# Visualization of Continuous Surface Shear Stress Vector Distributions

Lecture One

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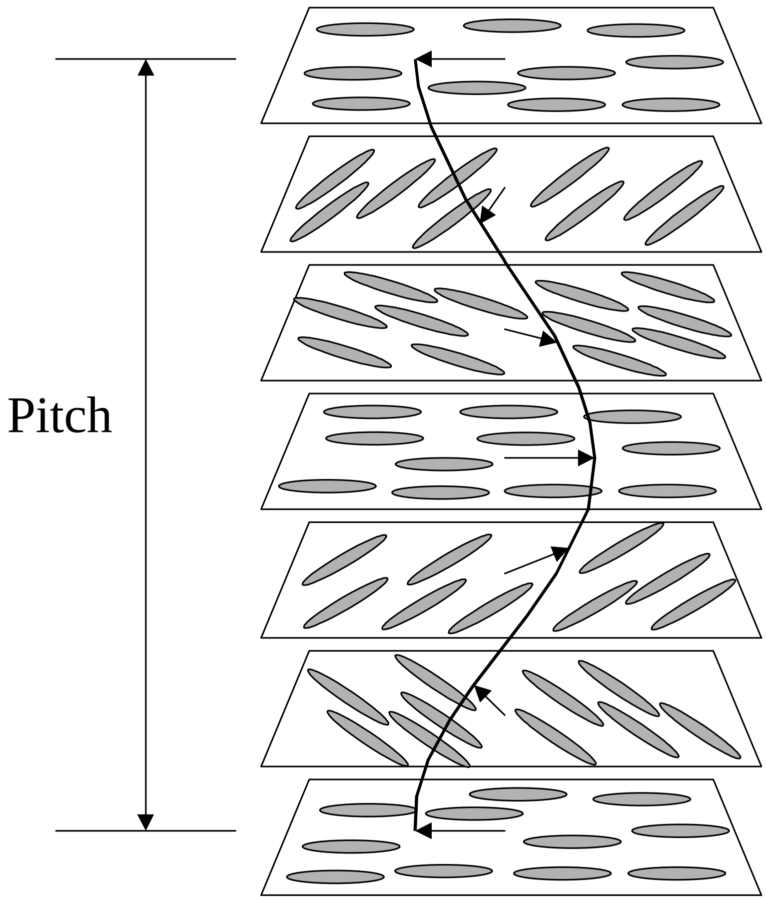
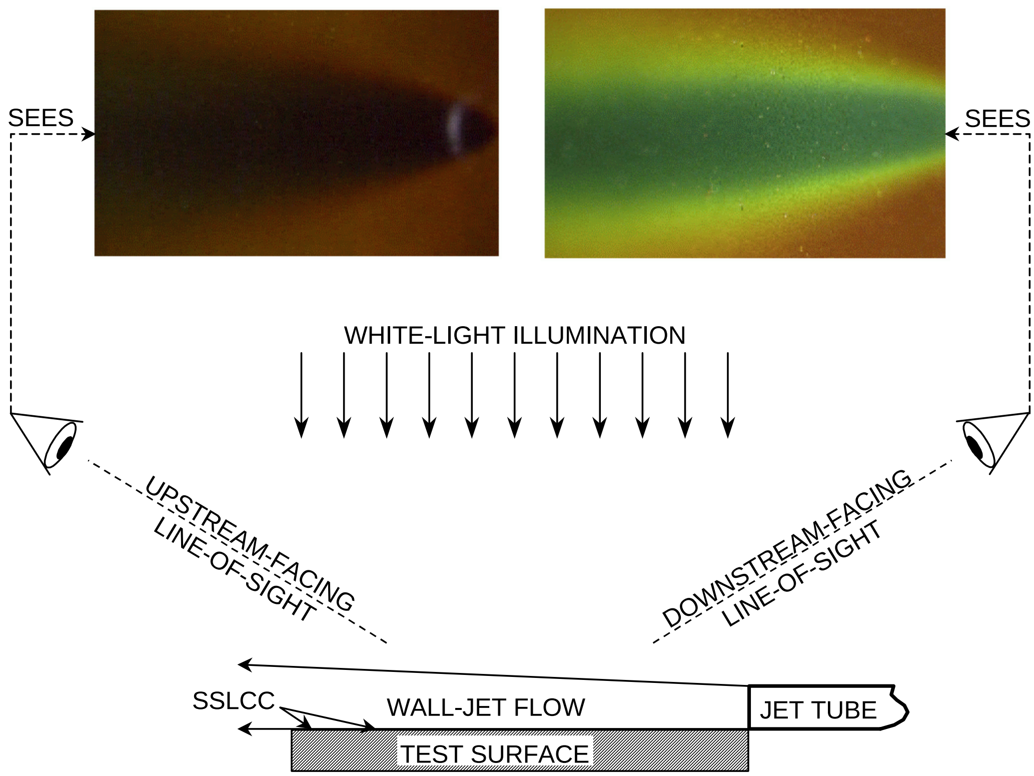



