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Use of Shear-Sensitive Liquid Crystals for Surface Flow Visualization

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The use of shear-sensitive liquid crystals has become an established technique for diagnostic flow visualization. This paper presents an overview of the state of the art of the liquid-crystal technique, including the historical development and a discussion of how it is used. Sample results from several researchers demonstrate the range of flow features that can be illustrated, including laminar boundary-layer transition, laminar separation bubbles, shocks, and separation. The technique has been demonstrated in flight and wind-tunnel environments from subsonic to hypersonic speeds.

Introduction

THE use of shear-sensitive liquid-crystal material has become an established technique for diagnostic flow visualization. A thin coating of liquid crystals applied to a surface scatters white light so that specific wavelengths are scattered in certain directions. The coating responds to changes in surface shear stress by altering the scattering angle for each wavelength, or color. Any abrupt change in shear stress such as through boundary-layer transition produces a dramatic change in the color "seen" at a fixed observation point. The liquid crystals do not become set at a particular condition, so many different test conditions can be studied with one application—an important advantage over other techniques such as sublimation, which must be reapplied after each test condition. The liquid-crystal technique has been demonstrated as an effective flow-visualization tool for flight and wind-tunnel testing, over the whole Mach number range from low speed to hypersonic.

This paper presents an overview of the state of the art of the liquid-crystal technique. The historical evolution of the technique is reviewed, followed by a detailed description of how liquid crystals are used. Sample results from several researchers demonstrate the range of flow features that can be illustrated and some of the challenges and pitfalls that may be encountered.

Development

The earliest use of liquid crystals for study of boundary layers was by E. J. Klein at NASA Ames Research Center in the late 1960s.[1,2] Klein attempted to quantitatively measure skin friction by calibrating the scattering angles of the coating as a function of shear stress. This proved to be impractical because temperature and incident light angle also affect the scattering angles, making the calibration too complex.

In the early 1980s, B. J. Holmes, C. J. Obara, and P. D. Gall at NASA Langley Research Center investigated the use of liquid crystals for quantitative illustration of surface flow features. They focused primarily on in-flight visualization of boundary-layer transition, but also discussed shocks and separated flow, and wind-tunnel application.[3–5] The sublimation technique was used to confirm the transition indications of the liquid crystals. This work pioneered the use of liquid crystals as a qualitative diagnostic tool for flow visualization. Holmes et al.[3] also advanced the accepted hypothesis of how the liquid-crystal technique works, and developed a formulation procedure and nomenclature to describe the required characteristics of the liquid crystals.

The successful demonstrations at NASA Langley lead to increased interest in the liquid-crystal technique at several places. J. P. Crowder and D. W. Lund at the Boeing Commercial Airplane Co. applied the technique on civil-transport models in the Boeing Transonic Wind Tunnel at dynamic pressures up to 675 psf. B. T. Anderson and R. R. Meyer at NASA Ames-Dryden Flight Research Facility used liquid crystals for a variable-sweep transition flight experiment on the F-14 aircraft.[6] Hot-film transducers and pressure rakes were used to confirm the transition locations indicated by the liquid crystals. D. C. Reda at Sandia National Laboratories demonstrated the dynamic capability of the liquid crystals on an oscillating airfoil,[7–9] and found that the liquid-crystal response was fast enough to track 1-Hz oscillations. Reda also investigated the use of liquid crystals at hypersonic speeds.[10] L. Gaudet and T. G. Gell at the Royal Aerospace Establishment in Farnborough, England, have recently revisited the question of direct shear-stress measurement.[11] They studied the quantitative calibration of shear-sensitive liquid-crystal coatings using modern signal-processing techniques on digitized color video images.

