29th Congress of the International Council of the Aeronautical Sciences
St. Petersburg, Russia; September 7-12, 2014

PROBLEMS AND ACHIEVEMENTS IN PANORAMIC SHEAR STRESS DIAGNOSTICS BY LIQUID CRYSTALS

Kovrizhina V.N.*, Shapoval E.S., Zharkova G.M.***
***S.A. Khristianovich Institute of Theoretical and Applied Mechanics, Novosibirsk, Russia,**
****FSUE Central Aerohydrodynamic Institute (TsAGI), Zhukovsky, Russia**

Keywords: *visualization, shear stress sensitive liquid crystals, surface flow, boundary layer transition*

Abstract

For panoramic diagnostics of the mean shear stresses τ on the studied model, thin-film coatings based on optically-active liquid crystals which are sensitive to shear stress (SS LCs) may be applied.
Different LC materials and approaches are considered in this work including choice of experimental technique, practical technological aspects and data processing.
Potentialities of cholesteric LCs manufactured at ITAM (Novosibirsk) are studied and tested under subsonic and transonic flow conditions in commercial wind tunnels (WT) T-128 and T-103 (TsAGI). Visualization of laminar-turbulent transition, flow separation and shock waves was successfully performed.
The method of using nematic LCs twisted by the flow for shear stress diagnostics is investigated in laboratory subsonic wind tunnel (ITAM). Calibration functions of the reflected light intensity dependent on shear stress were obtained.
Experiments showed that liquid crystals are a promise for panoramic shear stress diagnostics.

1 Introduction

To improve the aircrafts aerodynamic performances it is necessary to control the heat and mass transfer, to reduce the shear stress, to hold back the laminar-turbulent transition of the boundary layer, to control the flow separation and shock wave positions.
Each flow disturbance is accompanied by shear stress change. That's why visualization and distribution diagnostics of this parameter on the investigated surface allows identification of the flow structural peculiarities.
At the moment, large enough experimental material is accumulated on the investigation and application of two types of liquid crystals: cholesteric (CLCs) and nematic (NLCs) for shear stress diagnostics in aerodynamic tests.
The method of shear stress sensitive liquid crystals is well known but is rarely used in commercial tests.

2 Experimental Methods and Procedures

There are three main methods of performing tests using shear stress sensitive liquid crystals, based on twisting of nematic LCs, texture transformation of cholesteric LCs and shift of selective reflection peak of cholesteric LCs, induced by the air flow on the model surface.
Each experimental method includes several aspects. The first aspect is choosing the appropriate liquid crystal mixture for performing tests. Then the model preparation should be performed and it is necessary to provide illumination and observation of the investigated model surface. After that the tests can be performed.

2.1 First method: Twisting of nematic LCs

This effect is realized using nematic liquid crystals with planar texture. The optical measurement schematic is presented in the figure 1.

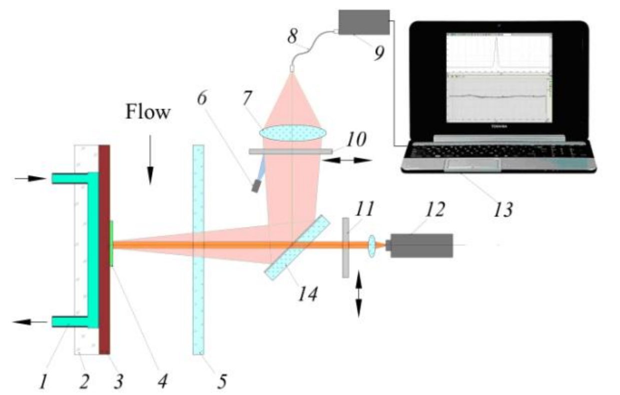

Fig. 1. Schematic of Measuring the Optical Response of Nematic LCs on Shear Stress Induced by the Flow.

