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Fig. 1

Figure 1: Fig. 1

Abstract

Full Text

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APPLICATION OF THE DIFFRACTION SHADOW METHOD FOR THE QUANTITATIVE DETERMINATION OF THE INTENSITY OF A PLANE SHOCK WAVE AT A MODEL IN A SUPERSONIC FLOW

(Presented by Academician I. V. Obreimov on 13 I 1964)

One of the common objects of study in gas dynamics is plane shock waves formed at a model in a supersonic flow. The determination of their intensity—the ratio or difference of the gas densities before and after the shock—is usually carried out either with the aid of interferometers or by calculation from the experimentally measured angle of inclination of the shock.

For the quantitative determination of the intensity of a plane supersonic shock at a model, an attempt was made to apply the diffraction shadow method, which had previously shown good results on simpler models—phase plates.

Fig. 1

The method used is based on comparing the light intensity at the center of the diffraction pattern at the phase discontinuity and at an opaque boundary. The calculation formula for determining the intensity of a plane shock has the form

$$2\sin\frac{\delta}{2} = 10^{(D-D_0)/2\gamma}, \tag{1}$$

where δ is the sought optical path difference of the rays passing in the zones before and after the shock under study; D is the photographic blackening optical density at the maximum at the shock; D_0 is the photographic blackening optical density at the maximum at the opaque boundary; γ is the contrast coefficient of the photographic material.

The theory of the method was derived under the assumption that the light source is a luminous point, the diaphragm is an infinite slit, and the shock is parallel to the edge of the shadow instrument. If the shock is not parallel to the

Fig. 2

Figure 2: Fig. 2

edge, then the light distribution in the diffraction pattern is determined by the parameters of the visualizing diaphragm in the direction perpendicular to the section of the shock being studied.

In deriving formula (1), it was assumed that the shock is infinitely thin and is located parallel to the optical axis of the instrument. This condition is easily satisfied in studies of phase plates. In gas-dynamic studies, the shock is usually not exactly parallel to the optical axis. Moreover, gas-dynamic shocks are often not rectilinear because of the nonconstancy of the parameters of the gas flow. In considering the conditions necessary for applying this method, it is necessary to take into account possible errors caused by deviations of the real processes from the assumed ones.

To estimate the errors due to these causes, let us calculate the distribution of light intensity in a shock having the form shown in Fig. 1. In this case the formula for determining the light disturbance in

in the image plane of the shadow instrument has the form

$$S(x', y') = C \int_{\xi_0}^{r} \left\{ \int_{-R}^{0} \exp\left[\frac{ik\xi}{F}(x + x')\right] dx + \int_{0}^{a} \exp\left[\frac{ik}{F}\xi(x + x') + \frac{ikx\delta}{a}\right] dx + \right.$$
$$\left. + \int_{a}^{R} \exp\left[\frac{ik}{F}\xi(x + x') + ik\delta\right] dx \right\} d\xi. \qquad (2)$$

Here $k = 2\pi/\lambda$ is the wave number, where λ is the wavelength of the light wave; R is the aperture size limiting the light wave; r is the size of the diaphragm of the receiving part of the shadow instrument; F is the focal length of the shadow instrument; ξ is the current coordinate in the plane of the Foucault knife edge; $x, y; x', y'$ are the coordinates in the object plane and the image plane, respectively; C is a constant. In practical measurements the intensity of light at the center of the diffraction pattern is determined. For small amounts of "smearing" of the pattern (the quantity a in Fig. 1), it is equal to

Fig. 2

$$I\left(\frac{a}{r}\right) = 4\sin^2\frac{k\delta}{2}\ln^2\frac{r}{\xi_0} + \frac{ka(r-\xi_0)}{2F}\left[-8\sin\frac{k\delta}{2}\ln\frac{r}{\xi_0}\frac{\sin k\delta/2}{k\delta/2} + \right.$$
$$\left. + 8\sin\frac{k\delta}{2}\cos\frac{k\delta}{2}\ln\frac{r}{\xi_0}\right] + \left(\frac{k\delta}{2F}\right)^2\left[-2\sin^2\frac{k\delta}{2}\ln\frac{r}{\xi_0}(r^2 - \xi_0^2) + \right.$$

$$+4\left(\cos\frac{k\delta}{2}-\frac{\sin k\delta/2}{k\delta/2}\right)^2(r-\xi_0)^2$$

$$-4\sin\frac{k\delta}{2}\ln\frac{r}{\xi_0}\left(\frac{\cos k\delta/2}{k\delta/2}-\frac{\sin k\delta/2}{(k\delta/2)^2}\right)(r^2-\xi_0^2)\Bigg] \quad (3)$$

Comparing this expression with the formula for the intensity distribution in a sharp plane density jump, we see that the intensity (3) can be represented as the sum of the intensity of a sharp jump with an optical path increment equal to δ, and a certain additional term. In order for a nonsharp jump to be regarded as ideal, it is necessary that the additional term be sufficiently small in comparison with the principal one. The error in determining the intensity of the jump, due to the linear part of the additional term, is determined by the expression

$$\frac{d\delta_1}{\delta}=\frac{a(r-\xi_0)}{\delta F\ln r/\xi_0}\left(1-\frac{\operatorname{tg}k\delta/2}{k\delta/2}\right). \quad (4)$$

