Shear-Sensitive Liquid Crystal Coating Method: Surface-Inclination Effects on Shear Vector Measurements

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Abstract

The shear-sensitive liquid crystal coating (SSLCC) method is an image-based technique for both visualizing dynamic surface-flow phenomena, such as transition and separation,[1] and for measuring the continuous shear-stress vector distribution acting on an aerodynamic surface.[2,3] Under proper lighting and viewing conditions (discussed below), the coating changes color in response to an applied aerodynamic shear. This color-change response is continuous and reversible, with a response time of milliseconds, and is a function of both the shear magnitude and the shear vector orientation relative to the observer.

The liquid crystal phase of matter is a weakly-ordered, viscous, non-Newtonian fluid state that exists between the nonuniform liquid phase and the ordered solid phase of certain organic compounds.[4] Cholesteric liquid crystal compounds posses a helical molecular arrangement that selectively scatters white light, incident along the helical axis, as a three-dimensional spectrum. This property is linked to the helical pitch length, which is within the range of wavelengths in the visible spectrum. The pitch length, and hence the wavelength of the scattered light, is influenced by shear stress normal to the helical axis. This unique optical property produces a measurable color change in response to an applied shearing force.

The full-surface shear stress vector measurement method, developed at NASA-Ames, is schematically illustrated in Fig. 1. As with the visualization method, the coated test surface is illuminated from the normal direction with white light and the camera is positioned at an above-plane view angle of approximately 30 deg. For quantitative measurements, images of the SSLCC color-change response to the shear field are recorded from multiple in-plane view angles encompassing all shear vector directions to be measured (shown as ϕ_{C1} to ϕ_{C4}). The color-change response to a constant shear stress vector is a Gaussian function of the relative in-plane view angle between the observer and the vector orientation.[5] Therefore, the shear vector orientation can be determined at each physical point on the test surface by fitting a Gaussian curve to the variation in measured color (dominant wavelength, λ_D) with changing in-plane view angle (ϕ_C) at that point on the surface. In theory, a minimum of four images is required to obtain the Gaussian curve fit, but in practice this number is generally increased consistent with optical access. The in-plane angle corresponding to the maximum color-change value of the curve-fit determines the vector orientation (ϕ_τ), and the value of the vector-aligned color ($\lambda_{D,VA}$) is then related to the shear magnitude (τ) via a calibration curve acquired using

conventional point-measurement techniques (e.g., the fringe-imaging skin friction, or "oil-drop," technique[6]).

Experiments have been initiated at NASA Ames to begin the process of quantifying surface-inclination (surface-curvature) effects on shear vector measurement accuracy. The apparatus used for this purpose is shown in Fig. 2. An axisymmetric, turbulent wall jet of initial diameter 0.33 in. blows tangentially across the test surface, a smooth, flat, 8 in. diameter disc. Total pressure at the jet exit centerline is monitored and controlled by a feedback loop.[2] Two important new features have been added to this apparatus: (1) the jet tube is now locked directly to the circumference of the test plate; (2) the test surface can be systematically tilted about either of two orthogonal axes through its center by the insertion and rotation of interchangeable, inclined-surface, plates (see again Fig. 2). This arrangement ensures that the same shear stress vector distribution is applied to the test surface at all surface-inclination angles. Figure 3 shows this continuous shear stress vector distribution as measured on the untilted surface.[2]

In preliminary experiments,[7] surface-inclination angles θ_X, θ_Y of 0, ±5, ±10, and ±15 deg were employed. Since the wall-jet axis is aligned with the X axis, θ_X inclination angles simulate surface slope variations transverse to the principal flow direction (such as would be experienced for flow along a fuselage), while θ_Y inclination angles simulate surface slope variations along the principal flow direction (such as would be encountered for flow over a two-dimensional airfoil).

In this arrangement, white-light illumination was positioned normal to the untilted test surface, and the camera above-plane view angle was set at 30 deg relative to the untilted test surface. A SSLCC (Hallcrest mixture BCN/192), of nominal thickness 0.002 in., was applied to the test surface for each preset θ_X or θ_Y value. Color (λ_D) of the coating was then measured with a 3-CCD video camera focused on a small 5x5 pixel area at the center of the test plate for sequentially-applied jet total pressures of 0, 2, and 4 psig (shear magnitudes of 0, 0.27, and 0.53 psf).

Resultant vector-aligned λ_D measurements "at a point" on the wall-jet, shear-field centerline are shown in Fig. 4 versus surface-inclination angles θ_X and θ_Y with jet total pressure as the parameter. As can be seen, vector-aligned λ_D values showed no dependence on θ_X or θ_Y for absolute values of these tilt angles $\leq$ 15 deg. Acquisition and analyses of full-surface color images are presently underway to definitively document the insensitivity limits of the shear vector measurement methodology to surface-slope variations.

