Table 1 Maximum suction peaks, corresponding α, and C_ℓ found in McCroskey et al.[10] for the NACA-0012 airfoil stalling over a range of reduced frequencies, mean angles, and amplitudes of oscillation

Case	α	$C_{p_{max}}$	C_ℓ	k	α_0	M_∞
7021	13.7	−9.06	1.47	0.100	8.99	0.299
7023	13.6	−9.13	1.53	0.201	8.99	0.299
7101	13.8	−9.23	1.51	0.150	8.99	0.301
7112	13.8	−9.03	1.41	0.025	9.97	0.301
7113	13.8	−9.10	1.51	0.099	9.95	0.301
7114	13.8	−9.08	1.56	0.199	9.91	0.301
7117	14.0	−8.98	1.41	0.025	10.92	0.301
7118	13.9	−9.01	1.47	0.050	10.92	0.301
7119	13.9	−9.05	1.52	0.099	10.92	0.301
7120	14.1	−9.08	1.54	0.149	10.96	0.301
7121	14.1	−8.99	1.57	0.198	10.88	0.301
7200	14.0	−8.97	1.40	0.025	11.92	0.301
7205	14.0	−9.07	1.52	0.099	11.92	0.302
7207	14.4	−9.01	1.59	0.198	11.88	0.302

being caused by a new phenomenon not seen at low Mach number.

Conclusions

From the observed behavior of the flow before separation, we have shown that the parametric dependency of separation on frequency for supercritical flows is different from that for subcritical flows. For subcritical flows, increasing the reduced frequency delays separation of the boundary layer and, hence, allows the airfoil to attain higher lift values at higher angles of attack. However, as the airfoil assumes lift values higher than the value at static stall, the flow around it can easily reach supercritical conditions. The formation of a local supersonic region and the associated shock can occur at a location close to the leading edge where the radius of curvature is small and the boundary layer laminar. The vortical content of the flow is intensified due to the relatively short extension of the local supersonic region. The local outer flow and the boundary layer are no longer stable. Hence, compressibility effects pose a limit on lift enhancement by increasing unsteadiness.

Our studies here suggest that it is important to consider compressibility effects for freestream Mach numbers as low as 0.2.

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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]Harper, P. W., and Flanigan, R. E., "The Effect of Change of Angle of Attack on the Maximum Lift of a Small Model," NACA TN-2061, March 1950.

[3]Dadone, L. U., "Two-Dimensional Wind Tunnel Test of an Oscillating Rotor Airfoil," NASA CR-2914, Dec. 1977.

[4]Lorber, P. F., and Carta, F. O., "Airfoil Dynamic Stall at Constant Pitch Rate and High Reynolds Number," AIAA Paper 87-1329, June 1987.

[5]McCroskey, W. J., McAlister, K. W., Carr, L. W., Pucci, S. L., Lambert, O., and Indergrand, R. F., "Dynamic Stall on Advanced Airfoil Sections," *Journal of the American Helicopter Society,* Vol. 26, No. 3, 1981, pp. 40–50.

[6]Ericsson, L. E., and Reding, J. P., "Shock-Induced Dynamic Stall," *Journal of Aircraft,* Vol. 21, No. 5, 1984, pp. 316–321.

[7]Katary, M., "An Experimental Study of the Development of a Supersonic Zone Near the Leading Edge of an Airfoil Oscillating in Subsonic Flow," AIAA Paper 83-2133, Aug. 1983.

[8]Carr, L. W., McCroskey, W. J., McAlister, K. W., Pucci, S. L., and Lambert, O., "An Experimental Study of Dynamic Stall on Advanced Airfoil Sections, Vol. 3, Hot-Wire and Hot-Film Measurements," NASA TM-84245, Dec. 1982.

[9]Visbal, M. R., "Effects of Compressibility on Dynamic Stall of a Pitching Airfoil," AIAA Paper 88-0132, Jan. 1988.

[10]McCroskey, W. J., McAlister, K. W., Carr, L. W., and Pucci, S. L., "An Experimental Study of Dynamic Stall on Advanced Airfoil Sections," NASA TM-84245, Sept. 1982.

