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THE PASSAGE OF SHOCK WAVES OVER A RECTANGULAR BLOCK

AT VARIOUS ANGLES

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THE PASSAGE OF SHOCK WAVES OVER A RECTANGULAR BLOCK

AT VARIOUS ANGLES

This report describes a series of tests carried out with the University of Michigan shock tube at the request of the Armed Forces Special Weapons Project. The newly completed Mach-Zehnder interferometer was used.

Fringe shifts were obtained about a two-dimensional 1- by 2-inch rectangular model at a shock strength of $1/\xi$ = 1.62. The block was mounted so that its long side made angles of 15°, 30°, 45°, and 60° with the incident shock, as shown in Figure 1 below. The photographs were taken as nearly as possible to the times τ = 2/3, 1, 1-1/2, 2-1/2, and 4 (see paragraph on notation under "Theory" below for definition of τ). For θ = 45° several additional times were included to give more complete data, since these results are intended to be compared later with results obtained using a three-dimensional glass-block model cemented to one of the windows.[1]
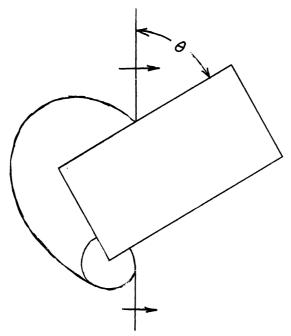

Figure 1

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[1]Brickl and Bleakney, "The Diffraction of a Shock Wave Over a Three-Dimensional Object", Technical Report II-14, Department of Physics, Princeton University, April, 1953.

DESCRIPTION OF EQUIPMENT AND EXPERIMENTAL TECHNIQUES

The University of Michigan shock tube has been somewhat modified since its description by Geiger, Mautz, and Hollyer[2] in June, 1949. The cross section is still 2 by 7 inches. The compression chamber, however, is 7 feet long, and the distance from the diaphragm to the test section is 15 feet. The velocity of the incident shock is measured to $\pm 0.2\%$ by two schlieren detecting stations, located about 4 feet upstream of the test section, with auxiliary electronics. To obtain a shock strength of $1/\xi = 1.62$, an overpressure of approximately 800 mm Hg of helium was used in the compression chamber with atmospheric air in the expansion chamber.

Commercial plate glass 1 inch thick was used for the test section and compensating chamber windows. The glass was selected by a schlieren optical system for freedom from striae. The thickness of glass in the compensating chamber was matched to the thickness of glass in the test section to within 0.002 inch. The plates also were rotated with respect to each other so as to compensate for wedge defects as much as possible. It was possible to obtain reasonably good monochromatic fringes and also white-light fringes with sufficient contrast to permit picking out the central fringe easily. By superposition of flow and no-flow interferograms, a pattern is obtained which is exactly the same as would be obtained if the interferometer were adjusted for an infinite fringe spacing.[3,4] This method of superposition cancels out the deviations that are present in the no-flow fringes. Therefore it is possible to obtain the fringe shifts almost as accurately as if perfect windows were used.

Actually we did not take separate flow and no-flow interferograms, but instead took a double exposure of the flow and no-flow fringes. This accomplished the same result (see Figure 2). White-light interferograms were taken simultaneously with the monochromatic fringe pictures by a suitable half-silvered mirror arrangement. These white-light fringes were used

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[2] F.W. Geiger and C.W. Mautz, "The Shock Tube as an Instrument for the Investigation of Transonic and Supersonic Flow Patterns", Engineering Research Institute, University of Michigan, June, 1949.

[3] Bleakney, "The Diffraction of Shock Waves Around Obstacles and the Transient Loading of Structures", Technical Report II-3, Department of Physics, Princeton University, March 16, 1950.