Schematic of shear-sensitive liquid-crystal coating (SSLCC) molecular structure (after Fergason, 1964).

The liquid-crystal phase of matter is a weakly ordered, viscous, fluid-like state that exists between the nonuniform liquid phase and the ordered solid phase of certain organic compounds. Liquid crystals can exhibit optical properties that are characteristic of solid, crystalline materials.

Shear-sensitive cholesteric (chiral nematic) liquid crystal coatings are comprised of helical aggregates of long, planar molecules arranged in layers parallel to the coated surface. Each layer of molecules is rotated, relative to the layer above and below it, about an axis perpendicular to the coated surface. The longitudinal dimension along the helical axis (the pitch) is on the order of the wavelengths of visible light. This layered, helical structure causes such materials to be extremely optically active. White light incident normal to the coating surface is selectively scattered at a wavelength proportional to the pitch of the helix. Under applied shear at either boundary of the coating, the local pitch of the helical structure is altered and the local helical axis is tilted relative to the no-shear state. The net result is that the incident light is reflected in a highly directional manner, as a three-dimensional color spectrum in space.




In the top-light/top-view mode, color-change response of a shear-sensitive liquid-crystal coating (SSLCC) to aerodynamic shear depends on both the magnitude of the local shear vector and its direction relative to the observer's in-plane line of sight. The surface of the SSLCC exposed to aerodynamic shear is illuminated with white light from the normal direction and observed from an oblique above-plane view angle of order 30 deg. Shear vectors with components directed away from the observer cause the SSLCC to exhibit color-change responses. At any surface point, the maximum color change (measured from the no-shear red or orange color) always occurs when the local vector is aligned with, and directed away from, the observer. The magnitude of the color change at this vector-observer-aligned orientation scales directly with shear stress magnitude. Conversely, any surface point exposed to a shear vector with a component directed toward the observer exhibits a non-color-change response, always characterized by a rusty-red or brown color, independent of both shear magnitude and direction. Such color changes are continuous and reversible, with time response of order milliseconds. These unique, highly directional color-change responses of SSLCCs to aerodynamic shear allow for the full-surface visualization and measurement of continuous shear stress vector distributions.

## Coating Application

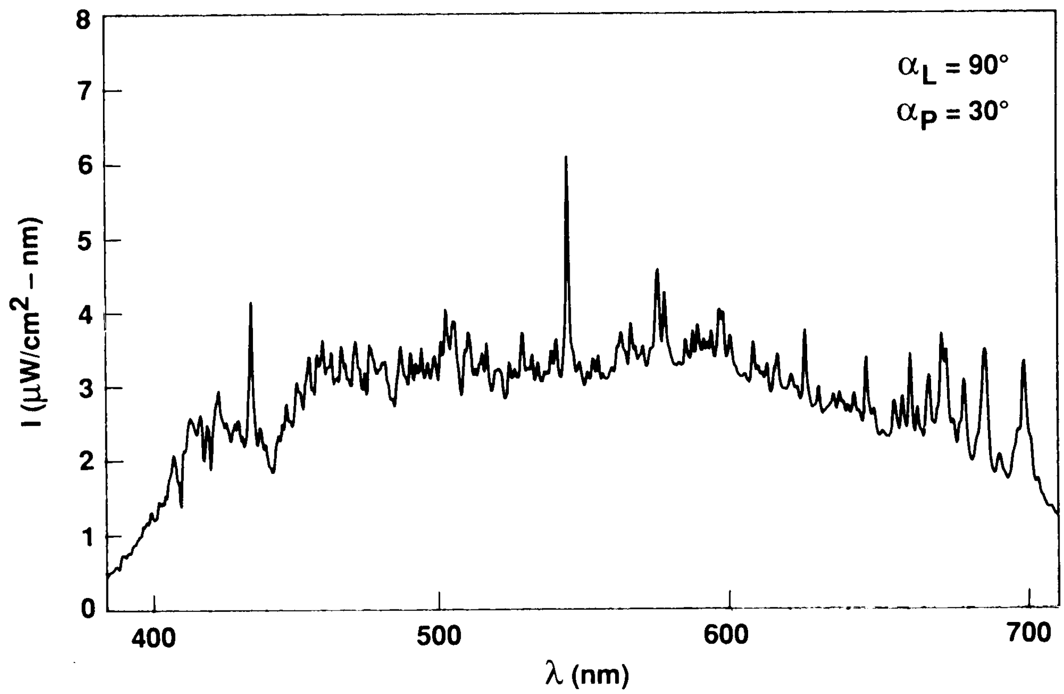
Liquid crystal materials are commercially available from the Liquid Crystal Division of Hallcrest, Inc. in Glenview, Illinois. A wide variety of SSLCC materials exists, covering a wide range of viscosities. The “correct” compound for any experiment is the one that yields a full-range (red-to-blue) color change response under the range of shear magnitudes experienced in the experiment, yet is viscous enough not to flow over the surface. Color measurements of the light scattered by the SSLCC are valid only in the absence of such macroscopic migrations.