References:

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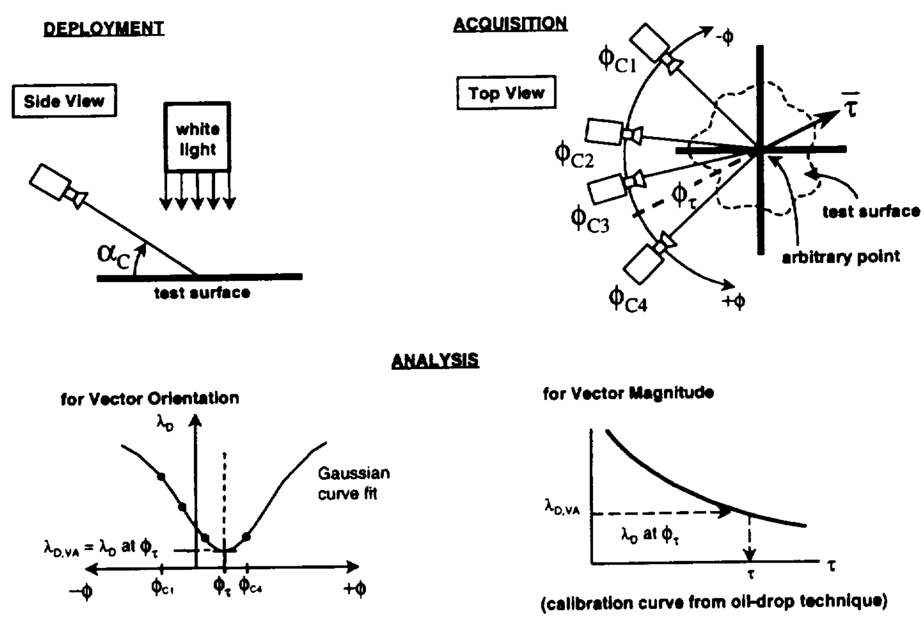

Fig. 1 Schematic of full-surface shear stress vector measurement methodology.

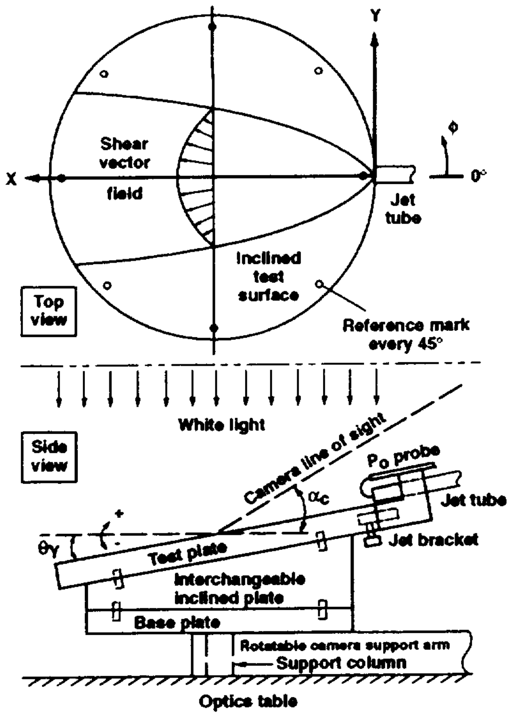

Fig. 2 Schematic of experimental arrangement for quantification of surface-inclination effects.

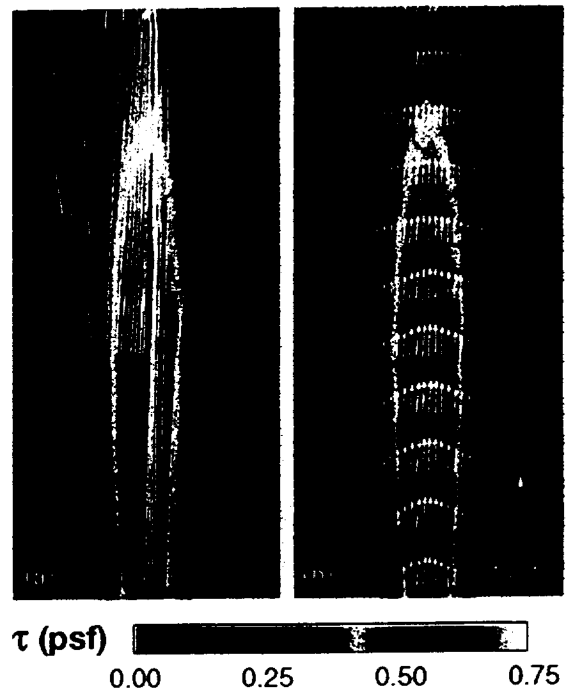

Fig. 3 Measured surface shear stress vector field for wall-jet flow at P_0=4 psig: (a) streaklines originating from X/D = 5 and 10; (b) vector profiles every ΔX/D = 1.23.

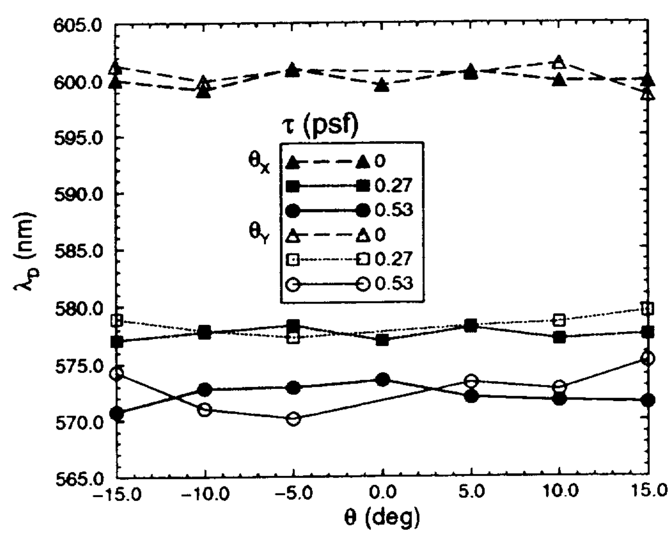

Fig. 4 Vector-aligned dominant wavelength at center of test surface vs. surface-inclination angle.