[4] Ashkenas and Bryson, "Design and Performance of a Simple Interferometer for Wind Tunnel Measurements", Jour. Aero. Sciences, 18, 82 (1951).
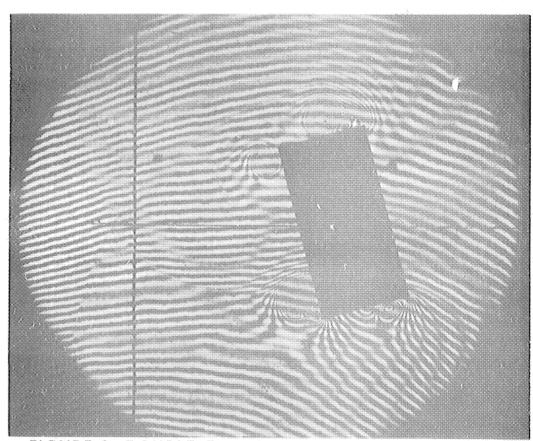
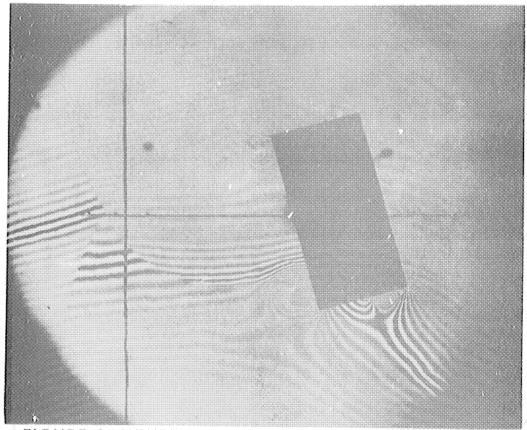FIGURE 2. DOUBLE EXPOSURE FLOW AND NO-FLOW
INTERFEROGRAM.

FIGURE 3. WHITE LIGHT FRINGES (EXPOSURE MADE
SIMULTANEOUSLY WITH ABOVE).

to trace through the reflected shocks. An example of such a white-light fringe picture is shown in Figure 3. This photograph was taken simultaneously with the interferogram of Figure 2.

The method used to obtain the isopycnic diagrams was as follows. The doubly exposed flow plus no-flow fringe picture was enlarged on a Kodalith sheet. Vellum was placed over this and the isopycnics were traced by hand with the help of a light table. These patterns were then traced in India ink. As can be seen from Figure 2, it was easiest to trace through the fuzzy region where the flow fringes were shifted by half-integral values.

This double-exposure technique, however, has a disadvantage as compared to separate flow and no-flow interferograms. With the latter method it is possible to observe the relative amount of the fringe shifts in the flow around the model, where there are no shocks, merely by counting the number of no-flow fringes that a particular flow fringe has crossed. This cannot be done with the double-exposure technique. As can be seen from Figure 2, an individual flow fringe cannot be followed except through regions of rapidly changing density, such as vortices or expansions. An interferogram of the flow made with the interferometer adjusted for an infinite fringe width would, of course, suffer from a somewhat similar defect. Here also the numbering of the isopycnics cannot be determined from the fringe pattern alone.

If the characteristics of the passage of a shock over a model are known, however, this defect can be largely overcome. It is known, for example, that the numbering of the isopycnics must decrease monotonically through rarefactions such as occur at the top and bottom corners of the block. Also it is possible to tell whether the numbers of the isopycnics must increase or decrease by the curvature of the reflected or diffracted shock. Reference 3 has served as a useful guide in this connection. Another device is to observe the path of the white-light fringes through the flow about the model. The use of all these devices leaves little doubt about the relative numbering of the isopycnics, especially for this relatively simple model. The shift of the central white-light fringe is used to trace across the shock waves to find the absolute numbering of the isopycnics.

THEORY

The notation used in this report is as follows:

p = pressure. n = fringe shift.

ρ = density. a = sound speed.

The subscript 0 refers to the conditions ahead of the incident shock; the subscript 1 refers to the conditions in the region behind the incident shock which has not yet been disturbed by the model; and symbols without subscript refer to local conditions about the model.

U = velocity of incident shock.

ξ = p_0/p_1 = reciprocal of shock strength.

θ = angle between incident shock and long side of the model.

n_1 = fringe shift across incident shock.

τ = time interval between passage of incident shock over lead edge of model and instant of taking picture, in units of the time for the incident shock to travel a distance equal to one block height.