Compounds utilized in aerodynamic applications include BCN/192, BCN/195, CN/R1 and CN/R3. The usable shear range for these materials is approximately 5 to 50 Pa (0.1 to 1 psf). Hydrodynamic applications should utilize more-viscous compounds, e.g., CN/R7 and CN/R8. All such compounds are broad-band insensitive to temperature, freezing at $0^oC$ and melting at $50^oC$. The shelf life is quoted as one year.

A mixture of one part liquid crystal to nine parts, by volume, of a solvent such as Freon or a Freon replacement (for example, DuPont Vertrel KCD-9571) is sprayed onto the test surface. The solvent evaporates at atmospheric conditions, leaving a uniform liquid crystal coating. Unlike paint, the coating does not dry, but remains viscous and should not be touched. A smooth, flat-black surface (e.g., anodized aluminum) is essential for color contrast: the color response is a low-intensity scattered field that is easily overpowered by light scattered from a bright surface finish. Reference marks are required on the surface for image registration. The solvent should be used to clean the test surface prior to the coating application, as well as to remove the coating after testing.

Recommended coating thicknesses are of the order 75 $\mu$m (0.003 in.). Assuming a 50% spray loss, this requires a sprayed volume of the nine-to-one mixture equal to 0.15 $cc/cm^2$ (1 $cc/in^2$) of test surface. Cost to coat a test surface is approximately $\$200/m^2$ ($\$20/ft^2$).

The molecules within a newly sprayed coating are generally not aligned in the helical molecular orientation required to disperse white light into a spectrum of colors. The optically active arrangement can be achieved by shearing the coating, either by passing a pressurized air jet over the coated surface prior to the experiment, or by the flow under investigation itself. For this second alternative, it is important that the initial flow provide the maximum shear condition that the coating will experience during the experiment, otherwise lightly sheared regions of the coating may not achieve the proper molecular arrangement.

