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PRINCIPLES AND APPLICATION OF VISUALIZATION METHODS

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The article treats the principles of optical visualization methods applied to the flow characteristics and velocity profiles measurement and to the evaluation of properties of optically transparent materials , especially transparent polymeric foils.

K e y w o r d s: optical visualization, shadowgraph, schlieren method, interferometric method, flow visualization, polymeric foils visualization

1 INTRODUCTION

Optical visualization methods offer numerous advantages in studies of optically transparent materials and hydrodynamic properties of fluids, especially resolution of laminar and turbulent states. Fluids, and particularly gases, are normally transparent and therefore invisible. In order to observe the flowing fluid it is necessary to use special optical visualization methods depending on the fact that the optical behavior of liquid is related to the density. The most common means of visualizing flow field is to record the refractive behavior of a transparent flowing liquid when illuminated by a beam of visible light. The fluid density is a function of the refractive index of the flowing fluid representing now, in optical terms, a phase object. A light beam transmitted through the tested object is affected with respect to its optical phase but the density or amplitude of the light remains unchanged after passage. Optical methods which are sensitive to changes of the index of refraction in the tested field can provide information on the density distribution in the flow and from the so- determined density values further information on other flow parameters, *eg* velocity.

2 DEFLECTION AND RETARDATION OF LIGHT IN A DENSITY FIELD

We consider a light beam of finite width which is transmitted through a flow field and which distorts the charge configuration of the fluid molecules. Optical visualization methods are based on the interaction of the flowing fluid with a light beam

$$\frac{n^2-1}{n^2+2} = \frac{\rho N_A e^2}{3\pi m_e M} \sum_i \frac{f_{oi}}{f_i^2 - f^2} \,. \tag{1}$$

Clausius-Mosotti equation (1) expresses a relation between the refractive index n and fluid density ρ in terms of atomic constant and properties of the fluid and the frequency f of the light used. N_A is Avogadro's number, e is the charge and m_e the mass of an electron, f_{oi} are oscillator strengths and f_i are resonant frequencies. Clausius-Mosotti equation should be used if the fluid is not a gas. In the case of gases the refractive index is very close to one, the Clausius-Mosotti equation can be simplified to the so-called Gladstone-Dale equation (2)

$$n - 1 = \frac{\rho N_A e^2}{2\pi m_e M} \sum_i \frac{f_{oi}}{f_i^2 - f^2} \,. \tag{2}$$

It is necessary to solve the problem concerning the transmission of the light through the flow field that represents now, in optical terms, a phase object with a variable index of refraction. The problem now is to investigate the question of how the light transmitted through the flow field is affected by the refractive index variations. The refractive index n is considered to vary as a function of the three spatial coordinates x, y and z, *eg*, $n = n(x,y,z)$.

Let us imagine that an incident light beam, initially parallel to the z direction, is transmitted through the flow (Fig. 1). In a practical arrangement viewing windows are normal to the z direction. The propagation of a single light ray in the phase object is described by Fermat's principle [1] which states that the variation of the optical path length along the light ray in the object must vanish. Then

$$\delta \int n(x,y,z)\mathrm{d}s = 0 \tag{3}$$

where s denotes the arc length along the ray, and $\mathrm{d}s$ is defined by

$$\mathrm{d}s^2 = \mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2 \,. \tag{4}$$

The main problem consists in determining $x = x(z)$ and $y = y(z)$ describing the path of the light ray through the

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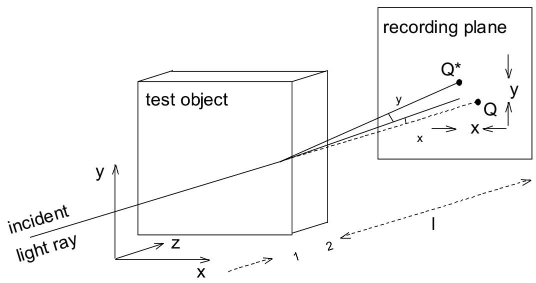