λ = wavelength of light.

η = index of refraction.

The index of refraction of a gas is given by the equation

$$\eta = 1 + K \frac{\rho}{\rho_s} ,$$

where K is the Gladstone-Dale constant for air ($K = 0.000293$ for a wavelength of 5170Å), ρ is the local density, and ρ_s is the density at 760 mm Hg pressure and 0°C. From this the expression for the fringe shift, n, can be derived as

$$n = \frac{LK}{\lambda} \frac{273}{760} \frac{p_0}{T_0} \left(\frac{\rho}{\rho_0} - 1 \right) ,$$

where L is the width of the test section and λ is the wavelength of monochromatic light. The width of the University of Michigan shock tube test section is 2.015 inches or 5.1 cm. The wavelength of monochromatic light used was approximately 5170Å. p_0 is given in mm Hg and T_0 in °K. The fringe shift across the incident shock is then

$$n_1 = \frac{LK}{\lambda} \frac{273}{760} \frac{p_0}{T_0} \left(\frac{\rho_1}{\rho_0} - 1 \right) .$$

ρ_1/ρ_0 was calculated from ξ using the Rankine-Hugoniot relation for air

$$\frac{\rho_1}{\rho_0} = \frac{6 + \xi}{1 + 6\xi} .$$

ξ in turn was calculated from the measured velocity of the incident shock using the equation

$$\xi = \frac{6}{7\,(U/a_0)^2 - 1} \ .$$

The term U/a_0 is often called the "Mach number" of the incident shock.

The usual method of calculating the pressures about a model is to assume that the flow behind the incident shock is isentropic, so that

$$\frac{p}{\rho^\gamma} = \frac{p_1}{\rho_1^\gamma} \ .$$

Then

$$\frac{p}{p_0} = \frac{p_1}{p_0}\left(\frac{\rho}{\rho_1}\right)^\gamma = \frac{p_1}{p_0}\left(\frac{\rho_0}{\rho_1}\right)^\gamma \left(\frac{\rho}{\rho_0}\right)^\gamma \ .$$

Solving for ρ/ρ_0 from the fringe-shift equation above gives

$$\frac{\rho}{\rho_0} = 1 + \frac{n}{\dfrac{LK}{\lambda}\dfrac{273}{760}\dfrac{p_0}{T_0}} = 1 + \frac{n}{n_1}\left(\frac{\rho_1}{\rho_0} - 1\right) \ .$$