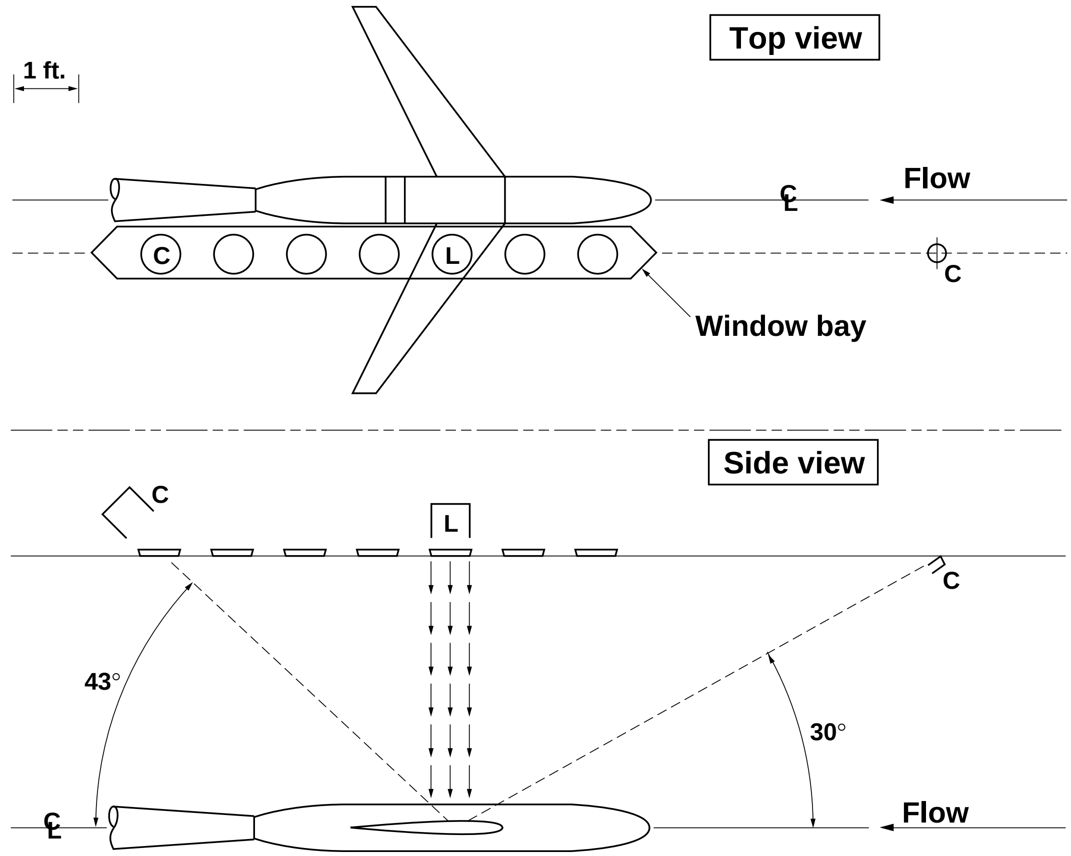



White-light spectrum; scattering intensity vs wavelength.

## Lighting and Imaging

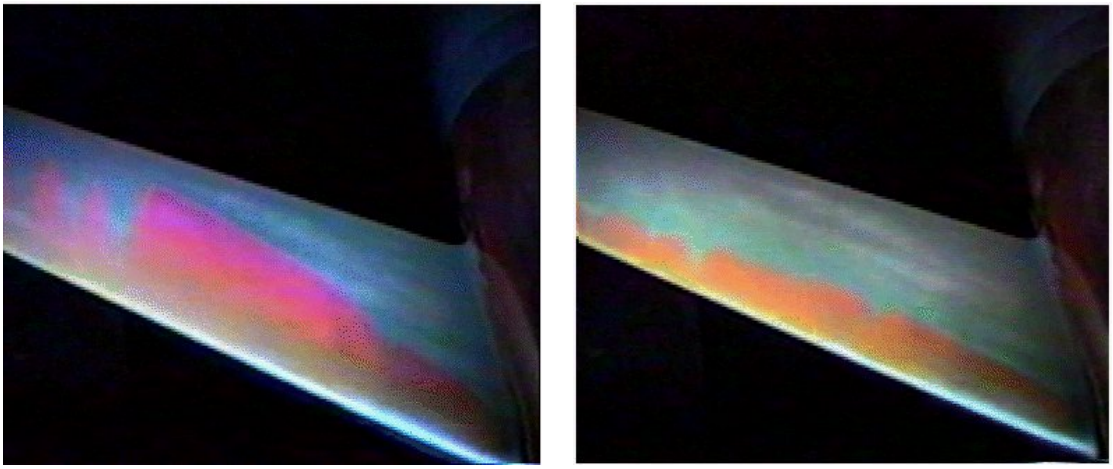
The SSLCC must be illuminated with white light (color temperature near 5600 K) in order for the color-change response to produce the full visible spectrum. The 1200-W Sylvania PAR64 BriteBeam is an example, and should be operated with a flicker-free ballast and an ultraviolet filter.

For qualitative flow visualizations, the color-change response can be imaged using standard color video cameras.




To capitalize on the 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 planar-like, i.e., no regions of extreme curvature, and that it be uniformly illuminated from above. This figure shows a schematic of the experimental arrangement utilized to demonstrate the SSLCC technique in the Boeing 8x12 ft transonic wind tunnel.

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 zero degrees angle of attack.