In figure 1 the following numbers stand for: 1 – thermostat heat carrier, 2 – side wall of the wind tunnel test section, 3 – copper plate, 4 – nematic LC layer, 5 – transparent wall of the test section, 6 – blue LED, 7 – lens, 8 – optical fiber, 9 – spectrophotometer, 10 – analyzer, 11 – polarizer, 12 – laser diode λ=645nm, 13 – PC, 14 – flat mirror with a transparent central part.

Linearly-polarized quasi-monochromatic light falls on the nematic LC layer perpendicularly to the surface. Polarizer is set parallel to the direction of NLC molecule long axis and perpendicular to flow. Optical response registration is performed in crossed nicols. Tests were performed in the flow velocity range up to 80 m/s.

Software of the spectrophotometer allows obtaining measurement results as time dependencies of the reflection spectra I(λ,t) and time dependences of the reflection intensity at a fixed wavelength $I(t)_{\lambda=\lambda i}$ with high time resolution.

Dependencies obtained in multiple wind tunnel runs for normalized intensity of the reflected light I(τ)/I(τ=0) dependent on the level of shear stress experimentally prove the effect of the polarization plane rotation angle change by the flow and principle ability of shear stress visualization (Figure 2). For all the investigated NLC mixtures dependencies of normalized intensity on shear stress are monotonous and can be easily approximated by polynomials of low degree. It leads to simple interpretation of visualization results of the shear stress field.

However as it can be seen in the figure 2 during multiple tests sensitivity of LC coating decreases but it stays monotonous.

Besides, it is seen, that there are the areas with low shear sensitivity near the ends of tested velocity range. To increase shear sensitivity NLC with low viscosity should be used at low velocities.

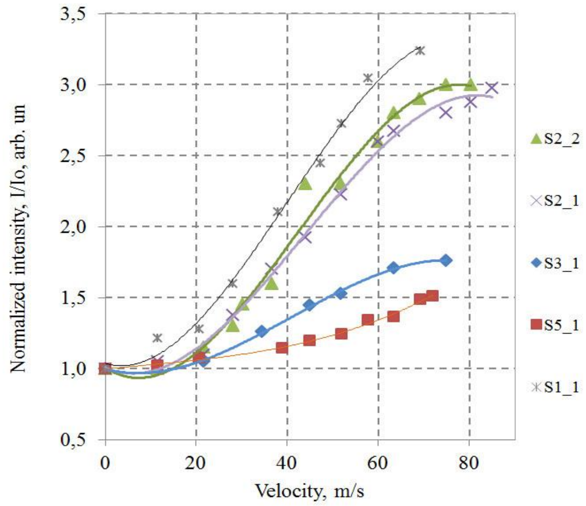

Fig. 2. Changes in Calibraton During Multiple Measurements by Single Coating (5 Series, More then 50 Runs with Short Duration and Total Duration of 5 Minutes)

2.2 Second method: Texture transformation of cholesteric LCs with low temperature sensitivity

Such type of liquid crystals as cholesteric LCs is generally used for diagnostics of shear stress by the texture transformation method. The periodical helical structure of cholesteric LCs defines their ability to reflect the falling white light selectively [1]. At the fixed observation angle the LC layer in its temperature range of selective reflection seems to have one color which is defined by the helix pitch P. This pitch in its turn can be dependent to many factors: temperature and shear stress, for example.

Two textures of cholesteric LCs are practically used in aerodynamic tests performed by the method. The first one is the focal-conic texture in which the long axes of the molecules are not parallel to the surface plane in the general case and the helical axes are oriented chaotically.

The second one is the planar texture in which the molecules are parallel to the surface and the helical axes are perpendicular to it (Figure 3).