Properties of Liquid Crystals

The liquid-crystal material is a cholesteric (fatty acid) compound with a consistency similar to grease. The liquid-crystal molecules are assembled to form a spiral- or helical-shaped structure. This structure causes visible light to be scattered selectively so that different wavelengths are scattered in specific directions. The helical structures within a film of liquid crystals tend to align themselves so that the coating will scatter specific wavelengths of light in particular directions, similar to the scattering properties of solid, crystalline materials—hence the name "liquid crystals." The scattering direction of a given wavelength, or color, is determined by the pitch of the helix, which is effected by temperature, shear stress, electromagnetic fields, and other environmental factors. The chemical structure of the liquid crystals is not affected, so the liquid-crystal coating can respond reversibly and repeatably to these external effects. Holmes notes that there are two families of liquid-crystal materials that have this helical property: chiral-nematic and cholesteric.[4]

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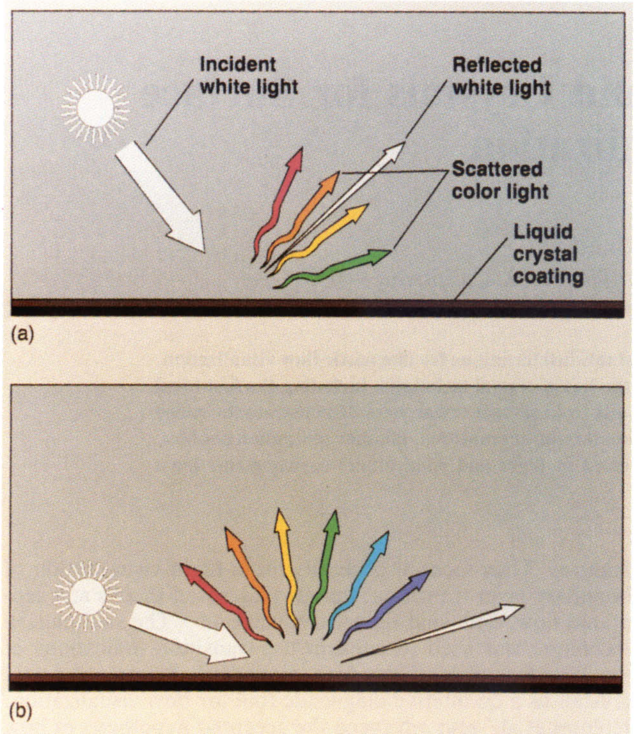

Fig. 1 Scattered light pattern from liquid crystals: a) steep light angle; and b) shallow light angle.

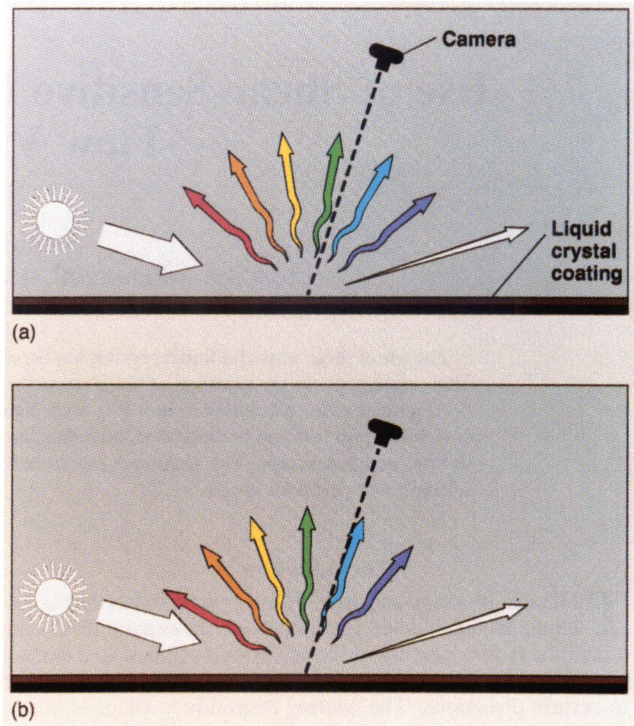

Fig. 2 Surface shear stress alters scattered light angles: a) camera sees green color from laminar boundary layer; and b) blue color from turbulent boundary layer.

Fig. 3 Liquid crystals indicate transition on the wing glove of a F-14 in flight (Ref. 6).