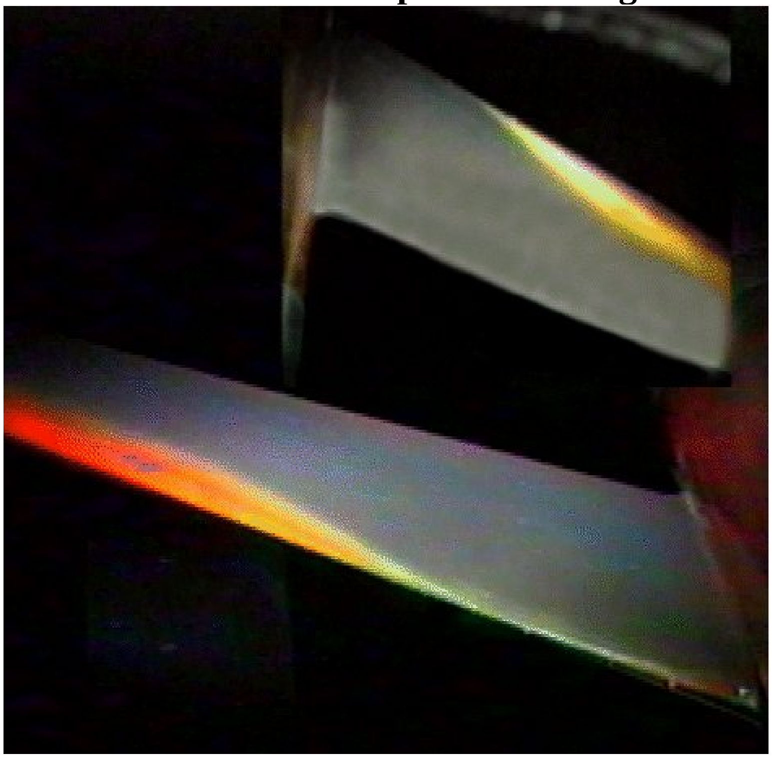
**α = 0 deg** **α = 2.3 deg**

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

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 SSLCC color-change response recorded with the downstream-facing camera.

Regions of low shear magnitude were delineated by a red or yellow color, while regions of high shear magnitude appeared as green or blue. Several important features of the surface shear field were made visible by these SSLCC 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.

**Upstream-facing camera**

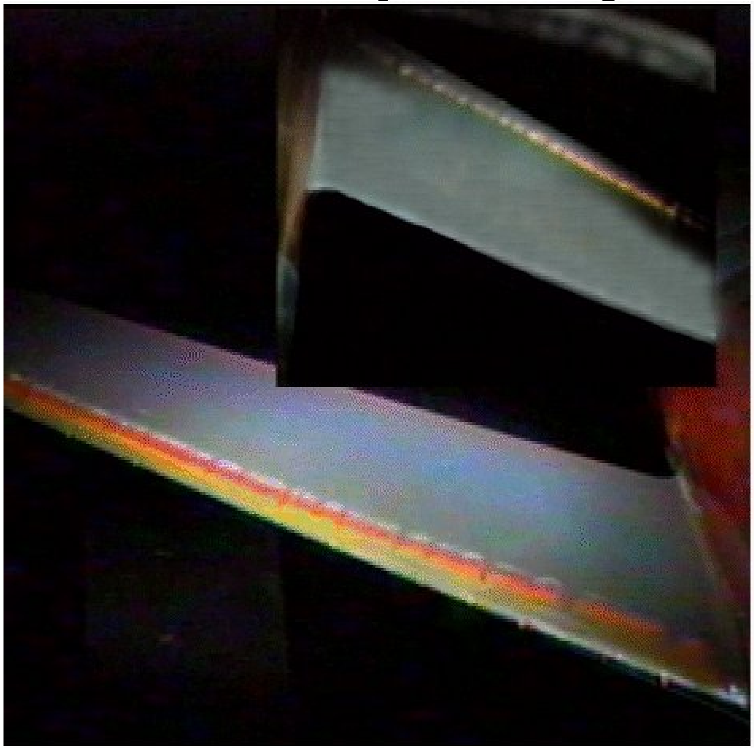


**Downstream-facing camera**

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

This figure shows synchronized SSLCC color-change responses as recorded by opposing-view cameras for $\alpha$ = 8° at $M_\infty$ = 0.4, $Re_\infty$ = 2.5 x $10^6$/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.

