An Experimental Investigation of an Airfoil Undergoing Large-Amplitude Pitching Motions

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Abstract

FLOW visualization and near-surface hot-wire experiments were performed in the U.S.A.F Academy Aeronautics Laboratory subsonic wind tunnel on an airfoil undergoing large-amplitude pitching motions about its quarter chord. The experiments were conducted using a NACA 0015 airfoil at an airfoil Reynolds number of 45,000. Two cases are presented in which the angular pitching rate $\dot{\alpha}$ is maintained constant during the motion. These two cases represent two different nondimensional pitching rates α^+, where α^+ is equal to $\dot{\alpha}$ nondimensionalized by the chord c and the freestream velocity U_∞ ($\alpha^+ \equiv \dot{\alpha}c/U_\infty$). Data for the two cases where values of α^+ are equal to 0.2 and 0.6 show the dramatic effect of pitch rate on flow structure. Large-scale vortical structures are seen in both cases at high angles of attack but appear much later and are of a different form for the case with the larger α^+ value. These structures are very energetic, producing reverse flow velocities near the airfoil surface of 1.0-2.1 times the freestream velocity.

Contents

Experimental Arrangement

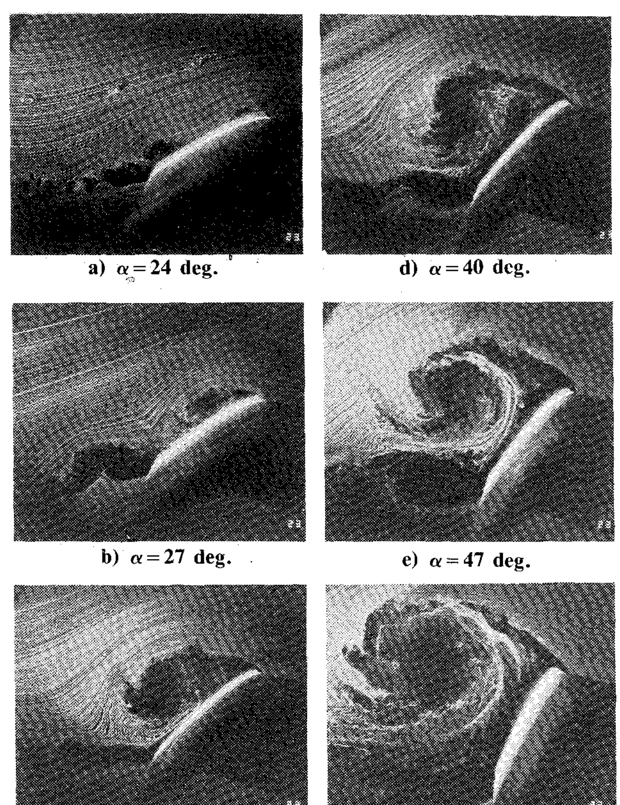
All data were obtained using a pitch oscillator described by Francis et al.[1] to impart constant $\dot{\alpha}$ motions to the airfoil. The pitch axis was located at the airfoil quarter chord. The flow visualization scheme utilized a "smoke wire" placed across the tunnel upstream of the pitching airfoil and normal to the spanwise direction and freestream flow direction. The smoke was illuminated by a high-intensity strobe light placed downstream of the airfoil.

The near-surface velocity measurements were obtained using seven hot wires mounted on the upper surface (suction side) of the airfoil which protruded above the airfoil surface approximately 3% of the chord length.

Experimental Results

Flow-visualization data are shown in Figs. 1 and 2 at selected angles of attack for the two pitching rates. The differences in flow structure are rather dramatic at similar angles of attack for the two cases. Data at the lower α^+ value in Fig. 1 show a separation bubble (vortex) beginning to form at the leading edge at an angle of attack of about 20 deg. As this vortex continues to grow, it begins to move away from the upper surface of the airfoil, which has by then reached an angle of attack of approximately 40 deg. Data of Francis et al.,[2] which were taken under slightly different conditions from Fig. 1, suggest that the maximum lift, at the lower pitch rate, is produced at angles of attack between 30-35 deg. From the flow-visualization data this, in turn, suggests that maximum lift occurs when the vortex on the suction side is well developed yet still relatively close to the surface.