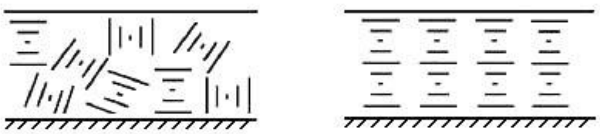

Fig. 3. Cholesteric LC Textures: a) Focal-Conic, b) Planar

Focal-conic texture is usually formed while spraying the LC coating perpendicular to the surface. In contrast to transparent planar texture which selectively reflects color the focal-conic texture scatter the light and looks opal, opaque. Texture transition from focal-conic texture to planar one occurs under influence of shear. The image that appears after the flow influence on the focal-conic texture has memory properties due to the long-term relaxation. That’s why this effect can be used to visualize the stationary flows in conditions of visual access absence [2].
The experimental method is based on registration of the optical response of the liquid crystals on the shear stress induced by the flow in the wind tunnel [3].
The process of texture transformation is irreversible. This method does not depend on the light source and observation angle as it is based on the dependence of time of color appearance versus shear stress level. The calibration of liquid crystals in this case may be easily obtained, using special software.

2.2.1 Model preparation

To perform tests by the method of texture transformation the model should be prepared in the following way.
Before applying the LC coating the investigated model surface should be black painted. Such painting is needed to decrease the amount of light reflected by the model surface and to increase thereby the contrast of the visualization image produced by light scattered by the liquid crystals. Black paint can be applied by spray or by brush. When this coating dries up the LC mixture can be applied by spray or by brush in different tests. The drying process takes nearly 20 minutes. The thickness of the black paint is approximately 20 μm and the total thickness of the coatings is about 40-50 μm. Therefore such thin layer does not change the model geometry.
In our experiments the mixture of acetone and toluene was used as a solvent of liquid crystals. That’s why it is better to apply the LC coating by brush if it’s possible to reduce the hazardous exhalations. And this fact also influences on choosing the black paint as it should not be dissolved by the solvent and there should be no interaction between the paint and the LC solvent.
If the tests are performed by the method of texture transformation than the LC coating should have the focal-conic texture. So it should be applied by spray or if it is possible it can be applied by brush and then heated up till it turns to isotropic liquid. Then it should be cooled down and the mixture obtains the focal-conic texture too. For such tests the model preparation ends at this stage.

2.3 Third method: Shift of selective reflection peak of cholesteric LCs

In the third method the liquid crystal mixture obtains planar texture at the beginning. This texture selectively scatters light with the dominant wavelength which changes under shear stress [4]. It is a reversible process as the dominant wavelength will return to its initial value when there is no shear stress. This technique is mainly used for visualization of shear distribution. There are some difficulties in using this method for quantity measurements because of necessity to account the angular dependence of LCs selective reflection.

2.3.1 Model preparation

To perform tests by the method of selective reflection the model should be prepared in the same way as for the second method. But at the end it is necessary to perform so-called initialization process when the LC coating dries up. The texture of the LC coating should be transformed from focal-conic to planar. This process is performed by applying shear stress. If the LC coating is applied by brush this process performs automatically. But if the mixture is applied by spray the initialization can be performed by brush or even by finger as the response of the LC coating is the same. When it is possible the regime with maximal studied flow velocity may be used also for that purpose.

2.3.2 Illumination and registration systems

The method of selective reflection peak shift of shear stress sensitive liquid crystals needs a measurement system which consists of two parts: the illuminator and the color camera.

The model is illuminated with the white light. The pulse illumination is preferred in conditions of the external lighting and the vibration of the model or/and photo-camera.

The spatial arrangement of the light source and the camera can be different. Three variants were investigated while performing tests and some of them were found acceptable. These variants were:

- The light source is down-stream the model, the camera is up-stream the model;
- The light source is above the model, the camera is up-stream the model;
- The light source is up-stream the model, the camera is above the model.

The first layout was found unacceptable due to the glare which was situated practically in the center of the investigated model surface and occupied its considerable part.

The second layout is recommended in literature [5, 6] and the optimal observation angle (between the camera and the model surface) is considered to be equal to 30º with respect to LC sensitivity.

The third layout differs from the second one only in the interchange of the positions of the light source and the camera. The third layout is found to be the most attractive in respect to the perspective of the model observation and to the realization convenience, especially in wind tunnels with closed test sections. It is easier to arrange the light source than the camera up-stream the model.

While arranging the equipment according to the second and the third layouts the glare is situated at the front edge of the investigated model surface and does not considerably prevents the surface flow visualization. So the second and the third variants were considered to be acceptable and it was also found that the angle between the light source and the camera can vary in some neighborhood of 30º without considerable losses in LC sensitivity.