The lowest temperature where liquid crystals scatter visible light is called the event temperature, which is associated with a phase change of the liquid crystals to the "nematic" phase. The highest temperature is called the clearing temperature, which seems to occur when the helical pitch exceeds the wavelengths of visible light, but may also be associated with a phase change to an isotropic phase, where the crystal-like structure is lost. The temperature range between the event and clearing temperatures is determined by the formation of the liquid-crystal material.

Use of Liquid Crystals for Flow Visualization

The most desirable characteristics of liquid crystals for flow visualization are high sensitivity to shear stress and low sensitivity to temperature. A broad range of active temperature allows one formulation to be used over a wide range of ambient temperatures, and it assures that color changes are indicative of local changes in shear stress. In Ref. 4, Holmes describes a mixing procedure for formulating chiral-nematic liquid crystals to achieve a desired temperature range. The cholesteric liquid-crystal formulation used by the author and others at NASA Ames exhibits an extremely wide temperature range from approximately 5–115°F.

The viscosity of the liquid-crystal material is also an important characteristic that must be chosen for a particular application. Excessive flowing of the liquid-crystal coating causes oil-flow patterns with abrupt variations in coating thickness. This often leads to spurious or ambiguous color indications. At very high dynamic pressures, the shear stress will wipe a low viscosity coating off the model surface. Cholesteric liquid crystals can be formulated in a wide range of viscosities without significantly influencing the light-scattering characteristics of the coating.

The particular color scattered in one direction depends on the illumination angle, the viewing angle, the temperature, and the shear stress on the coating. As shown in Fig. 1, the scattering is strongly related to the included angle between the light source and the viewer, and somewhat related to the orientation of the surface. Incident light strikes the coating at a relatively steep angle in Fig. 1a, and a shallow angle in Fig. 1b. In both cases, red wavelengths are scattered back toward the incident light, and green wavelengths are scattered nearly perpendicular to the incident light. In both cases, white light is reflected directly from the surface, and the scattered light has the highest intensity in directions nearly perpendicular to the surface.

For fixed lighting and viewing angles, the scattered color seen at the viewing point is then effected by shear stress. Figure 2 shows how the color seen at a fixed viewing point is changed by the boundary-layer characteristics. In this example, the light scattered to the camera is green in the laminar boundary layer and blue in the turbulent region. A typical liquid-crystal indication of boundary-layer transition is shown in Fig. 3, on the wing glove of an F-14 in flight from Ref. 6.

These observations have great practical importance, since lighting and viewing angles must be selected to avoid specular reflection or "glare," but are constrained by limitations of optical access for a particular wind tunnel. The author has