[11]Morawetz, C., "On The Non-Existence of Continuous Transonic Flow Past Profiles, I," *Communications on Pure and Applied Mathematics,* Vol. 9, 1956, pp. 45–68.

[12]Morawetz, C., "On The Non-Existence of Continuous Transonic Flow Past Profiles, II," *Communications on Pure and Applied Mathematics,* Vol. 10, 1957, pp. 107–131.

[13]Morawetz, C., "On The Non-Existence of Continuous Transonic Flow Past Profiles, III," *Communications on Pure and Applied Mathematics,* Vol. 11, 1958, pp. 129–144.

Observations of Dynamic Stall Phenomena Using Liquid Crystal Coatings

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Introduction

UNSTEADY boundary-layer flows occur on airfoil surfaces of wind energy conversion systems, rotary-wing aircraft, and maneuvering fixed-wing aircraft. In such flows, the airfoil angle of attack varies with time, and both boundary-layer transition and turbulent separation locations can undergo extensive and rapid movements, particularly on the airfoil lee surface. For transient angle-of-attack excursions beyond an airfoil's static-stall limit, complex leading-edge-separation/vortex-shedding ("dynamic stall") phenomena occur. An excellent review of the state-of-the-art concerning dynamic stall phenomenology was recently given by Carr.[1]

In the present research, newly formulated (shear-stress-sensitive/temperature-insensitive) liquid crystal coatings[2] were applied to the surface of an oscillating airfoil in order to investigate the unsteady fluid physics associated with the dynamic stall process. Surface-mounted microtufts and laser-sheet/smoke-particle flow visualization were also utilized to complement the liquid crystal technique. Boundary-layer transition and turbulent separation locations were measured as a function of geometric angle of attack, and results are presented in comparison with predictions generated with the Eppler airfoil design code.[3]

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Liquid Crystals

Liquid crystals are highly anisotropic fluids that exist between the solid and isotropic liquid phases of some organic compounds.[4] As such, they exhibit optical properties characteristic of a crystalline (solid) state, while displaying mechanical properties characteristic of a liquid state. In flow-visualization applications, a mixture of one part nonmicroencapsulated liquid crystals to five parts solvent (here, trichlorotrifluoroethane) is sprayed on the aerodynamic surface under study (a flat-black surface is essential for color contrast). Recommended applications (after spray losses) are ~10 ml liquid crystals, measured prior to mixing with the solvent, to each square meter of surface area. The solvent evaporates, leaving a uniform thin film of liquid crystals (approximately 10^{-3} cm in thickness) that selectively scatters incident white light as discrete colors.

This behavior is traced to the molecular structure of the compounds, a helical structure whose characteristic pitch length falls within the wavelength range of the visible spectrum. For "thermochromic" liquid crystals, the two primary factors that influence this molecular structure (and, thus, the light-scattering response of the liquid crystal coating) are temperature and surface shear stress. In low-speed incompressible flows, wherein temperature is (or can be held) essentially constant, the shear stress dependence dominates. Surface color patterns are then displayed in response to varying surface shear stress loads, once some threshold level of shear stress has been exceeded. So long as the chemical structure of the liquid crystals remains unaltered, temperature and/or shear stress responses are theoretically rapid, continuous, and reversible indefinitely.

The literature shows several applications of this technology to fluid mechanics research. The first was by Klein,[5] who used the temperature response of liquid crystals in high-speed/compressible flows to measure surface temperature contours from which transition locations were inferred. Attempts to decouple the influences of temperature and shear stress and make quantitative measurements of shear stress under isothermal flow conditions were difficult and generally not productive.[6] A hiatus ensued until the recent investigations by NASA Langley researchers,[7] who successfully applied this technique as a qualitative shear stress (boundary-layer transition) indicator in subsonic flight tests of airplanes. More recently, oscillating airfoil experiments were conducted by Reda[8] to test the frequency response of thermochromic liquid crystal coatings to unsteady surface shear stresses under isothermal flow conditions.