3 Test results

Three series of tests were performed in TsAGI using the method of selective reflection peak shift.

The first experiment was performed in the transonic WT T-128 (TsAGI). The tests were performed at Mach numbers in range of M = 0.2-0.93. Three different coating were tested while performing these tests. At the area of each of three used liquid crystal coating sample rows of the trips were mounted on the fin parallel to the leading edge before applying the LC coatings. The trips represent cylinders 0.2 mm height with 1 mm diameter which were applied with 2.5 mm pace by standard technique.

White light illumination of the model was performed by two halogen lamps (50 W capacity each) approximately perpendicular to the test surface. Digital color camera Nikon D3X was used to register the image of the model and it was situated up-flow the model. Selection of the fin as a test surface was defined only by the arrangement of windows in test section which allowed to illuminate the fin perpendicularly and to register the diffused light at 45º angle up-flow. This angle is not the optimal one in respect to LC sensitivity (the optimal angle is 30º) but it is a compromise between sensitivity and arrangement of the windows.

The results of visualization of shear stress fields at two different Mach numbers M=0.2 and 0.4 are presented in the Figure 4.

At Mach numbers M = 0.2 and 0.4 all three types of liquid crystal coatings showed their efficiency. However the viscosity of the upper coating was not sufficient and it flowed rapidly at the model surface even at these flow velocities. The other two coatings were efficient at all the researched regimes.

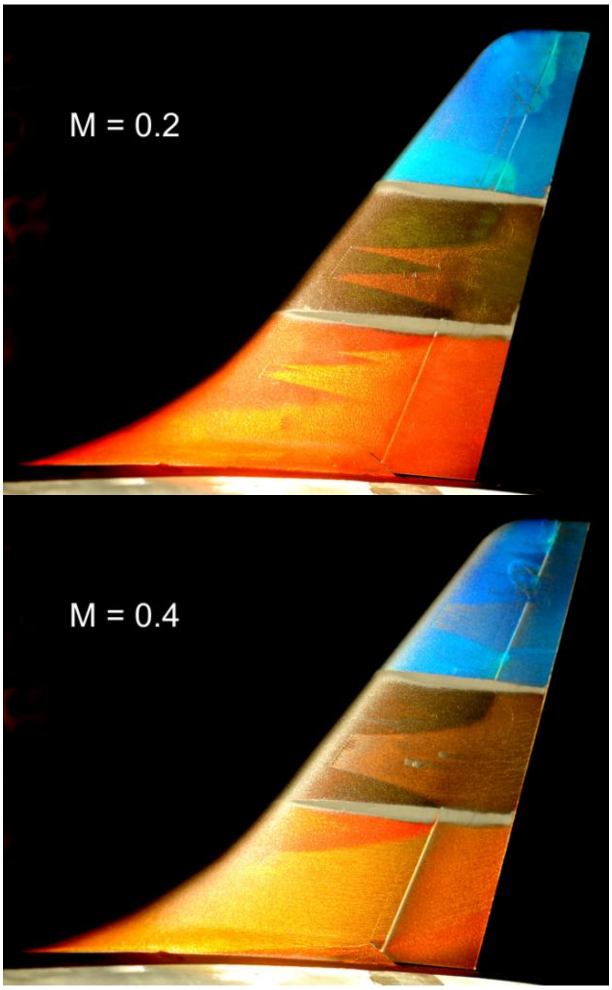

Fig. 4 LC Visualization at the Vertical Fin at Mach Numbers M=0.2 and M=0.4 in T-128 Transonic Wind Tunnel (TsAGI)

The second experiment was also carried out in the commercial transonic wind tunnel T-128 (TsAGI). At this time the metal wing panel of a half-model of a passenger plane RRJ-95 was used as a model under test. Surface flow visualization was performed at Mach number M=0.78 and Re= $3x10^6$, $6x10^6$ и $9x10^6$. Angles of attack varied in the range of -4.5 to 7º. Registration of images was performed by the digital color camera VS-11002 which was situated perpendicularly to the investigated surface. The light source was situated up-stream the model. Visualization was performed using five different types of liquid crystals. During the performed tests 26 regimes of flow were investigated on the whole. Some of the results obtained are presented in Figure 5.