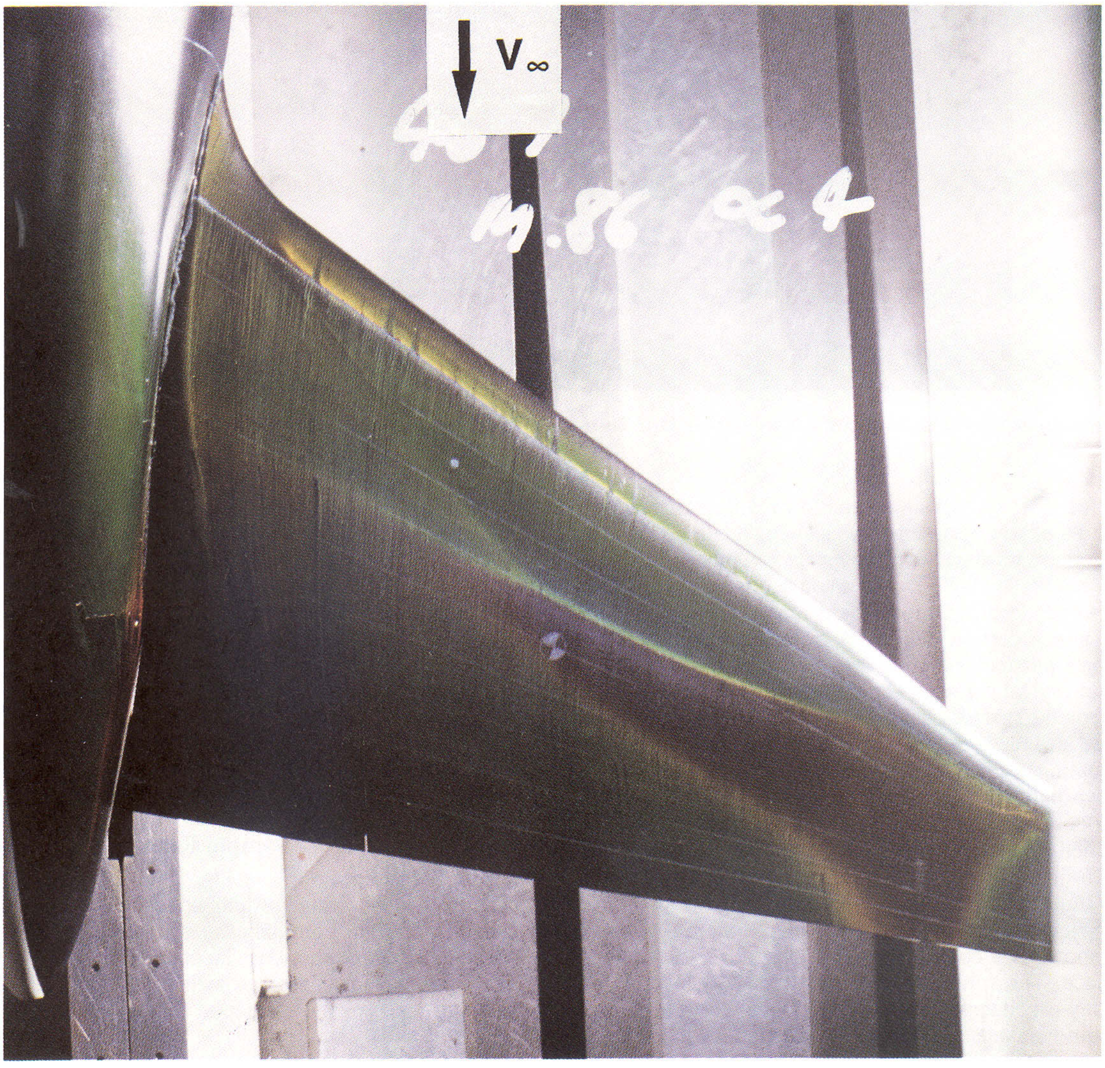

Fig. 4 Horizontal tail in the Boeing Transonic Wind Tunnel.

