VISUALIZATION OF THE PRESSURE FIELDS OF GAS STREAMS BY THE METHOD OF HOLOGRAPHIC INTERFEROMETRY

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The pressure field is determined from the deformation of an assembly of membranes uniformly distributed over the walls confining the stream. The deformations are recorded by the method of two-exposure holographic interferometry. The possibilities of the method are illustrated on the examples of flow over a Zhukovskii profile and flow in a nozzle. Direct visualization of the isobars in the field of flow is accomplished.

One of the principal tasks of experimental aerodynamics is the determination of the pressure fields in gas streams with high temporal and spatial resolution. A great many methods of measuring pressure are described in the literature [1, 2]. Common to the majority of them is the principle of the recording of displacements and deformations which arise under the effect of the pressure being measured. It is known that the most sensitive methods of determining small displacements are the optical methods based on the recording of the phase change of a light wave (interferometry) [3]. The attractiveness of the optical methods also consists in the possibility of the simultaneous observation of the entire field of flow being studied ("panoramic" recording) and the high temporal resolution. However, classical interferometry imposes rigid limitations on the shape and the optical purity of the surface studied, which hinders its use in an actual experiment. Attempts to bypass this requirement inevitably lead to results which are poorly reproducible and difficult to interpret [4]. The recording of the compression, rather than deformation, of columns of liquid in a "remote" system of manometers is proposed in [5] for a similar purpose. Besides the limitations in the speed of response, a drawback of this method is the replacement of two-dimensional by one-dimensional visualization. The contradiction between the aerodynamic and optical demands on the experiment is removed in the method of holographic interferometry [6], which is applicable for surfaces of arbitrary shape and quality. This method also possesses a unique capacity to bring out directly the difference between two different states of the object, which is very important for calibration. The results of the surface of a body over which flow occurs are described in the present report.

In the surface being studied (the wall 1 in Fig. 1) openings 4 with a diameter of 0.2 mm, which then passed into through channels 3 mm in diameter, were made in staggered order. Brass foil 2 with a thickness of 0.05 mm was soldered on the entire field of openings on the other side. The foil was preliminarily etched with iron chloride to bring out the microstructure and impart to it diffuse reflection. The foil, rigidly fixed at the soldering points, is divided into independent membranes whose deflection is sensitive to the amount of pressure. The model 3 being studied was glued onto the foil.

The scheme of the holographic interferometer is evident from Fig. 1. The source of the coherent radiation is a supermode laser of type LG-36A. The dividing plate 9 splits the laser radiation into the reference and object beams. The reference beam falls directly on the hologram 10 while the object beam falls on it after diffuse scattering on the foil. The two beams were spread by the microscope objective 7 and filtered by the microscope diaphragms 6 with a diameter of 0.03 mm.

The holographic photography was carried out by the method of two exposures, which were regulated by the shutter 8. Because of the appearance of interference bands in the reconstruction of the hologram

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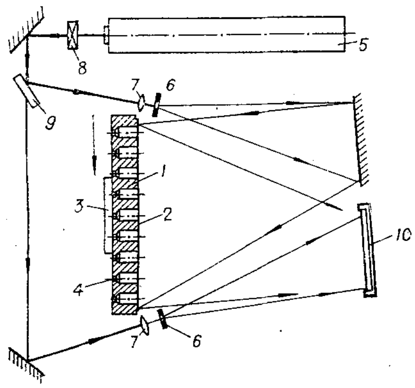

Fig. 1

only those sections of the foil which moved between exposures are distinguished against the general background. Calibration of the membranes can be accomplished by exposing the hologram at one reference pressure and different excess static pressures. Interference bands also appear on those sections of the foil which are poorly soldered to the substrate. The latter fact made it possible to monitor the quality of soldering of the foil. A sample of a reconstructed image from a double-exposed hologram at two different static pressures (a difference of 0.03 atm) is presented in Fig. 2. The images of all the membranes are characterized by a rather high degree of identity.

For the visualization of the pressure field at the wall in a stream the first exposure was made under static conditions and the second after the stream was "turned on." In the second case the pressure distribution in the stream at small subsonic velocities is described by the Bernoulli equation. In the reconstruction of the hologram those membranes at which the pressures in the static and dynamic cases coincide do not stand out against the general background. At the same time the image of the sections of the type of "membranes" at which the pressure changed are darker than the background because of the deformation and the corresponding phase shift of the optical wave, with the degree of darkening being the greater, the larger the pressure difference.