Very recent advances in liquid crystal technology have now led to the formulation of compounds that display no temperature response over broad temperature regimes; for these mixtures, color changes result solely in response to applied shear stress, making them more suitable for flow-visualization applications.[2] Measurements obtained in the present research showed that these liquid crystal coatings are capable of making transient surface shear stress events visible in a continuous and reversible manner, with a color-change response time of less than 0.03 s (the framing rate of standard video equipment).

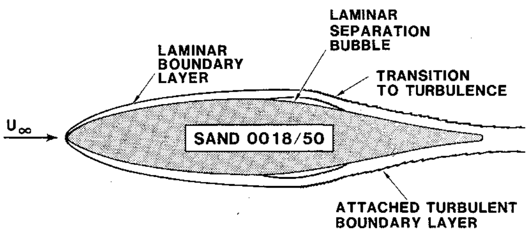

Fig. 1 Flowfield schematic, $\alpha = 0$ deg.

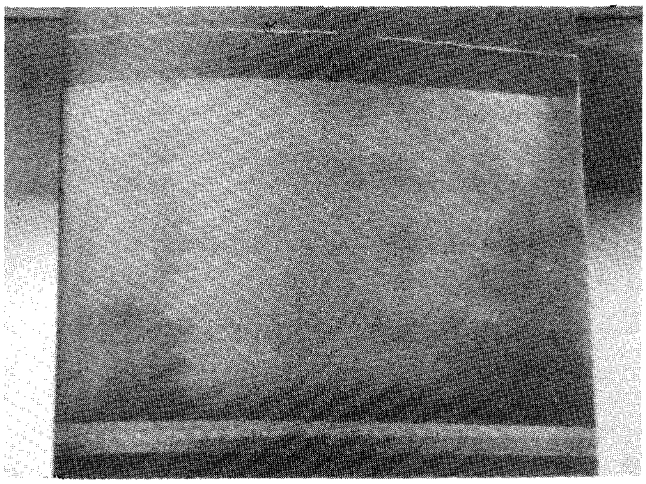

Fig. 2 Liquid crystal pattern, $\alpha = 6$ deg, showing transition front.

Airfoil and Test Conditions

The airfoil employed in the present research was the SAND 0018/50 (see Fig. 1); the "18" denotes an 18% (of chord) maximum thickness, while the "50" denotes a design specification for a 50% (of chord) run length of laminar flow at zero angle of attack. This symmetric airfoil was designed specifically for vertical axis wind turbine applications by Gregorek and Klimas[9] using the Eppler code.[3]

A full-span (0.91 m) model of this airfoil, of chord length $C = 0.35$ m, was tested in the Ohio State University 0.91 × 1.52 m subsonic wind tunnel. Freestream Reynolds number, based on chord and freestream velocity U_∞ was 10^6. Angle-of-attack α oscillations of ± 19 deg about 0 deg (about the midchord) were imposed at several discrete frequencies ($f = 0.2$ and 0.6 Hz) to induce the unsteady flowfields. Data acquisition was accomplished with a video camera recording at 30 frames/s. Reference 10 provides a more complete description of the experimental approach and detailed discussion of the experimental results.

Results

A summary of the experimental observations exists in the form of a 13-min color video. Interested researchers may request a copy of this tape by writing to the author. Observations of liquid crystal coating and microtuft responses were made for slowly increasing α (steady-state conditions), as well as for $f = 0.2$ and 0.6 Hz. Reduced frequencies ($\pi f C/U_\infty$) ranged from 0 to 0.018. Figure 2 shows a black and white photograph of the liquid-crystal-defined transition front for $\alpha = 6$ deg (positive α denotes leeside). Frame-by-frame analyses of the video records allowed boundary-layer transition and turbulent boundary-layer separation locations (in terms of nondimensionalized chordwise distances X/C) to be measured as functions of geometric angle of attack. Results are shown in Fig. 3 in comparison with Eppler code predictions.