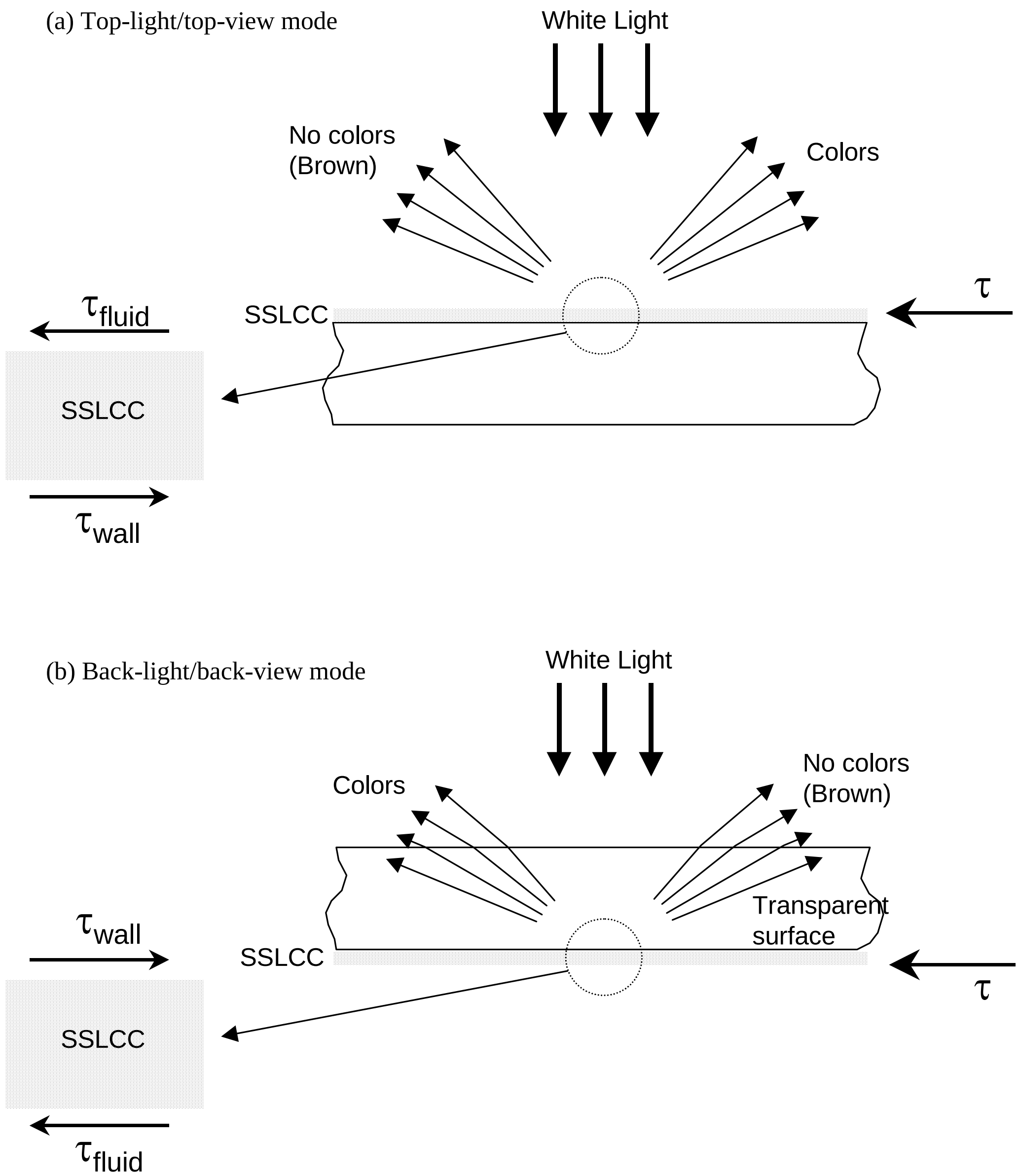
**Upstream-facing camera**



**Downstream-facing camera**

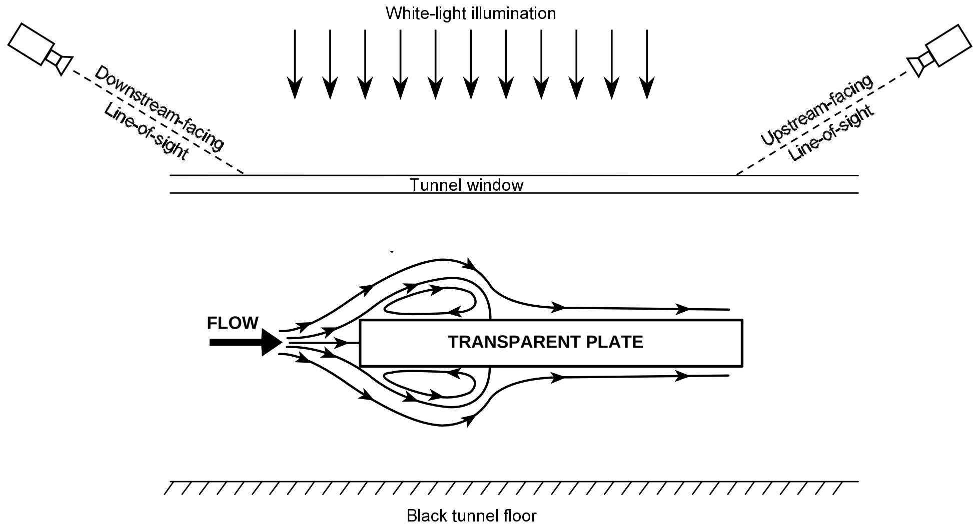
SSLCC color-change responses as recorded by opposing-view cameras for normal-shock/boundary-layer interaction at $\alpha$ = 5 deg, $M_\infty$ = 0.8, $Re_\infty = 3.4 \times 10^6$/ft

This figure shows synchronized SSLCC color-change responses as recorded by opposing-view cameras for $\alpha = 5°$ at $M_\infty$ = 0.8, $Re_\infty = 3.4 \times 10^6$/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 isolated 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.




Two SSLCC operational modes and the macroscopic view of the forces applied to the coating

Research was recently conducted to explore application of the Shear-Sensitive Liquid Crystal Coating (SSLCC) flow-visualization method through a transparent test surface. In this previously untested back-light/back-view mode, the exposed surface of the SSLCC was