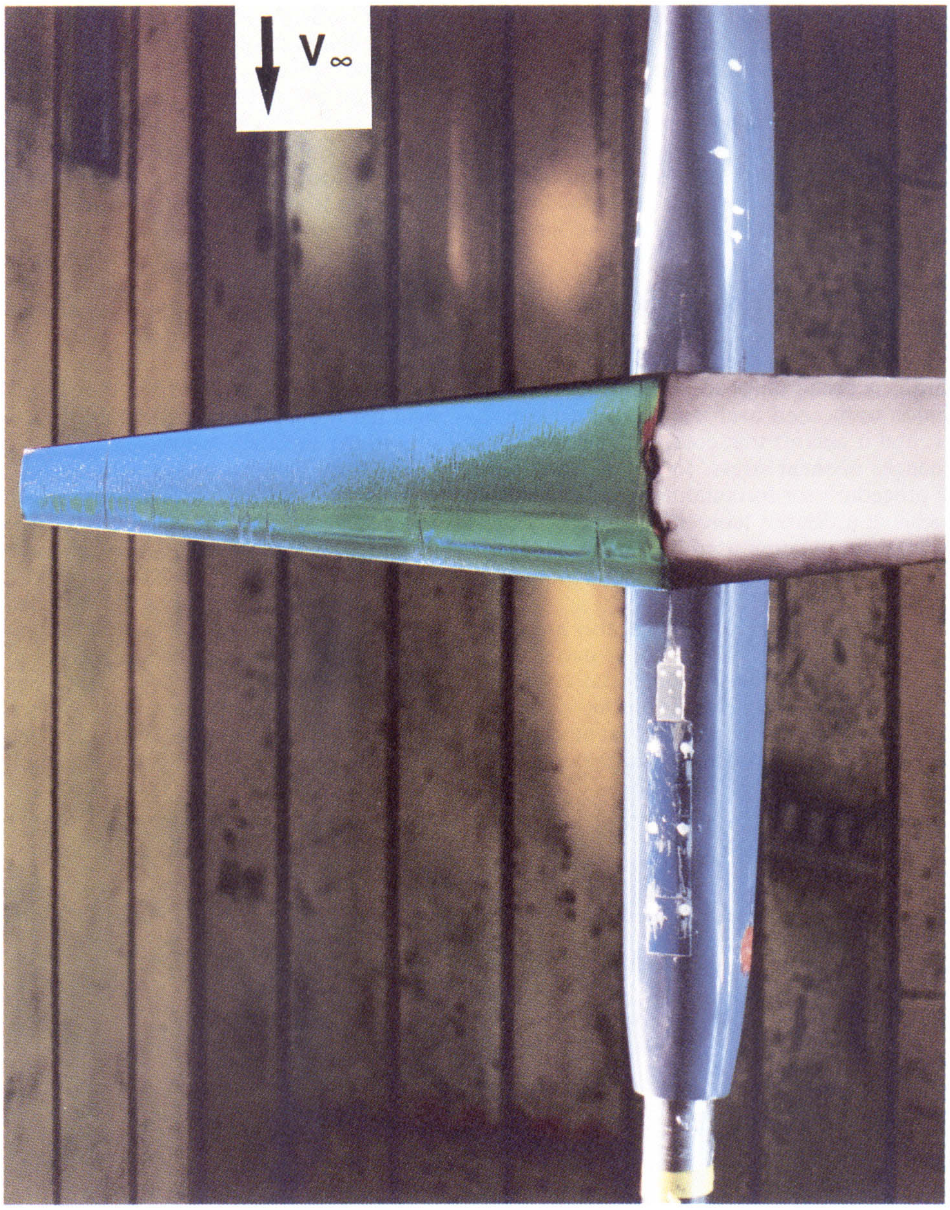

Fig. 5 Unswept supercritical wing in the NASA Ames 11-ft Transonic Wind Tunnel (sublimation on right side, liquid crystals on left side).

found that for most applications a shallow lighting angle along the span and a nearly perpendicular viewing angle work best. This arrangement produces intense green and blue colors similar to the results in Fig. 3, and avoids reflection or glare problems. Other lighting and camera angles have also been successful, and a certain degree of experimentation will be required for a particular facility and model arrangement.

The liquid-crystal material should be applied to a black or very dark-coated surface. The diffuse reflected light from a light-colored surface is much brighter than the scattered light from the coating, so the scattered light will not be visible. A flat black synthetic-enamel finish, sanded with 600-grit sandpaper, works quite well. The liquid-crystal coating may be applied directly by brushing or thinned and sprayed on. A mixture of four to eight parts Freon or 1,1,1-trichloroethane to one part liquid crystals is satisfactory for spraying. In either case, the objective is to develop an even coat that is thick enough to show vivid colors but thin enough to resist flowing on the surface. The sprayed coating may initially have a dull brown or grey-green appearance, called "focal-conic texture," since the liquid crystals are randomly oriented, or at least not systematically oriented perpendicular to the surface. As soon as the coating is stressed by airflow, the molecules align perpendicular to the surface, called "Grandjean texture," and the scattered color pattern will appear.[11]

Availability of Liquid Crystals

A listing of sources of liquid crystals has been compiled by Holmes.[3,5] Reference 5 describes a nomenclature for identifying the characteristics of various formulations, but this "code" does not appear to be widely used, and does not provide for specification of the viscosity. A standardized method of specification of properties must be adopted to facilitate widespread use of liquid crystals by the aerodynamic testing community.

