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Technical Notes

Simultaneous, Full-Surface Visualizations of Transition and Separation Using Liquid Crystal Coatings

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I. Introduction

RECENT research conducted at NASA Ames Research Center[1,2] has shown that liquid crystal coating (LCC) color-change response to shear depends on both shear stress magnitude and the direction of the applied shear vector relative to the observer's line of sight. Under normal white light illumination and for oblique observation, color video images of LCC subjected to surface shear stress vectors of known direction showed that any point exposed to a shear vector with a component directed away from the observer exhibited a color-change response. This response was characterized by a shift from the no-shear orange color toward the blue end of the visible spectrum, with the extent of the color change being a function of both shear magnitude and shear direction relative to the observer. Conversely, any point exposed to a shear vector with a component directed toward the observer exhibited a non-color-change response, always characterized by a rusty red or brown color independent of both shear magnitude and direction. These unique LCC color-change responses make possible a flow-visualization technique for the simultaneous, full-surface definition of transition-front locations and reverse-flow zones.

In addition, these LCC color-change responses were quantified by subjecting a planar coating to a wall-jet shear flow; scattered-light spectra were measured at a point on the wall-jet centerline using a fiber-optic probe and a spectrophotometer. At any fixed shear stress magnitude, the maximum color change was always measured when the shear vector was aligned with and directed away from the observer; changes in the relative in-plane view angle to either side of this vector/observer aligned position resulted in symmetric Gaussian reductions in measured color change. For this vector/observer aligned orientation, color change was found to continually increase with increasing shear stress magnitude over an eightfold range. Based on these observations and point-measurement results, a full-surface shear stress vector measurement methodology was formulated and successfully demonstrated.[3]

II. Experimental Arrangement

To capitalize on these unique shear-direction-indicating capabilities of liquid crystal coatings, two opposing-view, synchronized, color video cameras need to be deployed: one with an oblique, downstream-facing view of the test surface and the other with an oblique, upstream-facing view. Present understanding dictates that the test surface be planarlike, i.e., no regions of extreme curvature, and that it be uniformly illuminated from above. Figure 1 shows a schematic of the experimental arrangement utilized to demonstrate this new technique.

A generic commercial-transport model with a tip-to-tip wing span of 67 in. was positioned on the centerline of the Boeing 8 $\times$ 12 ft transonic wind tunnel. The model had a cylindrical 8-in.-diam centerbody with boundary-layer trips positioned near the nose; the wings were of 12-in. root chord and were swept back at a 35-deg angle. No trips were present on the inboard two-thirds span of the test wing.

The closed-return facility was operated at a total pressure of 1 atm; total temperature was held constant at $\sim$90°F (550°R) by diverting a small portion of the circuit air to atmosphere and replacing it with cool, ambient air. Nominal test conditions were a freestream Mach number $M_\infty = 0.4$ at a freestream unit Reynolds number $Re_\infty = 2.5 \times 10^6$/ft and $M_\infty = 0.8$ at $Re_\infty = 3.4 \times 10^6$/ft. Angle-of-attack α sweeps to $+10$ deg at $M_\infty = 0.4$ and to $+5$ deg at $M_\infty = 0.8$ were conducted.

The test surface was the upper surface of the starboard wing. The inboard portion of this wing was positioned directly below one of the off-centerline window ports and could thus be uniformly illuminated by a white light (L) from above. Two synchronized, opposing-view color video cameras (C) were deployed. The downstream-facing camera was a miniature device positioned within a vent slot in the tunnel ceiling; this placement yielded an optimum 30-deg above-plane view angle of the wing upper surface at zero degrees angle of attack. The upstream-facing camera was positioned outside the test section, within the surrounding plenum chamber, and viewed the test surface through a window at a 43-deg above-plane viewing angle when the model was at 0-deg angle of attack.

In this arrangement, transition to turbulence on the wing upper surface, characterized by an abrupt increase in surface shear stress magnitude in the principal flow direction, was made visible by the LCC color-change response recorded with the downstream-facing camera. Conversely, regions of reverse flow enveloped by

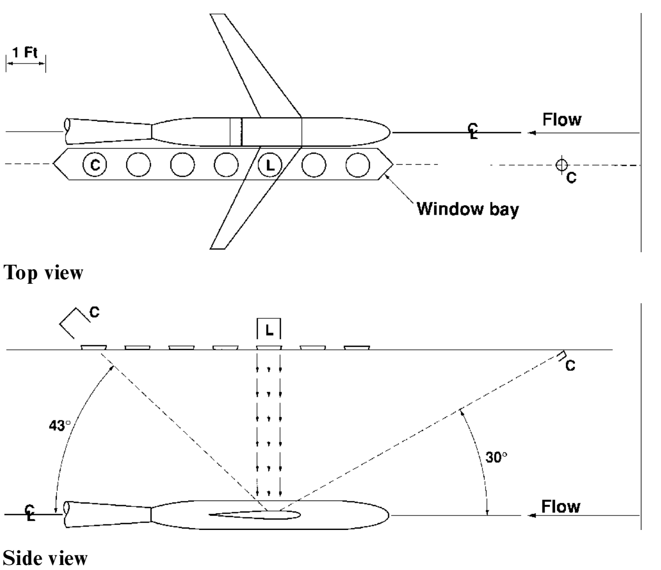

Fig. 1 Schematic of experimental arrangement.