Fig. 1. Deflection of a light ray in an inhomogeneous test object

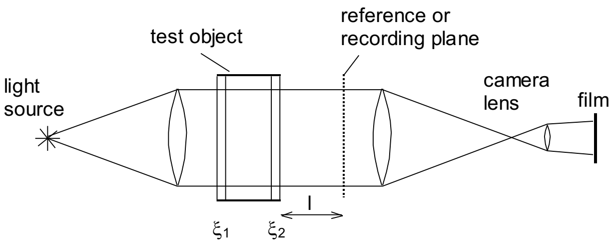


Fig. 2. Shadowgraph system with parallel light through the test field

refractive index field. To solve the system it is necessary to determine an initial condition specifying the particular light ray in the transmitted parallel beam, that means to specify coordinates $x = \xi_1$ and $y = \eta_1$, where the ray enters the test volume. From the solution of the system also the coordinates ξ_2 and η_2 of the ray in the exit plane of the flow test volume as well as the inclination of the ray at the exit point can be determined. Here l is the distance between the recording plane and the exit plane of the test volume in the optical arrangement in Fig. 1. In order to predict the observable pattern in the recording plane one has to determine, for each ray, three quantities:

- the displacement QQ^* of a deflected or disturbed ray with respect to an undisturbed ray (ray passing through a homogeneous field)
- the deflection angles ε_x and ε_y of the ray at the end of the test volume
- the retardation of the disturbed ray with respect to an undisturbed ray that can be expressed by the time difference Δt between the arrival of the two rays in the recording plane.

Each of these three quantities corresponds to a particular class of optical visualization methods. It is possible to determine these quantities only under some simplifying assumptions:

- the deviations from the z direction in a compressible flow are negligibly small but the ray may leave test volume with a nonnegligible curvature,
- the slopes of the ray, $\mathrm{d}x/\mathrm{d}z$ and $\mathrm{d}y/\mathrm{d}z$ are very small as compared with unity.

With the aid of these assumptions one can determine the three aforementioned observable quantities. Expressing the displacement QQ^* and the deflection angle ε in terms of respective x and y components, one obtains:

$$\left(\overline{QQ^*}\right)_x = l\int_{\xi_1}^{\xi_2} \frac{1}{n}\frac{\partial n}{\partial x}\mathrm{d}z\,,$$

$$\left(\overline{QQ^*}\right)_y = l\int_{\xi_1}^{\xi_2} \frac{1}{n}\frac{\partial n}{\partial y}\mathrm{d}z\,, \tag{5}$$

$$\operatorname{tg}\varepsilon_x = \int_{\xi_1}^{\xi_2} \frac{1}{n}\frac{\partial n}{\partial x}\mathrm{d}z\,,$$

$$\operatorname{tg}\varepsilon_y = \int_{\xi_1}^{\xi_2} \frac{1}{n}\frac{\partial n}{\partial y}\mathrm{d}z\,, \tag{6}$$

$$\Delta t = \left(\frac{1}{c}\right)\int_{\xi_1}^{\xi_2} \left[n(x,y,z) - n_\infty\right]\mathrm{d}z\,. \tag{7}$$

In (7), c is the velocity of light in vacuum, n_∞ the refractive index of the undisturbed test field in which the reference rate propagates and ξ_1 a ξ_2 are the z coordinates of the points where a ray enters and leaves the test field. The quantity Δt can be converted into the optical phase difference $\Delta\varphi$ between an undisturbed and disturbed ray in the recording plane

$$\frac{\Delta\varphi}{2\pi} = \frac{1}{\lambda}\int_{\xi_1}^{\xi_2} \left[n(x,y,z) - n_\infty\right]\mathrm{d}z \tag{8}$$

where λ is the wavelength of the light used.

There are three main optical visualization methods. The shadowgraph is a technique which visualizes the displacement QQ^* as represented by (5) and the schlieren system measures the deflection angle ε described by (6). Optical phase changes experienced by a light ray in the flowing field according to (7) can be made visible with optical interferometers. It can be shown that these three visualization methods exhibit different behavior.