Therefore the local pressure is given by
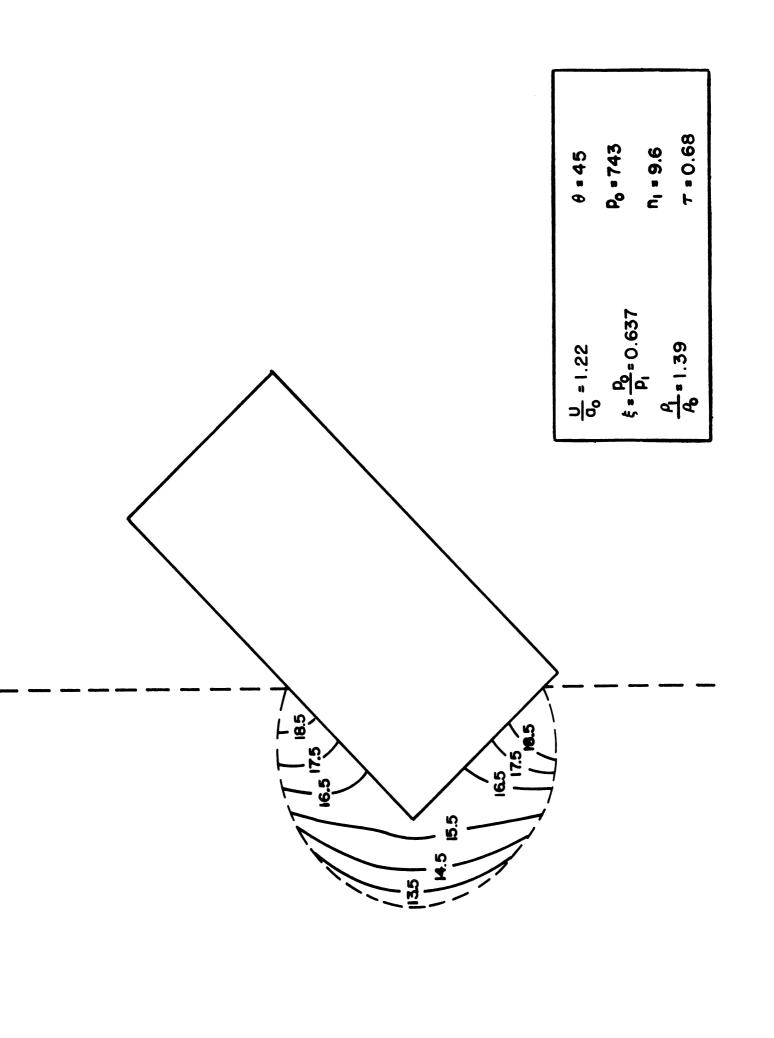
$$\frac{p}{p_0} = \frac{1}{\xi}\left(\frac{\rho_0}{\rho_1}\right)^\gamma \left[1 + \frac{n}{n_1}\left(\frac{\rho_1}{\rho_0} - 1\right)\right]^\gamma \ .$$
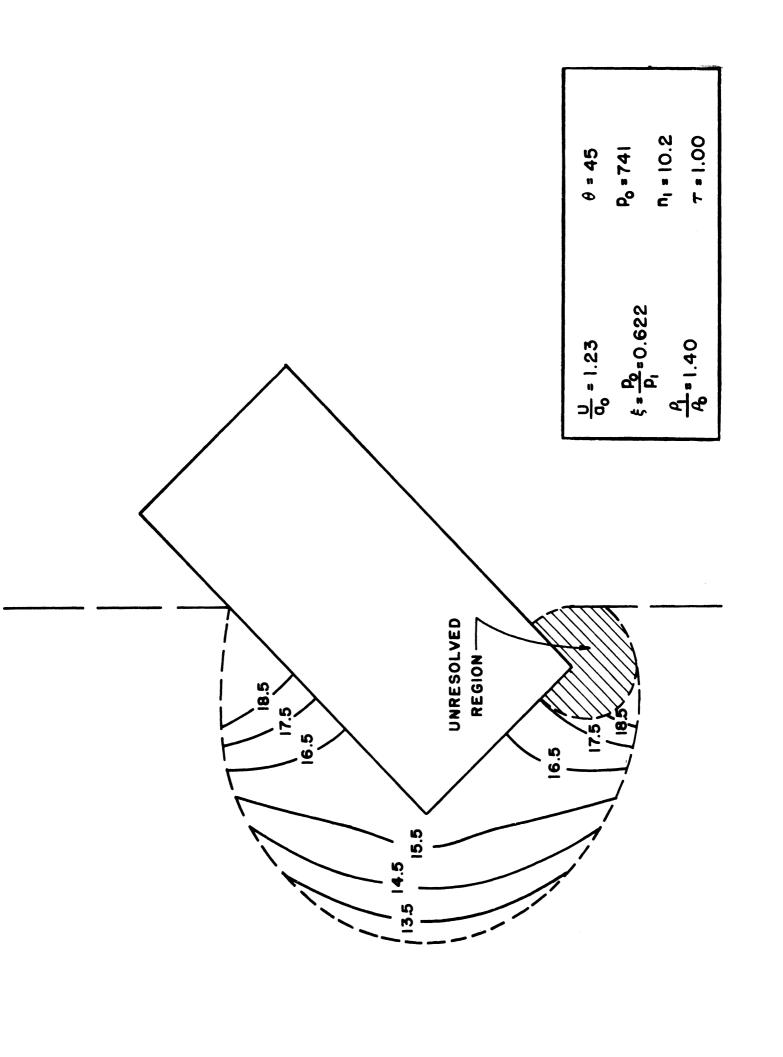
The quantities $\xi = p_0/p_1$, ρ_1/ρ_0, p_0, and n_1, which are needed for the calculation of pressures using the above equation, are given in a data block on each fringe-shift diagram.
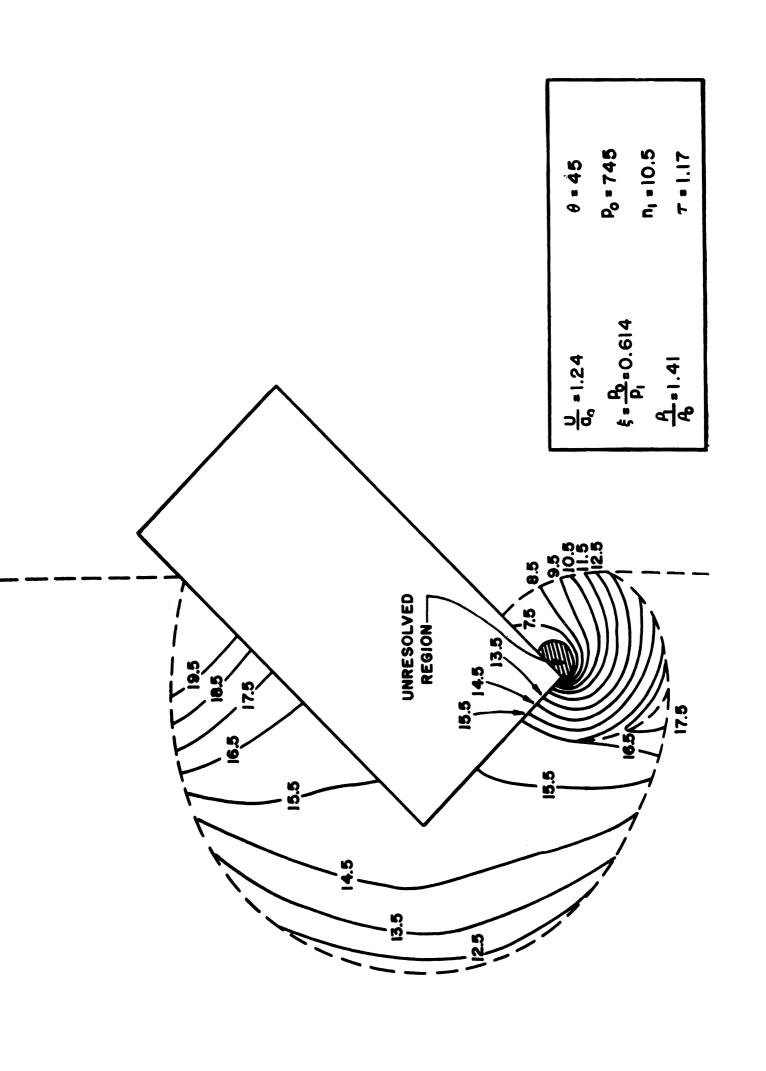
The double-exposure method has an inherent error. It is possible that the fringes might shift in between the exposures of the flow and no-flow fringes, a time