At the angles of attack starting form α = 2.5º the shock wave is clearly observed on the wing surface. The shock wave looks like an abrupt decrease of shear stress (color change). With the growth of the angle of attack the shock wave moves down the flow and its intensity increases. During the tests it was proved that the color of the LC coating sufficiently corresponds to the shear stress growth with the Reynolds number increase. Visualization of the laminar-turbulent boundary layer transition and the shock waves was successfully performed by all the types of liquid crystals.

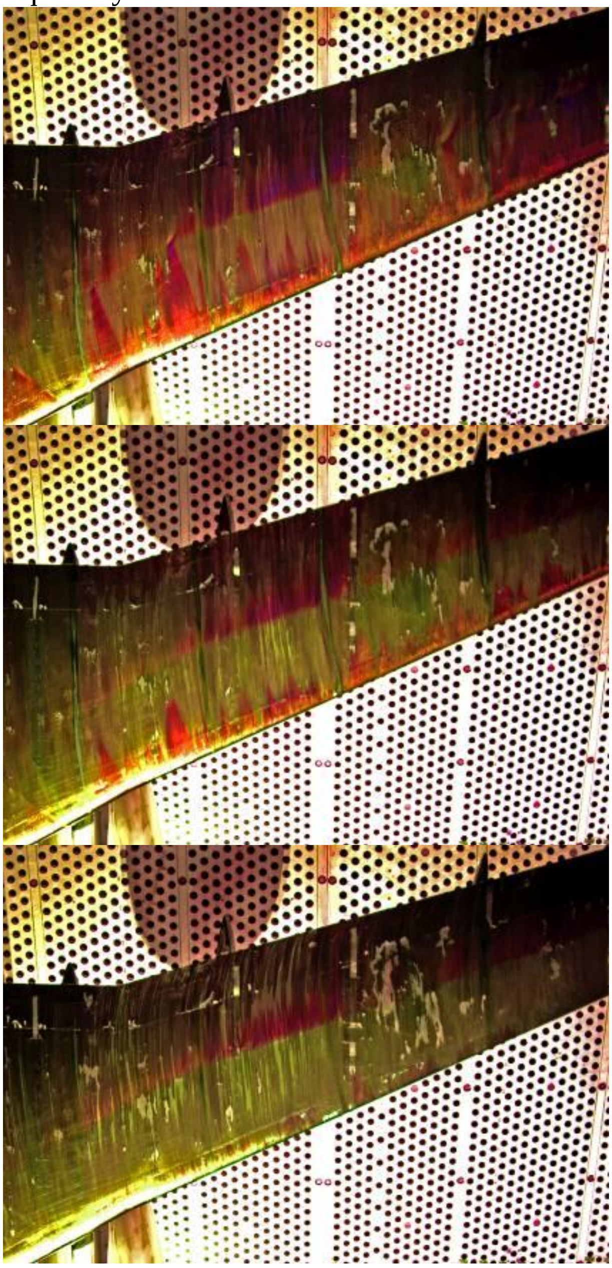

Fig. 5 LC Visualization of Surface Flow at the Metal Wing by Shear Stress Sensitive Liquid Crystals in T-128 Transonic Wind Tunnel (TsAGI), M=0,78, α = 4,5º, Re = 3×10^6, 6×10^6 and 9×10^6 Correspondingly

It is interesting to compare the obtained results with earlier experiments performed on this model. The comparison with the method of luminescent mini-tufts for one test conditions is presented in the Figure 6. The position of the shock wave was found to be absolutely the similar.