3 VISUALIZATION BY MEANS OF LIGHT DEFLECTION

In its simplest form, the shadowgraph does not need any optical components. The diverging light from a point-shaped light source is transmitted through the flow test field, and the shadow pattern produced by the phase object will be recorded in a vertical plane placed a distance l behind the test field. Instead of this simplest arrangement, a system will be regarded with parallel light

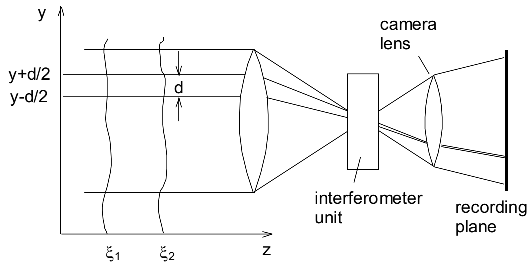


Fig. 3. Two-beam interferometer with parallel light through the test section

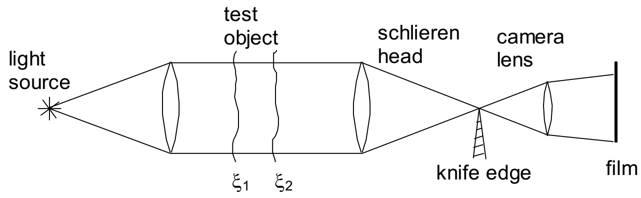


Fig. 4. Schlieren system

bounded by a plane viewing windows normal to the light. In order to avoid the use of too great a photographic plate, the recording plane can be focused by means of a camera lens onto a film or plate of reduced size. Shadow pattern produced by the phase object is recorded in a vertical plane placed behind the test object (Fig. 2).

The shadowgraph method uses parallel light bounded by plane viewing windows transmitted through the test flow field. The shadow pattern produced by the phase object is recorded in a vertical plane placed behind the test object.

$$\frac{\Delta I}{I} = I \int_{\xi_1}^{\xi_2} \Big(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \Big) (\ln n) \mathrm{d}z \,. \tag{9}$$

A photographic plate is sensitive to relative changes of the light intensity. Relative changes of the light intensity in the case of the shadowgraph [1] depends on the second derivative of the refractive index and therefore on the second derivative of the liquid density.

The flow field represents an optical disturbance which may change the phase of transmitted light ray with respect to an undisturbed ray. Such an alternation or differences in optical phase can be displayed by instruments known as interferometers. In an interferometric system one visualizes the interference of the ray passing through the test object with the second ray travelling to the recording plane along the different path. In optical visualization one deals with a class of a two-beam interferometers [1]. The general setup of two-beam interferometer is chosen to have a parallel beam of light traversing the test field (Fig. 3). A coordinate system is introduced with the incident light propagating in the z direction. Each ray of the incident light beam has a conjugate ray, and the principle of the interferometer is based on the measurement of the phase difference between the two conjugate rays after passage of the test field. If the condition of optical coherence is fulfilled, the conjugate rays may interfere with one another and produce a certain interference pattern in the recording plane onto which a camera lens focuses the test object. Interferometers allow to measure changes of absolute density ρ.

Schlieren system serves to measure the amount of light deflection generated by a transparent optical phase. In the fundamental arrangement, mostly referred to as the Toepler system, a parallel light beam traverses the test object and is focused thereafter by means of a lens or spherical mirror, named: "schlieren head" (Fig. 4). A knife edge is placed in the plane of the light source image to cut off part of the transmitted light. The camera objective focuses the test object onto the recording plane, where one receives a reduced intensity of light, depending on the amount of light cut off by the knife edge [2]. An optical disturbance in the optical transparent phase object will produce variations of the recorded light intensity which are a measure of the deflection experienced by the light in the test object. The schlieren system visualizes changes in the first derivative of density ρ,

$$\frac{\Delta I}{I} = K \int_{\xi_1}^{\xi_2} \frac{1}{n} \frac{\partial n}{\partial y} \mathrm{d}z \,, \tag{10}$$