of about 1/2 minute. It has been found, however, that in the undisturbed region where the shock has not yet penetrated the fringe pattern resulting from the double exposure is sharp. This indicates that the fringes have certainly shifted less than 1/2 of a fringe width and probably less than 1/4 of a fringe width. Therefore, the error introduced in this manner in the numbering of the fringe shifts is less than 1/4. The defocusing of some regions, especially near the center of the vortices and in strong expansion regions, prevented the resolution of fringe shifts in these areas. Such areas are indicated on the fringe-shift diagrams by
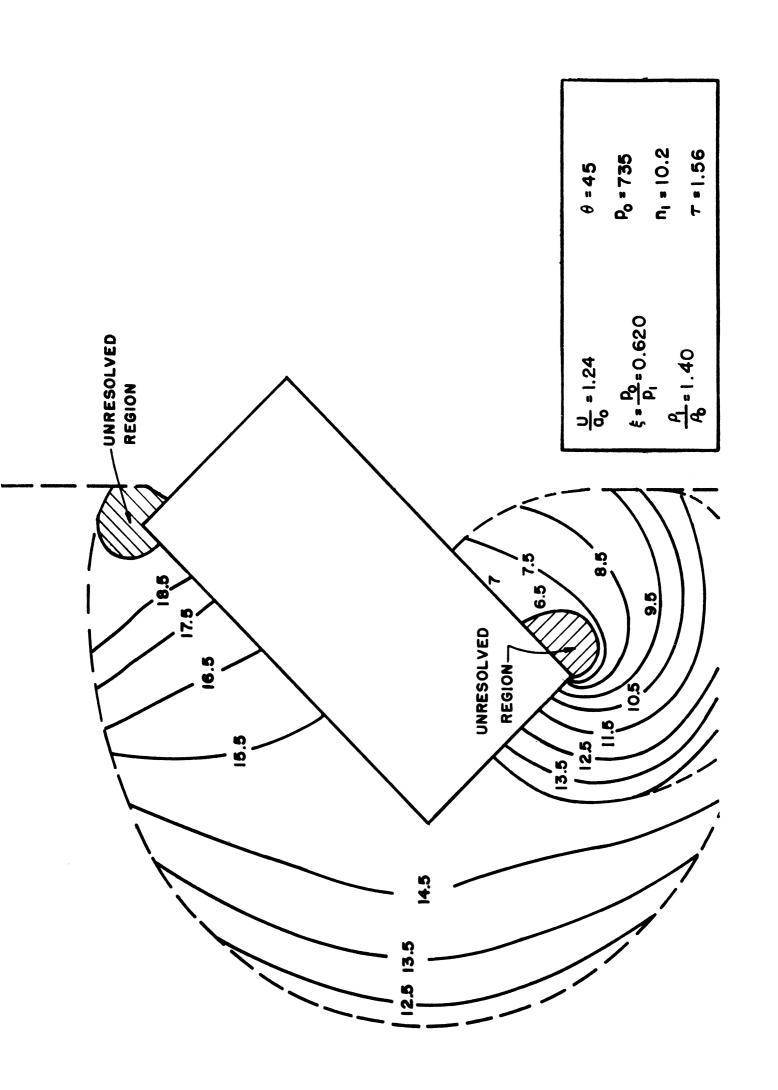