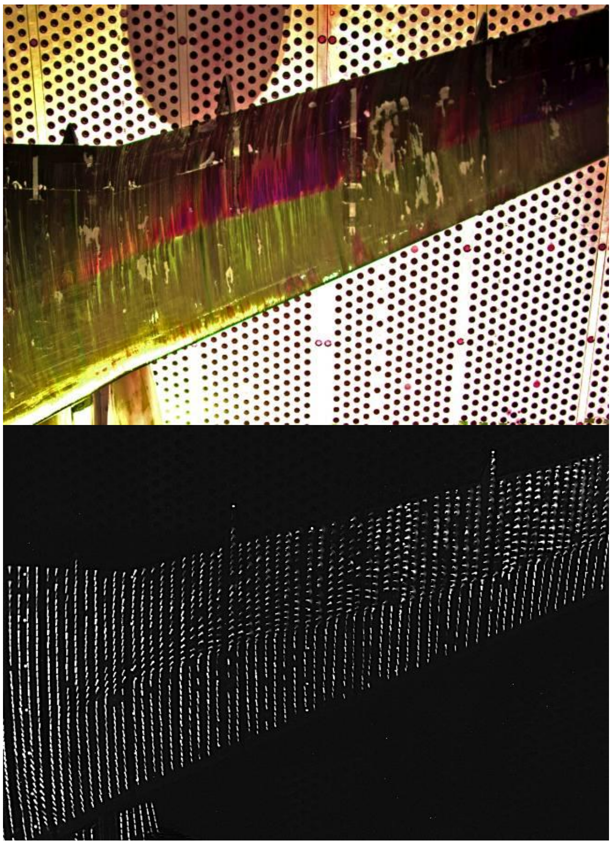

Fig. 6 Comparison of LC Visualization with the Method of Lluminescent Mini-Tufts

The third experiment was performed at subsonic flow velocity. It was performed at the subsonic wind tunnel T-103 (TsAGI) with an open test section. The flow velocity varied in the range of V = 10 m/s to V = 80 m/s. The method was investigated at a wing panel of a metallic fuselage-wing model. Two types of liquid crystal coatings were used while performing tests. Seven wind tunnel runs were made on the whole.

The results of surface flow visualization at different flow velocities at the angle of attack $\alpha = 3^{o}$ are presented in Figure 7. At the flow velocities V = 10 and 20 m/s the transition was not detected. Apparently the flow is entirely laminar at these velocities. The camera was situated perpendicularly to the model surface and the light source was situated up-stream the model on the nozzle.

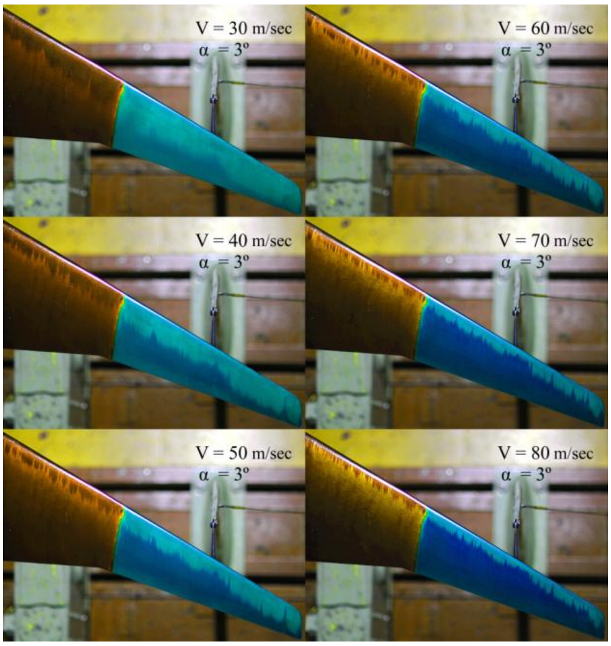

Fig. 7 LC Visualization of Surface Flow at the Metal Wing Panel at Different Flow Velocities, Angle of Attack $\alpha = 3^{o}$ in T-103 Subsonic Wind Tunnel (TsAGI)

Visualization of flow separation is a more complex task as it is not usually characterized by the abrupt shear stress change. Nevertheless in this test it was succeeded to detect the flow separation caused by the constructional mount at the wing tip. These results are presented in the Figure 8.