Let us estimate the sensitivity of the method. Small deflections W in a flat membrane are determined by the equations [7]

$$W = \frac{QR}{32}(1-\rho^2)^2,$$

where R is the radius of the membrane and ρ is the relative radius,

$$Q = \frac{\Delta p R^3}{2D},$$

where Δp is the pressure difference and D is the stiffness of the membrane to bending, and

$$D = \frac{E\delta^3}{12(1-\mu^2)},$$

where E is the elastic modulus, δ is the thickness of the membrane, and μ is the Poisson coefficient.

The deflection at the center of the membrane is

$$W_0 = \frac{3}{16}\Delta p \frac{1-\mu^2}{E}\frac{R^4}{\delta^3}.$$

For cold-rolled brass $\mu = 0.37$ and $E = 1.0 \cdot 10^{11}$ N/m^2. Hence

$$W_0 = 16.2 \cdot 10^{-8} \frac{\Delta p R^4}{\delta^3}.$$

The sensitivity of a membrane in our detector is

$$f = \frac{W_0}{\Delta p} \simeq 1.2 \cdot 10^{-10}\ \mathrm{N/m}.$$

The optical path difference τ of the beams between the two exposures is connected with the deflection by the expression

$$\tau = W(1+\cos\theta),$$

where θ is the angle between the direction of the beam incident on a given point of the detector and the line of observation. The values of the deflections corresponding to the system of bands can be obtained from the equation

$$W_k = k\lambda(1+\cos\theta)^{-1},$$

where k is the number of the band, counting from a point with zero deflection. The angle θ is limited by the resolving power of the material and usually does not exceed 15-20°. Taking $\lambda = 6 \cdot 10^{-5}$ cm, $\theta = 0$, and