subjected to aerodynamic shear stress while the contact surface between the SSLCC and the solid, transparent surface was illuminated and viewed through the transparent surface. The top part of this figure shows schematically the geometrical arrangement utilized in the conventional top-light/top-view mode, and the new back-light/back-view mode is shown in the bottom portion.

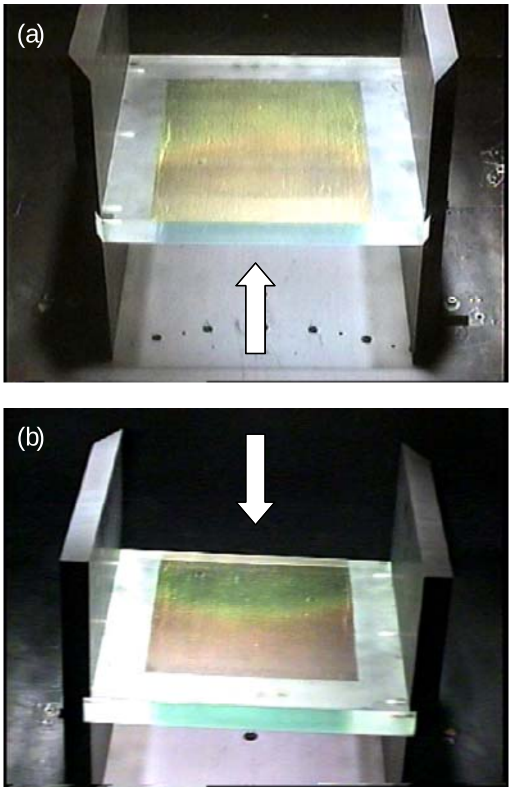



Schematic of experimental arrangement.

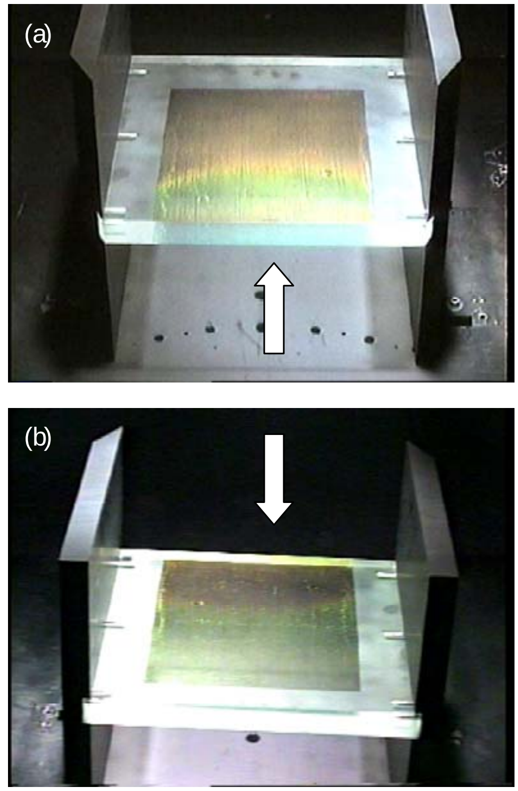
This figure shows a schematic of the experimental arrangement and resultant flow field used to illustrate the new method. A 12 x 12 in. plate, 1 in. thick, of transparent acrylic plastic was used as the model. One surface of this plate was bead blasted to a "frosty" surface finish to enhance SSLCC adhesion. Surface roughness, measured with a diamond-tip stylus apparatus, was 30 μ in., rms. The other surface was unaltered from its original, smooth/clear state.