Several points should be noted prior to discussing Fig. 3. First, the Eppler code[3] is a steady-state design tool; i.e., computations are made at discrete/fixed values of α, and α is parametrically varied to define airfoil performance trends. Second, the measurements shown in Fig. 3 were found to be reversible and repeatable over the frequency range investigated herein. No measurable dependence of these locations on frequency was apparent. Although this may imply quasisteady flows, independent surface pressure measurements taken on this airfoil under the same test conditions (see Fig. 8 of Ref. 10), when integrated over the airfoil contour, showed the existence of "hysterisis loops" in the lift coefficient and pitching moment coefficient vs angle-of-attack curves. Despite the relatively low values of reduced frequency imposed here, unsteady loads, dependent on the frequency of oscillation,

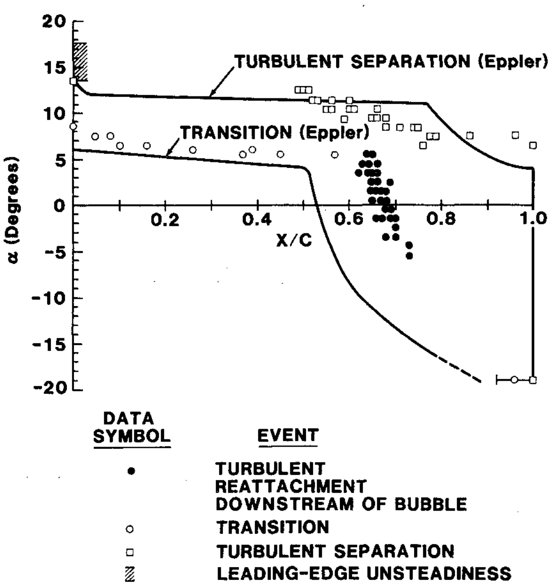

Fig. 3 Transition and turbulent separation locations vs angle of attack; Eppler code predictions compared to measurements.

were experienced, consistent with dynamic-stall events observed on other airfoils.[1]

Concerning transition to turbulence, surface shear stress patterns made visible by the liquid crystal technique clearly showed the existence of a laminar separation bubble beginning just downstream of the midchord position for $-5.5 \leq \alpha \leq +5.5$ deg, with a high shear stress turbulent reattachment zone occurring immediately downstream of the reverse-flow region. For $|\alpha| < 5.5$ deg, transition to turbulence, thus occurred in the separated shear layer above the bubble, not in an attached laminar boundary layer. (The Eppler code predicted transition to result from, and to be coincident with, laminar separation for $\alpha \leq 4$ deg on the leeside; details of the laminar separation bubble are not computed in this code.) For $5.5 < \alpha < 8.5$ deg, transition to turbulence occurred in the attached laminar boundary layer between the leading edge and the midchord location. Even with allowances for the fact that measured transition locations for $-5.5 \leq \alpha \leq +5.5$ deg were actually turbulent reattachment locations, data taken over the complete angle-of-attack regime ($-19 \leq \alpha \leq +19$ deg) showed the Eppler code to be conservative in its transition prediction capabilities, i.e., predicted transition locations were consistently upstream of measured locations.

Measured locations for turbulent boundary-layer separation were also found to be in quantitative disagreement with predicted values. Onset of the forward progression of turbulent separation from the trailing edge occurred at $\alpha = 6.5$ deg, as compared to the predicted incipient separation angle of attack of 4 deg. Both the rate of forward progression and the forward-most quasistable location for turbulent separation were observed to be in disagreement with Eppler code predictions. Finally, turbulent separation was observed to flash to the immediate vicinity of the leading edge for $\alpha = 12.5$ deg, as compared to a predicted static-stall angle of 11 deg.

Concurrent with this rapid forward movement of turbulent separation to the leading edge, the liquid crystal coating showed the onset of unsteadiness in the surface shear stress pattern in, and downstream of, the leading-edge region. These shear stress fluctuations occurred as large-scale, three-dimensional events and were felt to be associated with vortical structures shed from the airfoil leading edge and then convected rearward over the airfoil lee surface by the outer/inviscid flow. This unsteady response was seen in the liquid crystal coating over the regime $13.5 \leq \alpha \leq 17.5$ deg under both static ($f = 0$ Hz) and dynamic ($f = 0.2$ and 0.6 Hz) conditions.