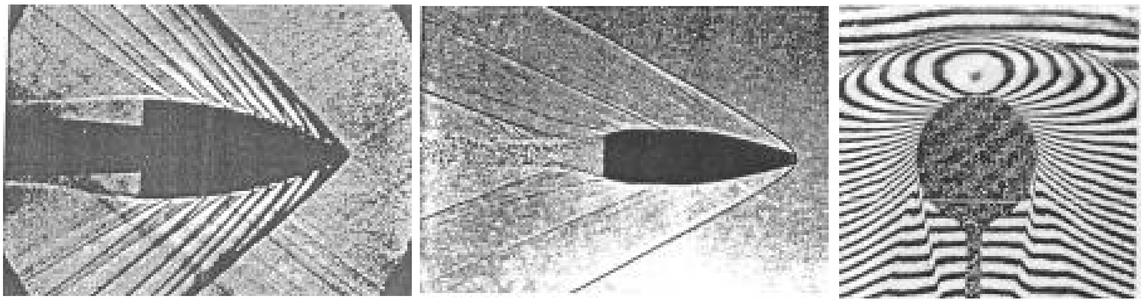
where constant K depends on the geometry of the arrangement.

The fundamental schlieren system has found a great variety of modifications introducing colour, using the double-pass schlieren system, Doppler principle or combination of the schlieren system with holographic methods.

In Fig. 5 there are examples of pictures obtained by the different visualization techniques. There is a picture of a projectile flying at an ultrasound speed taken by the shadowgraph (a), a picture of a body that is flowing around at ultrasound speed taken by the schlieren method (b) and the picture of a cylinder flowing around at ultrasound speed taken by the interferometric method (c).

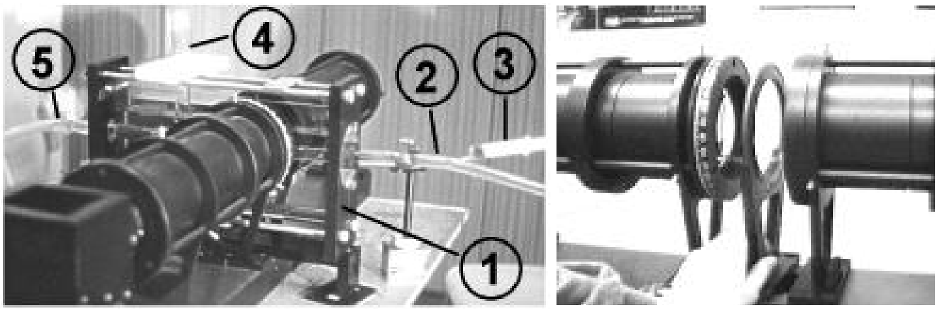
There has been a very rapid improvement of shadow, schlieren and interferometric optical visualization methods connected with the availability of lasers and holographic methods during the last decade. A major problem requiring a solution is the development of efficient evaluation procedures .

Considering the available instrumental facilities and the required sensitivity of measurements, we have chosen the schlieren visualization method. A special optical apparatus constructed after J. Bolf [2] allows to record the static state or the dynamic phenomenon. At present we obtain the image by means of the optical system of



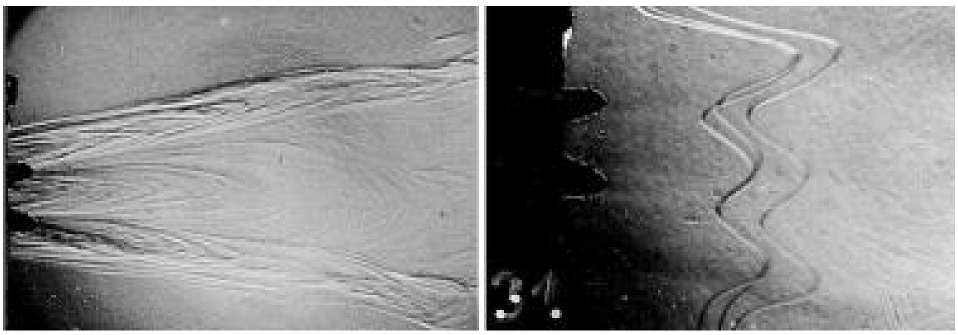
(a) (b) (c)

Fig. 5. Examples of visualization



(a) (b)

Fig. 6. Schlieren apparatus used for flow visualization 1 — cuvette, 2 — feed pipe, 3 — salt solution feed, 4 — pouring of salt crystals, 5 — outflow (a), part of apparatus used for visualization of polymeric foils with the sample holder (b)



(a) (b)

Fig. 7. Streamlines and velocity profiles for St. Jude Medical bileaflet heart valve

a high-quality slide projector and a CCD camera. The image obtained in this way is directly recorded into the computer memory. Pre-processing of images consists in modifying the recorded picture into a form which is suitable for further processing.