Data at the higher α^+ value in Fig. 2 show the formation of two distinct large vortices. Initially, there appears to be a region of boundary-layer separation which moves from the trailing edge toward the leading edge. At around 40 deg a leading-edge vortex formation has grown large enough to retard the forward movement of the trailing-edge separation region. Futhermore, the clockwise vorticity being shed at the trailing edge due to increasing bound circulation reattaches the flow at the trailing edge and produces a counter-clockwise vortex in the trailing-edge separation region similar to the leading-edge vortex. Similar behavior has been noted on airfoils undergoing harmonic oscillations by McAlister and Carr[3] although the effects were much less pronounced due to the low



a) $\alpha = 24$ deg. d) $\alpha = 40$ deg.
b) $\alpha = 27$ deg. e) $\alpha = 47$ deg.
c) $\alpha = 36$ deg. f) $\alpha = 59$ deg.

Fig. 1 Flow visualization data; $Re = 45{,}000$, $\alpha^+ = 0.2$, constant $\dot{\alpha}$ motion, and pitch axis at 25% chord.

Received March 23, 1984; synoptic received Oct. 5, 1984; presented as Paper 85-0039 at the AIAA 23nd Aerospace Sciences Meeting, Reno, Nev., Jan. 14-17, 1985. This paper is declared a work of the U.S. Government and therefore is in the public domain. Full paper available from AIAA Library, 555 W. 57th Street, New York, N.Y. 10019. Price: microfiche, $4.00; hard copy, $9.00. **Remittance must accompany order.**

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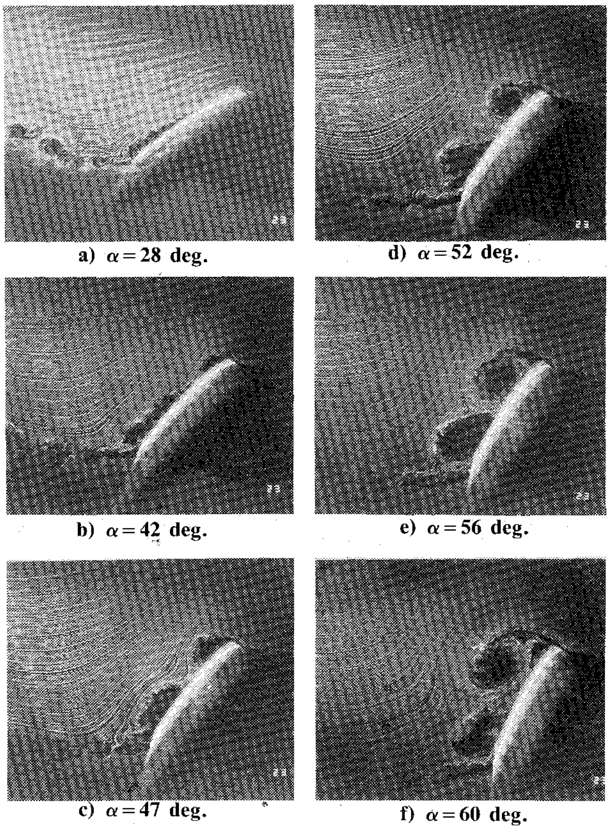

Fig. 2 Flow visualization data; $Re = 45{,}000$, $\alpha^+ = 0.6$, constant $\dot{\alpha}$ motion, and pitch axis at 25% chord.

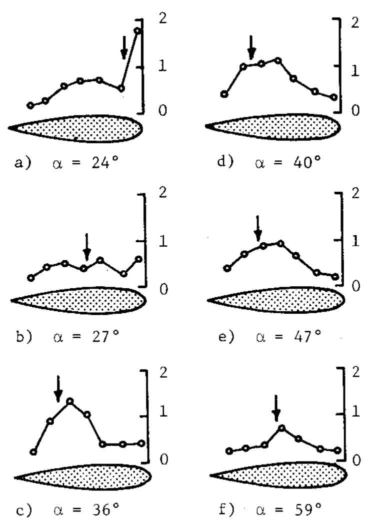

Fig. 3 Absolute velocity ratio $|u|/u_\infty$ obtained from surface hot wires; $Re = 45{,}000$, $\alpha^+ = 0.20$, constant $\dot{\alpha}$ motion, and pitch axis at 25% chord.