To investigate this unsteady phenomenon in more detail, frame-by-frame analyses of the $\alpha = 14$ deg video record were conducted. Liquid crystal and microtuft responses, when viewed in this manner, both clearly indicated the presence of a quasiperiodic switching of the flow between separated and attached states over large portions of the airfoil lee surface. Frequency of flow switching (f_s) was measured via the liquid crystal technique to be ~ 2.2 Hz, a value well within the frequency-response range of this technique. Using hot-wire anemometry, Zaman et al.[11] observed similar leading-edge flow unsteadiness (in the 5–10 Hz range) for steady flows over several different airfoils placed at, or just beyond, their respective static-stall angle of attack. Utilizing their observed midrange frequency of ~ 7.5 Hz, Zaman et al. converted these results into a dimensionless frequency (or Strouhal number) $[f_s C \sin\alpha]/U_\infty \sim 0.02$, a value well below the established bluff-body/vortex-shedding value of ~ 0.2. Present results yielded a value for this dimensionless frequency of ~ 0.005, in general agreement with Zaman et al.'s findings.

Conclusions

1) Surface shear stress visualization with liquid crystal coatings provides a powerful diagnostic technique for investigations of unsteady viscous flows.

2) Boundary-layer transition and turbulent separation locations can experience extensive and rapid movements over airfoil surfaces undergoing angle-of-attack changes (particularly on lee surfaces).

3) Progression of turbulent separation to the immediate vicinity of the airfoil leading edge was seen (via the liquid crystal technique) to result in large-scale, three-dimensional fluctuations in the surface shear stress patterns. Frame-by-frame analyses of the video record indicated this unsteady phenomenon to be a result of a quasiperiodic (~ 2 Hz) switching of the flow between attached and separated states over large portions of the airfoil lee surface.

4) Comparisons of present results with predictions generated via the Eppler airfoil-design code indicate that the (empirically based) viscous flow modeling within this code requires improvements.

References

[1]Carr, L. W., "Progress in Analysis and Prediction of Dynamic Stall," *Journal of Aircraft*, Vol. 25, No. 2, 1988, pp. 6–17.

[2]Anonymous, "Liquid Crystals for Windflow Visualization: Mixtures TI511 and TI622," BDH Limited, Poole, England, 1988 (American distribution by EM Industries, Inc., Hawthorne, NY).

[3]Eppler, R., and Somers, D. M., "A Computer Program for the Design and Analysis of Low-Speed Airfoils," NASA TM-80210 and TM-81862, 1980.

[4]Fergason, J. L., "Liquid Crystals in Nondestructive Testing," *Journal of Applied Optics*, Vol. 7, 1968, pp. 1729–1737.

[5]Klein, E. J., "Liquid Crystals in Aerodynamic Testing," *Astronautics and Aeronautics*, Vol. 6, July 1968, pp. 70–73.

[6]Klein, E. J., and Margozzi, A. P., "Exploratory Investigation on the Measurement of Skin Friction by Means of Liquid Crystals," NASA-TM-X-1774, May 1969.

[7]Holmes, B. J. et al., "A New Method for Laminar Boundary Layer Transition Visualization in Flight: Color Changes in Liquid Crystal Coatings," NASA TM-87666, Jan. 1986.

[8]Reda, D. C., "Liquid Crystals for Unsteady Surface Shear Stress Visualization," AIAA Paper 88-3841, July 1988.

[9]Gregorek, G. M., and Klimas, P. C., "Tailored Airfoils for Wind Turbine Applications," *Proceedings of the Fourth ASME Wind Energy Symposium*, New York, 1985, pp. 141–146.

[10]Reda, D. C., "Observations of Dynamic Stall Phenomena on an Oscillating Airfoil with Shear-Stress-Sensitive Liquid Crystal Coatings," *Proceedings of the 17th ICAS Congress*, International Council of the Aeronautical Sciences, Sept. 1990, pp. 646–652.

[11]Zaman, K. B. M. Q., McKinzie, D. J., and Rumsey, C. L., "A Natural Low-Frequency Oscillation of the Flow Over an Airfoil Near Stalling Conditions," *Journal of Fluid Mechanics*, Vol. 202, 1989, pp. 403–442.