The schlieren method is mainly used for qualitative purposes, but with a much higher degree of resolution than the shadowgraph. Photographic or digital records enable one to distinguish between laminar and turbulent flows, which plays an important role while studying hydrodynamic properties of water taps, and especially of cardiac valve prostheses. In order to visualize streamlines we have used salt solution. Some quantitative results, *eg* velocity profiles of the particles carried by the stream can be investigated as well. For such experiments salt crystals have been used.

Schlieren method was successfully used for testing water taps and heart valvular prostheses when one of the main requirements is to maintain laminar flow. Different types of prostheses have been tested. There is a photo-

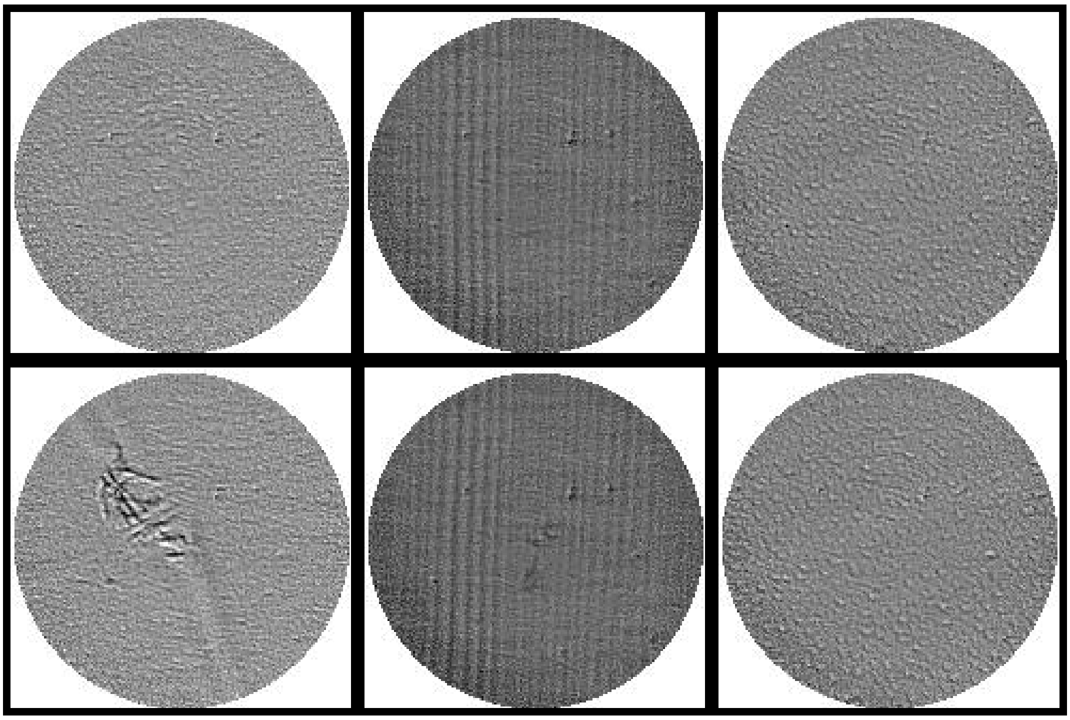


Fig. 8. Samples of tested foils without and with defects

graphic record of streamlines in Fig. 7a and velocity profiles for a Saint-Jude Medical bileaflet heart prosthesis in Fig. 7b in the case of laminar flowing.

The optical visualization method and particularly schlieren method can provide useful information on visually inaccessible objects such as optically transparent polymers and, especially, polymeric foils as well. The intensity of photon absorption changes especially in the area of deformation, which results in a change of the refraction index. The main advantage is that the information on the refraction index changes after photographic or digital recording is available for further processing. It is necessary to keep identical conditions while recording all samples and to assure that the optical apparatus and surrounding will affect neither the digital nor the graphical representation [3].