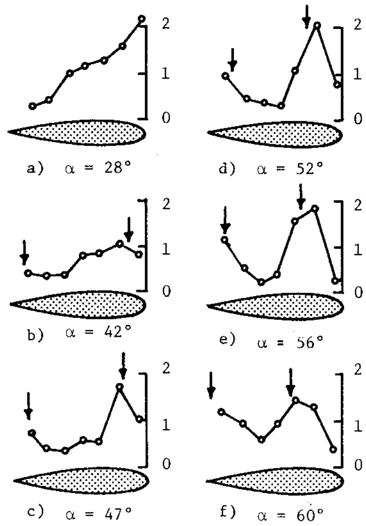

Fig. 4 Absolute velocity ratio $|u|/u_\infty$ obtained from surface hot wires; $Re = 45{,}000$, $\alpha^+ = 60$, constant $\dot{\alpha}$ motion, and pitch axis at 25% chord.

angles of attack in their study. They denote the leading-edge vortex as the "dynamic stall vortex" and the trailing-edge vortex as the "shear layer vortex." They also note that the shear layer vortex seems to disappear at high Reynolds numbers, leaving only the dynamic stall vortex. Both vortices are produced by boundary-layer separation and the disappearance of the trailing-edge vortex at high Reynolds numbers simply indicates that the flow does not separate in the trailing-edge region prior to the formation of the leading-edge vortex.

Selected near-surface velocity data are shown in Figs. 3 and 4 for the corresponding cases given in Figs. 1 and 2, respectively. The direction of the flow is not apparent from examination of the single element hot-wire but can be deduced in some cases with the aid of the flow-visualization data.

Maximum reverse flow velocities on the order of 140 and 210% of the freestream velocity were measured for α^+ values of 0.2 and 0.6, respectively. In each case the maximum reverse flow velocity occurs directly under the center of a vortex which is denoted by arrows in Figs. 3 and 4. Figure 4a shows what would appear to be a typical surface velocity distribution for flow over an airfoil in which separation is just beginning to occur at the rear of the airfoil. It should be noted, however, that under steady flow conditions this situation would occur at angles of attack of less than 10 deg whereas in the present case the angle of attack is 28 deg.

Conclusions

From the work presented herein, it can be seen that the flow structure is a strong function of the nondimensional pitching rate α^+. The higher the value of α^+, the higher the angle of attack reached before the beginning of flow separation, the more energetic the suction peak, the more energetic the leading-edge vortex, and the higher the reverse flow velocities near the surface of the airfoil. In addition, at the higher value of α^+ significant secondary vortical structures appear. Maximum reverse flow velocities occur for any given angle of attack directly under the center of a vortex.

Acknowledgments

The research described in this report was sponsored by the Frank J. Seiler Research Laboratory (AFSC), the U.S.A.F. Academy, Colorado Springs, Colo. Summer faculty support was made available by the Air Force Office of Scientific Research under Contract F49620-82-C-0035.

References

[1]Francis, M. S., Keesee, J. E., and Retelle, J. P., "An Investigation of Airfoil Dynamic Stall with Large Amplitude Motion," Frank J. Seiler Research Labs., Colo., FJSRL-TR-83-0010, Oct. 1983.

[2]Francis, M. S., Keesee, J. E., and Retelle, J. P., "A Two-Degree-of-Freedom Oscillator for Unsteady Aerodynamics Applications," Frank J. Seiler Research Labs., Colo., FJSRL-TR-81-0007, July 1981.

[3]McAlister, K. W. and Carr, L. W., "Water Tunnel Visualization of Dynamic Stall," *Journal of Fluids Engineering*, Vol. 101, Sept. 1978, pp. 376-380.