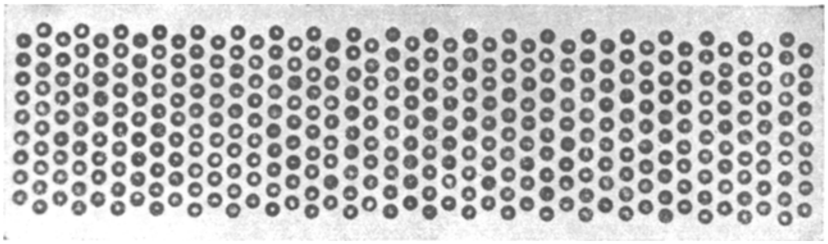

Fig. 2

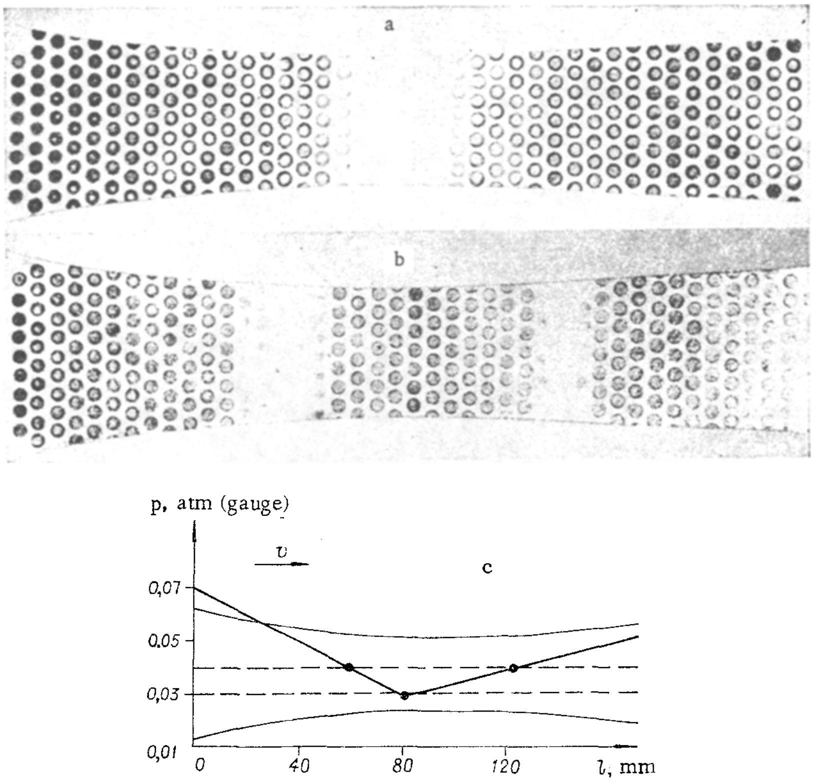

Fig. 3

k = 0.5, we obtain $\Delta p_{min} \simeq 0.01$ atm (gauge) as the lower limit of clearly detected pressure differentials for the chosen thickness and dimensions of the membranes. This value agrees well with experiment.

The flow of a gas through a flat Laval nozzle with subsonic velocity was chosen to test the method under the conditions of a gasdynamic stream which is subject to exact calculation. In this case the equation of the channel profile [8] for steady adiabatic gas flow has the form

$$\frac{dS}{S} = (M^2 - 1)\frac{dv}{v},$$

where S is the cross-sectional area, v is the stream velocity, and M is the Mach number. At subsonic velocities ($M < 1$) the flow velocity should increase ($dv > 0$) with a decrease in the cross section ($dS < 0$). It follows from the Bernoulli equation that the static pressure P should fall with an increase in the velocity.

Reconstructed two-exposure images of the nozzle channel are presented in Fig. 3. For direct visualization of the isobars the first exposure was made at a static pressure for which an isobar had to be obtained in the dynamic mode. The use of this procedure allows one to altogether exclude the operation of preliminary calibration of the membranes. Having identical membranes is unimportant in this case and only the reproducibility of their deformations under different loads is necessary. This potentiality is

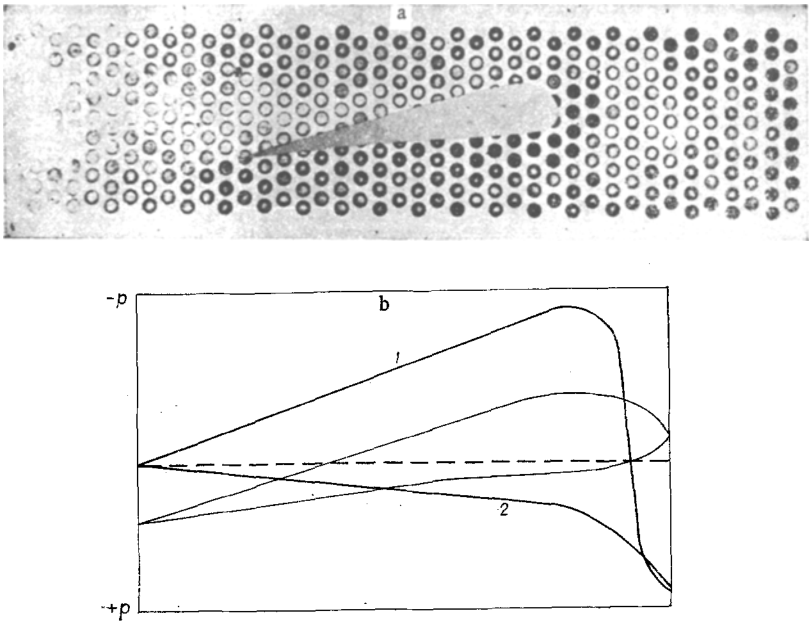

Fig. 4

specific to holographic interferometry and cannot be achieved with the use of other methods. The light bands of coincidence of the pressures in the two exposures are well seen in the photographs – the 1.03-atm isobar (Fig. 3a) and the 1.04-atm isobar (Fig. 3b). The position of the isobars is in good agreement with the calculated pressure profile (Fig. 3c).

In conclusion, let us illustrate the possibility of visualization of a pressure field on the example of the flow over a Zhukovskii profile. Conditions of holography: calibration static pressure 1 atm, angle of attack 10°, pressure differential in blowing over model obstacle 1.07-1.00 atm. In the region of the leading edge of the wing profile one observes an increased pressure which then spreads onto the lower surface, whereas the pressure at the upper surface is considerably lower (Fig. 4a). It is just this pressure differential which creates the lifting force acting on the wing. The calculated pressure profiles at the upper 1 and lower 2 surfaces of the model [9] are presented near it for comparison (Fig. 4b).

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