When the polymeric tube is made, a build-up of solid material and small defects in the extrusion die cause variations in the thickness of the film. This gives rise to die lines in the film, which can change as the film is produced. On some production lines the tube can rotate as it comes out of the die so that the angle of the die lines varies with respect to the folds and seals on the final product. Die lines can be seen in shadowgraph or schlieren images. The die lines formed by one die on the production line will not be the same as those made by a die on a different production line. Many foils have scratches, most of which run parallel to the extrusion direction, but occupy random positions across the surface. Most of these are derived from the manufacturing processes where the polymeric film passes over rollers and over surfaces during numerous manipulations to give the finished product.

Visual quality assessment allows to locate, on a preprocessed picture, the places with elastic strains and with stress regions which are marked by variations in the level of brightness (grade of grey). This method is suitable for on-line evaluation of the quality of foils in their production. There are samples of tested foils without a with defects. On some types of foils we have deliberately created defects for the purpose of visualizing the area of strain as is illustrated in Fig. 8. Using image processing and statistical approach, schlieren method can be successfully used in the field of identification and defectoscopy of polymeric foils [5], [7].

4 CONCLUSION

The above mentioned optical visualization methods allow to study the flow field and thus hydrodynamic properties of various objects. Schlieren method applied to assess optical transparent polymeric foils allows to locate even very small deformations and defects. Papers [4], [6] are devoted to the possibilities of applications of this method for defectoscopy and identification of polymeric foils using statistical approaches.

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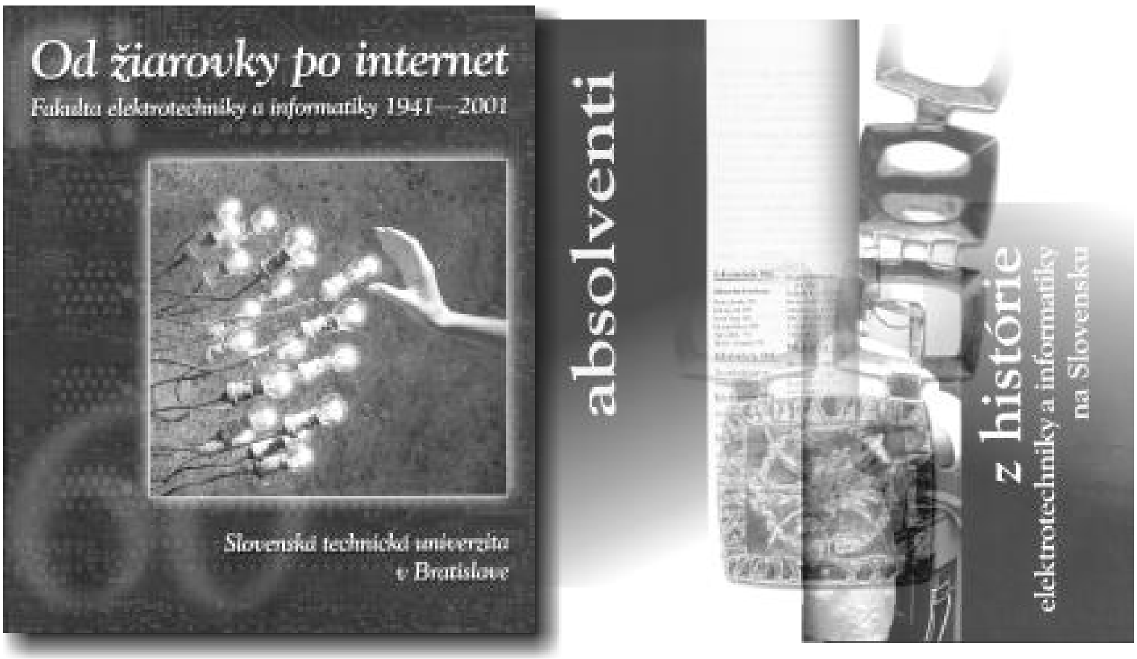

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