cross hatching. In most cases, however, we were able to obtain the fringe shifts at the surface of the block even though the vortex centers were unresolved.
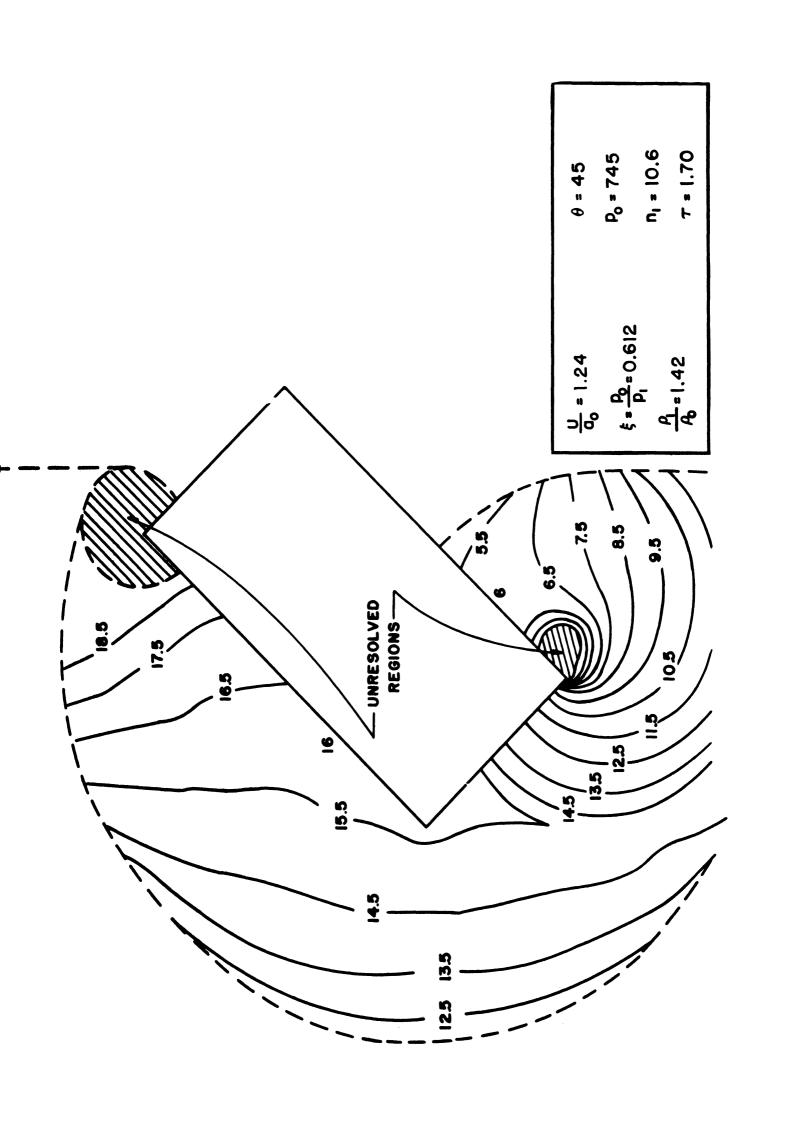
On fact should be emphasized here. Shocks, contact surfaces, and rarefaction fronts cannot be located accurately on interferograms. Therefore the positions of these discontinuities as shown on the fringe-shift diagrams should not be used for any quantitative measurements. They are shown only to help in the interpretation of the results. If accurate location of such discontinuities is desired, schlieren or shadowgraph methods should be used.

