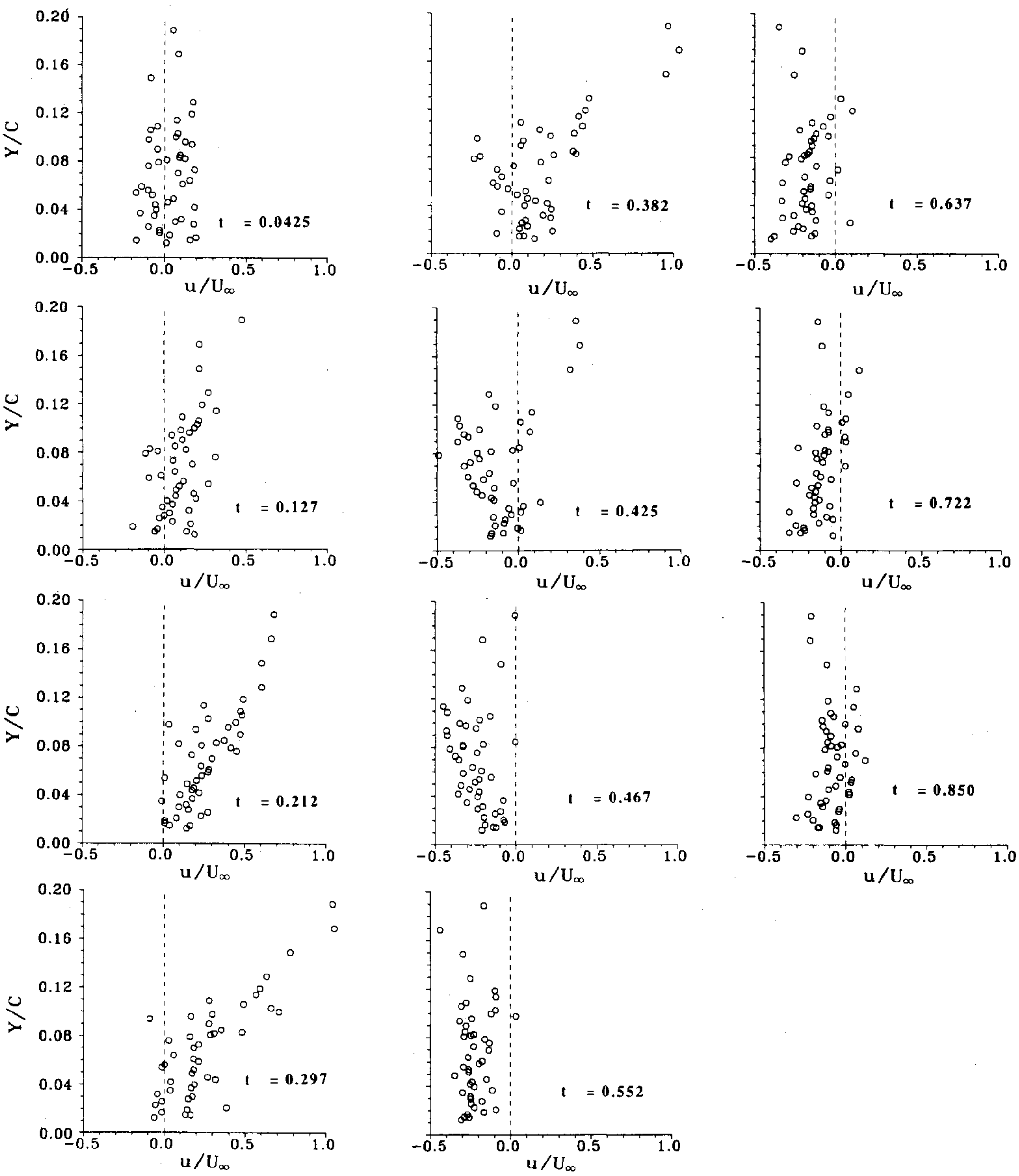

Fig. 3 Streamwise velocity profiles in wake-passage cycle, 70% chord, $\alpha = 22$ deg, $k = 0.09$.

nondimensionalized by one cycle period. The traces indicate that the separated region does respond to the periodic turbulent wake input at this reduced frequency. Values of u/U_∞ run from greater than 1.0 to -0.45 at a distance up from the surface of 19% chord. The responses closer to the airfoil section have smaller amplitudes, yet maintain the same general characteristics. Apparently the passage of the disturbance has a significant effect; the flow appears to reattach, then reverse direction, then return to the zero-velocity condition.

Figure 3 better demonstrates the actual behavior across the separating shear layer. Shown are ensemble streamwise velocity profiles at points in the wake-passage cycle. The profile at $t = 0.0425$ is almost identical to that of the undisturbed separated flow. As the cycle progresses in the next three frames, the profile approaches the shape of an attached boundary layer nearing separation. At $t = 0.382$, the inner layer begins to reverse direction; at $t = 0.425$, the outer layer is moving streamwise, whereas the inner layer is moving upstream. The flow is a reversed one within 12% of the section's surface. As the cycle progresses further, the complete layer reverses, then returns to a shear layer at the condition of near separation (zero streamwise velocity).

The separated flow passes through a stabilizing phase that reattaches the separated boundary layer for a brief period of time, most likely due to the increased freestream turbulence of the wake passage, which is on the order of 6%. Of interest for future studies is the time-dependent lift behavior, to compare to the beneficial effects commonly noted for dynamic stall. The following step will be to see how this phenomenon might be used for control at high angles of attack for enhanced pitch or roll maneuvering.

References

[1]Carr, L. W., "Progress in Analysis and Prediction of Dynamic Stall," *Journal of Aircraft*, Vol. 25, No. 1, 1988, pp. 6–17.

[2]Brendel, M., "Experimental Study of the Boundary Layer on a Low Reynolds Number Airfoil in Steady and Unsteady Flow," Ph.D. Dissertation, Dept. of Aerospace and Mechanical Engineering, Univ. of Notre Dame, Notre Dame, IN, May 1986.

[3]Bar-Sever, A., "Separation Control on an Airfoil by Periodic Forcing," *AIAA Journal*, Vol. 27, No. 6, 1989, pp. 820,821.

[4]Howard, R. M., and Miley, S. J., "Time-Dependent Boundary Layer Response in a Propeller Slipstream," *Journal of Aircraft*, Vol. 26, No. 9, 1989, pp. 863–869.

[5]Renoud, R. W., and Howard, R. M., "Airfoil Boundary Layer Response to an Unsteady Turbulent Flowfield," *AIAA Journal*, Vol. 28, No. 11, 1990, pp. 1894–1900.

[6]Gwilliam, D. J., Jr., and Howard, R. M., "Time-Dependent Post-Stall Airfoil Behavior in a Periodic Wake Flow," AIAA Paper 91-0431, Jan. 1991.