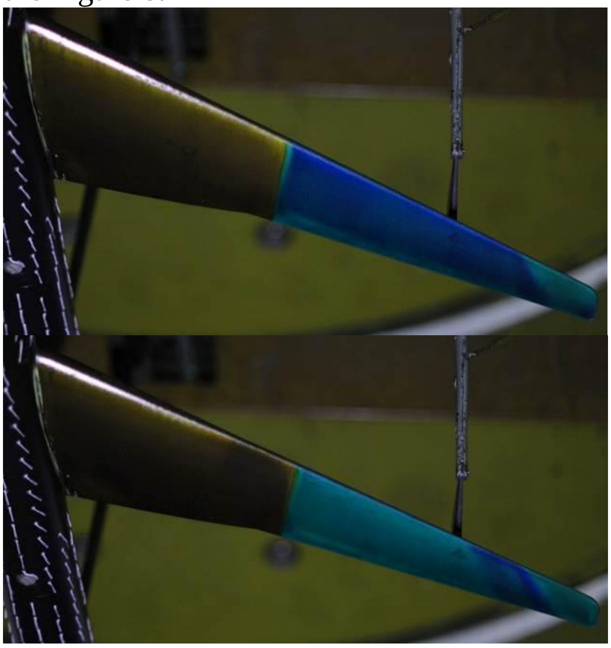

Fig. 8 LC visualization of flow separation caused by the constructional mount at V=60 m/sec

At $\alpha = 10^{o}$ angle of attack the vortex from the model mount causes the local flow separation. It can be seen as a green area (with low shear stress) against the blue background. At $\alpha = 14^{o}$

angle of attack the global flow separation occurs (the wing surface becomes green) and the vortex from the mount becomes blue to the contrary. This effect appears because the vortex from the mount gets to the wing surface and causes the shear stress increase.

It is significant that both types of LC coatings showed good efficiency. It is difficult to define the best one of them.

4 Conclusion

These three tests of shear stress sensitive cholesteric liquid crystals showed that the test method of selective reflection of the planar LC texture allows getting the flow visualization of the boundary layer on metal models in a wide range of flow velocities. The method can be used at subsonic and transonic flow velocities. It means that these detectors can be effectively used for laminar-turbulent transition, flow separation and shock wave visualization.

The other two methods are under father testing yet. All three methods of using shear stress sensitive liquid crystals allow getting panoramic visualization of shear stress on the investigated surface. But for obtaining detailed information about the magnitude and direction of the shear stress vector in each point calibration rig is needed. Besides, it is a task, which requires special software for sufficiently complex digital processing of video records; the improvement of technology for initial perfect LC texture obtaining on large areas as well as others LC related skills.

References

[1] Zharkova G.M. Optical phenomena in liquid crystals and their application in aerophysical studies. *Optics and Laser Technology*, Vol. 32, No. 7-8, pp. 611-619, 2000.

[2] Zharkova G.M., Kovrizhina V.N., Khachaturyan V.M. Visualization of flow structure in a channel with corrugated walls by liquid crystals. *Journal of Visualization*, Vol.5, No.4, p. 311, 2002.

[3] Reda D. et al. Measurement of surface shear stress vectors using liquid crystal coatings. *AIAA Journal*, Vol. 32, p.1576, 1994.

[4] Belyakov V.A. and Sonin A.S. *Optics of cholesteric liquid crystals*. Moscow, Nauka, 1983.

[5] Reda D.C., Wilder M.C., Farina D.J. and Zilliac G. New methodology for the measurement of surface shear stress vector distribution. *AIAA Journal*, Vol. 35, No. 4, pp. 608-614, 1997.

[6] Reda D.C., Wilder M.C., Mehta R.D. and Zilliac G. Measurement of continuous pressure and shear distribution using coating and imaging techniques. *AIAA Journal*, Vol. 36, No. 6, pp. 895-899, 1998.

Corresponding author

Shapoval Elena
E-mail: ElyaShapoval@gmail.com

Copyright Statement