$$\frac{U}{a_0} = 1.22$$

$$\xi = \frac{P_0}{P_1} = 0.637$$

$$\frac{P_1}{P_0} = 1.39$$

$$\theta = 45$$

$$P_0 = 743$$

$$n_1 = 9.6$$

$$\tau = 0.68$$

18.5

17.5

16.5

18.5

17.5

16.5

15.5

14.5

13.5

UNRESOLVED
REGION

18.5
17.5
16.5

15.5
14.5
13.5

16.5
17.5
18.5

$\frac{U}{a_0} = 1.23$

$\xi = \frac{p_0}{p_1} = 0.622$

$\frac{\rho_1}{\rho_0} = 1.40$

$\theta = 45$

$p_0 = 741$

$n_1 = 10.2$

$\tau = 1.00$

$\dfrac{U}{a_o} = 1.24$ $\theta = 45$

$\xi = \dfrac{P_o}{P_i} = 0.614$ $P_o = 745$

$\dfrac{P_i}{P_o} = 1.41$ $n_i = 10.5$

$\tau = 1.17$

UNRESOLVED REGION

8.5 9.5 10.5 11.5 12.5 7.5 13.5 14.5 15.5 16.5 17.5 15.5 14.5 13.5 12.5 19.5 18.5 17.5 16.5 15.5

UNRESOLVED REGION

UNRESOLVED REGION

$\dfrac{U}{a_0} = 1.24$

$\xi = \dfrac{P_0}{P_i} = 0.620$

$\dfrac{p_1}{p_0} = 1.40$

$\theta = 45$

$P_0 = 735$

$n_1 = 10.2$

$\tau = 1.56$

18.5
17.5
16.5
15.5
14.5
13.5 13.5
12.5 13.5
12.5

7
7.5
7.5
8.5
8.5
6.5
9.5
10.5
11.5
12.5
13.5
10.5

UNRESOLVED REGIONS

$\frac{U}{a_0} = 1.24$

$\xi = \frac{P_0}{P_1} = 0.612$

$\frac{P_1}{P_0} = 1.42$

$\theta = 45$

$P_0 = 745$

$n_1 = 10.6$

$\tau = 1.70$

5.5

6

6.5

7.5

8.5

9.5

10.5

11.5

12.5

13.5

14.5

15.5

16

16.5

17.5

18.5

15.5

14.5

13.5

12.5

$$\theta = 45$$
$$P_0 = 735$$
$$n_1 = 10.4$$
$$\tau = 2.45$$

$$\frac{U}{a_0} = 1.24$$
$$\xi = \frac{P_0}{P_1} = 0.615$$
$$\frac{\rho_1}{\rho_0} = 1.41$$