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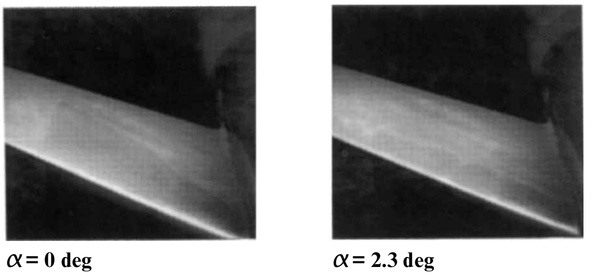
upstream-directed shear vectors were made visible by the LCC color-change response recorded with the upstream-facing camera. Regions of the coated test surface exposed to shear vectors, directed toward either camera, yielded no color-change response, appearing as either dark or reddish-brown zones, depending on the absolute light levels reaching the camera. Any regions of extreme transverse flow, enveloped by shear vectors directed either inboard or outboard and approximately perpendicular to the principal flow direction, would have appeared (if present) as a yellow color-change response simultaneously to both cameras.

III. Results

Figure 2 illustrates the transition-front visualization capability of the LCC technique. Here, regions of low shear magnitude were delineated by a red or yellow color, whereas regions of high shear magnitude appeared as green or blue. Several important features of the surface shear field were made visible by these LCC color-change responses. Transition at 0-deg angle of attack was seen to occur along a swept line ranging from ~25% of chord inboard to ~75% of chord outboard with turbulent wedges interspersed. This chordwise transition front moved forward with increasing angle of attack consistent with a dependence on the adverse-pressure-gradient onset location for this airfoil section. The discrete turbulent wedges originating from the wing leading-edge region were a result of isolated roughness elements caused by freestream contaminants impacting the surface.

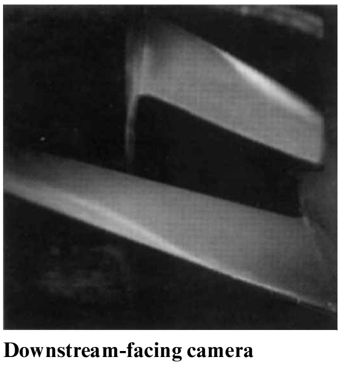
Figure 3 shows synchronized LCC color-change responses as recorded by opposing-view cameras for $\alpha = 8$ deg at $M_\infty = 0.4$



$\alpha = 0$ deg $\alpha = 2.3$ deg

Fig. 2 Transition-front visualization recorded by the downstream-facing camera at $M_\infty = 0.4$ and $Re_\infty = 2.5 \times 10^6$/ft.

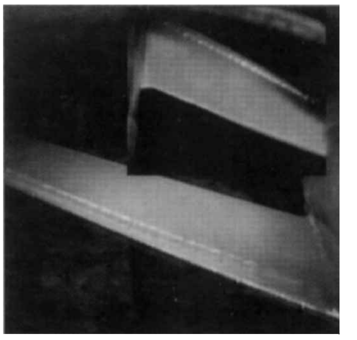
Upstream-facing camera



Downstream-facing camera

Fig. 3 LCC color-change responses as recorded by opposing-view cameras for a leading-edge separation at $\alpha = 8$ deg, $M_\infty = 0.4$, and $Re_\infty = 2.5 \times 10^6$/ft.

Upstream-facing camera



Downstream-facing camera

Fig. 4 LCC color-change responses as recorded by opposing-view cameras for a normal-shock/boundary-layer interaction at $\alpha = 5$ deg, $M_\infty = 0.8$, and $Re_\infty = 3.4 \times 10^6$/ft.

and $Re_\infty = 2.5 \times 10^6$/ft. Under these test conditions, a leading-edge separation occurred outboard on the wing upper surface, as indicated by the red zone in the downstream-facing view and the corresponding yellow zone in the upstream-facing view. High-shear (turbulent) attached flow existed everywhere else on the wing upper surface, as indicated by the blue color in the downstream-facing view and no color-change response in the upstream-facing view.

Figure 4 shows synchronized LCC color-change responses as recorded by opposing-view cameras for $\alpha = 5$ deg at $M_\infty = 0.8$ and $Re_\infty = 3.4 \times 10^6$/ft. Under these test conditions, a normal shock wave/laminar boundary-layer interaction occurred slightly downstream of the wing leading edge. Here, the yellow zone along the wing leading edge, recorded by the downstream-facing camera, indicated a low-shear (laminar) region upstream of the interaction. A narrow band of reverse flow formed beneath the interaction region, oriented approximately parallel to the leading edge; this region was indicated by the reddish-brown band in the downstream-facing view and, simultaneously, by the yellow band in the upstream-facing view. This reverse-flow region was breached by numerous turbulent wedges seen emanating from aforementioned roughness elements along the leading edge; passage of these locally attached turbulent wedges through the interaction region are best illustrated by the dark breaks in the yellow band recorded by the upstream-facing camera. High-shear (turbulent) attached flow existed everywhere downstream of the reverse-flow region, as indicated by the extensive blue zone in the downstream-facing view, and corroborated by the absence of color change downstream of the yellow band in the upstream-facing view.

References

[1]Reda, D. C., Muratore, J. J., Jr., and Heineck, J. T., "Time and Flow Direction Responses of Shear-Stress-Sensitive Liquid Crystal Coatings," *AIAA Journal*, Vol. 32, No. 4, 1994, pp. 693–700.

[2]Reda, D. C., and Muratore, J. J., Jr., "Measurement of Surface Shear Stress Vectors Using Liquid Crystal Coatings," *AIAA Journal*, Vol. 32, No. 8, 1994, pp. 1576–1582.

[3]Reda, D. C., Wilder, M. C., Farina, D. J., and Zilliac, G., "New Methodology for the Measurement of Surface Shear Stress Vector Distributions," *AIAA Journal*, Vol. 35, No. 4, 1997, pp. 608–614.

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