Sample Results

The F-14 photograph in Fig. 3 is an excellent example of boundary-layer transition indicated by liquid crystals. In this case, the laminar boundary layer is indicated by a green color and the turbulent boundary layer appears blue. The F-14 wing glove was also instrumented with hot-film probes and pressure rakes to confirm the transition indication of the liquid crystals.[6]

Figure 4 shows a liquid-crystal visualization of flow on the horizontal tail of a civil-transport model. This work was done by J. P. Crowder an D. W. Lund in the Boeing Transonic Wind Tunnel. The transition region appears yellow-green and the turbulent boundary layer is indicated by the darker olive-green color. A shock and subsequent separation is indicated by a thin yellow line and reddish-brown color. This example illustrates the versatility of the liquid-crystal technique, visualizing transition, shocks, and shock-induced separation. The colors are less vivid in this example because the high dynamic pressure (approximately 675 psf) required an extremely thin coating of liquid crystals. The author has seen cases where a lower viscosity liquid-crystal coating was simply wiped off the surface in a short time. Obtaining satisfactory results at high dynamic pressure remains a challenge for the liquid-crystal technique.

Liquid crystals were used as part of an investigation of supercritical airfoil performance at low Reynolds numbers in the NASA Ames 11-ft Transonic Wind Tunnel by R. A. Kennelly, Jr. and S. C. Smith. Figure 5 shows both liquid-crystal and sublimation techniques on an unswept supercritical wing at low angle of attack. Boundary-layer transition at about 85% of the chord is indicated by the sublimation technique on the right. The liquid-crystal coating on the left shows a blue color over the first 40% of the chord and a band of intense green color between 70% and 85% of the chord. The blue color appears in a region where the coating is flowing like a wave of very heavy oil. The color change from blue to green occurs where there is an abrupt change in coating thickness, not necessarily as a result of changes in the flow. This spurious result indicates that this particular liquid-crystal material had too low a viscosity for the dynamic pressure (approximately 300 psf) and/or the coating was too thick. The bright green band is believed to be a laminar separation bubble, terminated by turbulent reattachment at a location that agrees well with the indication of the sublimation material. It may be that a different camera angle would have captured a more dramatic color change in this region. The author will soon be evaluating two higher viscosity formulations for high dynamic pressure applications.

The result shown in Fig. 5 demonstrates two important points. First, an independent technique, such as sublimation, should be used on a few cases for a particular installation to confirm and aid in interpretation of the liquid-crystal results. In this case, the blue-to-green color change might be interpreted as transition without the additional guidance of the sublimation coating. Insufficient viscosity and/or excessive thickness of the liquid-crystal coating may aggravate this. Second, the liquid-crystal technique may be useful for visualizing subtle flow features such as laminar separation bubbles, which are otherwise difficult to detect.

Other examples of the use of liquid crystals on oscillating airfoils and for hypersonic flow are available on video tape from D. C. Reda,[7–10] now at the Fluid Mechanics Laboratory at NASA Ames Research Center.

Conclusions

The use of liquid crystals to visualize boundary-layer transition and other surface-flow features such as shocks and laminar separation bubbles has been well-established. The technique has been used for low-speed, transonic, and supersonic conditions in wind tunnels, and slow-speed and transonic conditions in flight experiments. A standardized nomenclature for specifying the properties of the liquid crystals should be adopted which indicates the useful temperature range and the viscosity of the formulation. Detailed techniques for testing at high dynamic pressure are not as well-developed as for low-speed testing, but generally higher viscosity formulations and careful application to avoid excessive coating thickness are required. Each testing facility presents different challenges for installation of lights and cameras, and a certain amount of experimentation will be required to obtain good results. It is important to use sublimation or other independent method of detecting transition as a confirmation and aid to interpretation of liquid-crystal indication until sufficient experience in a particular facility is obtained.

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