A 0.003 in. nominal thickness coating of Hallcrest SSLCC compound CN/R3 was spray painted onto the bead-blasted test surface. The model was mounted between two 12 in. high, sharp-leading-edge sidewalls with the plate chord 6 in. above, and parallel to, the tunnel floor; the flow-exposed spanwise dimension of the test surface was 11.5 in. The blunt leading edge of the model was thus positioned perpendicular to the freestream velocity vector.

Experiments were conducted in an in-draft subsonic wind tunnel with a 3 x 4 ft. test section. Test conditions were a total pressure of 1 atm, a total temperature of 72°F, and a freestream velocity of 180 ft/s. As shown, a large-scale separated flow region formed over both the upper and lower plate surfaces immediately downstream of the blunt leading edge. The streamwise extent of the reverse-flow region was slightly larger on the upper, unbounded surface of the plate. Reattachment occurred downstream of each reverse-flow zone, resulting in a high-shear, attached, turbulent boundary layer flow over the downstream extent of each surface.




SSLCC on upper surface, top lit and viewed with,
(a) downstream facing camera, (b) upstream facing camera.




SSLCC on lower surface, back lit and viewed with,
(a) downstream facing camera, (b) upstream facing camera.

The top-light/ top-view color-change responses are shown on the left, while the corresponding back-light/ back-view results are shown on the right. First, consider the top-light/top-view images. In (a), the downstream-facing view, shear vectors beneath the reverse-flow zone were toward the observer, and a non-color-change response (brown) was seen, while shear vectors downstream of reattachment (outlined by the thin yellow arc) were away from the camera, resulting in a green color-change response (the no-shear color for this compound being a reddish orange). In (b), the upstream-facing view, shear vectors beneath the reverse-flow zone were away from the observer, and a green color-change response was seen. Attached-flow vectors downstream of reattachment were toward the observer and the non-color-change (brown) response resulted.

Cross comparisons of the (a) and (b) frames clearly show that the color-change responses recorded for the back-light/ back-view mode were opposite to those recorded in the conventional top-light/top-view mode. On the macroscopic level, this finding can be explained by analyzing a free-body diagram of an elemental area of a thin, non-flowing coating. Applying Newton's second law of motion, the shear stress exerted on the coating by the fluid is equal to and opposite from the shear stress exerted on the coating by the solid surface.

## Summary

The color-change responses of SSLCCs to aerodynamic shear are:

- dependent on both shear vector magnitude and its direction relative to the observer
- continuous, i.e., a single-valued function of shear magnitude for a given shear direction
- reversible, i.e., the SSLCC can be subjected to a shear vector "history"
- rapid, with a time constant of order 1 millisecond

These characteristics allow for the simultaneous, full-surface visualizations of transition and separation, continuously and reversibly, over a complete range of test conditions. The simultaneous acquisition of SSLCC images and balance data can thus be used to define cause-and-effect relationships. This increased knowledge results in reduced design-cycle times and improved product performance.

Present results also clearly demonstrate that the SSLCC flow-visualization method can be extended to the back-light/back-view mode. This mode makes the SSLCC method applicable to the study of a new class of fluid-dynamic problems. First, the method can be utilized to visualize surface shear stress patterns in internal-flow problems. Examples include biomedical applications, such as flows in heart-assist devices; race-car applications, such as flows under inverted wings in close ground (or moving-belt) proximity; and aerospace applications, such as flows within engine inlets. Second, visualization of surface shear stress distributions on external surfaces of test bodies such as fuselages, hulls, keels, etc., can be accomplished through transparent ports using lights/cameras placed inside of these structures. Finally, this new back-light/back-view deployment mode overcomes surface obscuration limitations associated with mounting non-transparent appendages or protuberances onto the test surface.