The error due to the quadratic term is equal to

$$\frac{d\delta_q}{\delta}=\left\{(ka)^2\left[-2\sin^2\frac{k\delta}{2}\ln\frac{r}{\xi_0}(r^2-\xi_0^2)+4\left(\cos\frac{k\delta}{2}-\frac{\sin k\delta/2}{k\delta/2}\right)(r-\xi_0)^2-\right.\right.$$

$$\left.\left.-4\sin\frac{k\delta}{2}\ln\frac{r}{\xi_0}\left(\frac{\cos k\delta/2}{k\delta/2}-\frac{\sin k\delta/2}{(k\delta/2)^2}\right)(r^2-\xi_0^2)\right]\right\}\left\{4F^2\delta\cdot 4k\sin\frac{k\delta}{2}\cos\frac{k\delta}{2}\ln^2\frac{r}{\xi_0}\right\}^{-1} \quad (5)$$

Calculation of the error makes it possible to assess the applicability of the diffraction method for different parameters of instrument adjustment and for different jump magnitudes.

Experimental verification confirms the correctness of the conclusions drawn. Figure 2 presents a theoretical plot of the distribution of light intensity in the diffraction maximum on the phase plate as a function of the angle between the boundary segment under consideration and the edge of the knife. The experimentally obtained points are in complete agreement with the theory.

Small dips at the edges are explained by averaging of the optical density of the darkening during photometry.

The light intensity at the center of the diffraction maxima will be the same for boundaries parallel to the knife-edge and inclined to it, if the angle of inclination of the shock to the knife edge does not leave the zone of constancy. But the light intensity at points of the diffraction pattern on the "wings" of the diffraction image of the shock will change. As the quantities r and ξ_0, which occur in going over to boundaries inclined to the knife edge, increase, the width of the diffraction maxima decreases. Hence the experimental conditions must be chosen in such a way that, when the optical density of the photographic material darkening that occurs during photometry is averaged, this phenomenon does not affect the measurement error.

Fig. 3

The experiments were carried out in a shock tube. A wedge with an angle of 60° served as the model. Measurements were made with an IAB-451 shadow instrument. Spark photography of the process was performed. The system for synchronizing the light source with the process ensured triggering of the spark unit at the instant when the model was in the region of uniform flow parameters (between the shock wave and the contact surface). To eliminate gas glow on the model, light filters were placed in the receiving part of the shadow instrument; these were transparent to the glow of the light source and did not transmit the glow of the gas.

Fig. 4

In choosing the regimes for carrying out experiments in the shock tube, it was taken into account that the measurement range of diffraction shadow methods is equal to half the wavelength of light, since when the additional optical path difference in the shock exceeds this value, an ambiguity appears between the light intensity in the diffraction maximum from the shock and the shock intensity. Diffraction patterns from shocks differing in path difference by an integer number of wavelengths are identical to one another.

An experimentally obtained photograph in the shock tube is shown in Fig. 3. In the field of view of the shadow instrument, the shock wave (behind the model) and the uniform flow are clearly visible. The photograph was taken with narrow slits, strongly overlapped by the knife edge in the receiving part of the shadow instrument, which provided the conditions necessary for applying the method. Photometry was carried out at the center of the diffraction maxima on the shock wave and at the edge of the model.

Figure 4 gives the theoretical values of the increase in optical path difference in the shock wave on the model—a wedge with a half-angle of 30° and a dimension along the ray of 10 mm—for various regimes of the shock tube.

(for various initial gas pressures P_n and $\tilde{u}$). With the aid of this graph one can select those regimes and model dimensions for which the measured intensity of a plane supersonic shock wave will not fall outside the measurement range of this method.

The measurement results are summarized in Table 1 (ρ_0 is the initial density of the gas under study, $\tilde{u}$ is the velocity of the shock wave, ρ_2/ρ_1 is the intensity of the shock wave, δ is the optical path difference of the rays passing in the regions ahead of and behind the shock under study, in wavelengths of light λ). The table also gives theoretical values of the intensities of shock waves for several regimes, obtained by means of the relations for a normal shock from the known values of P_n, the shock-wave velocity, the model angle, and the angle of the attached shock wave at the model. Agreement of the experimental and theoretical data within an accuracy of 15% is observed.

Table 1

Experiment No.	ρ_0, 10^{-6} g/cm^3	$\tilde{u}$, m/s	$\frac{\rho_2}{\rho_1}$	δ_{exp}, in λ	δ_{theor}, in λ
17270	0.75	3220	4.2	0.175	0.17
17277	0.75	3300	4.0	0.167	0.16
17350	0.75	4310	3.6	0.22	0.26
17352	0.96	4060	3.8	0.33	0.33
17361	0.75	4030	3.5	0.26	0.29
17367	0.75	4060	4.1	0.24	0.21

Thus, as a result of the work it has been established that the method can be successfully applied in studies of gas-dynamic flows with plane shock waves and has prospects for the study of phenomena occurring during the propagation of shock waves.

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Note: Figure translations are in progress. See original paper for figures.