UNRESOLVED REGION

UNRESOLVED REGION

UNRESOLVED REGION

$\theta = 45$

$P_o = 735$

$n_1 = 10.4$

$\tau = 4.55$

$\dfrac{U}{a_o} = 1.24$

$\xi = \dfrac{P_o}{P_1} = 0.615$

$\dfrac{\rho_1}{\rho_o} = 1.41$

6.5
6
8
8.5
7.5
7.5
8.5
9.5
10.5
11.5
12.5
13.5
9
8
9
8.5
5
4.5
5.5
3.5
6.5
7.5
8.5
9.5
10.5
11.5
12.5
13.5

$$\frac{U}{a_0} = 1.24 \qquad \theta = 60$$

$$\xi = \frac{P_0}{P_i} = 0.620 \qquad P_0 = 735$$

$$\frac{P_i}{P_0} = 1.40 \qquad n_i = 10.2$$

$$\tau = 0.75$$

15.5
16.5
17.5

13.5
14.5
15

15.5
16.5
17.5

18.5
19.5
20.5
21.5
22.5

$\dfrac{U}{a_0} = 1.24$

$\theta = 60$

$\xi = \dfrac{P_0}{P_i} = 0.620$

$P_0 = 746$

$\dfrac{P_i}{A_0} = 1.40$

$n_i = 10.3$

$\tau = 0.92$

SLIP LINE

15.5
16.5
17.5
18.5

14.5
13.5

15.5
16.5
17.5
18.5
19.5
20.5

7.5
10.5
15.5
20.5

$\dfrac{U}{a_0} = 1.24$ $\theta = 60$

$\xi = \dfrac{P_0}{P_1} = 0.615$ $P_0 = 735$

$\dfrac{P_1}{P_0} = 1.41$ $n_1 = 10.4$

$\tau = 1.55$

SLIP LINE

16.5 17.5 18.5

15.5

14.5

13.5

15

14.5

15.5

13.5

16.5 15.5 14.5 13.5 12.5 11.5 10.5 9.5 8.5 8 7 7.5

16.5

$$\frac{U}{a_o} = 1.24 \qquad \theta = 60$$

$$\ell = \frac{P_o}{P_i} = 0.620 \qquad P_o = 735$$

$$\frac{A}{A_o} = 1.40 \qquad n_i = 10.2$$

$$\tau = 2.50$$

SLIP LINE

SHOCK

SLIP LINE

SHOCK

8.5
7.5
6.5
5.5
6.5
8.5
9.5
9.5
7.5
9
10.5
11.5
12.5
13.5
13.5
13
9.5
9
8.5
7.5
7
7.5
6.5
5.5
8.5
9.5
10.5
12.5
11.5
13.5

$\dfrac{U}{a_0} = 1.24$

$\xi = \dfrac{P_0}{P_i} = 0.615$

$\dfrac{\rho_i}{\rho_0} = 1.41$

$\theta = 60$

$P_0 = 735$

$n_i = 10.4$

$\tau = 3.95$

$\dfrac{U}{a_0} = 1.24$

$\xi = \dfrac{P_0}{P_1} = 0.618$

$\dfrac{A_1}{A_0} = 1.41$

$\theta = 30$

$P_0 = 748$

$n_1 = 10.5$

$\tau = 0.59$

SLIP LINE

15.5 16.5 17.5 18.5

14.5

13.5

19.5

18.5

17.5

16.5

15.5

$$\frac{U}{a_0} = 1.24$$

$$\xi = \frac{P_0}{P_i} = 0.618$$

$$\frac{\rho_i}{\rho_0} = 1.41$$

$$\theta = 30$$

$$P_0 = 748$$

$$n_i = 10.5$$

$$\tau = 1.00$$

SLIPLINE

19.5
18.5
17.5
16.5
15.5
14.5
13.5
15.5
16.5
17.5

THE NUMBERING OF
ISOPYCNICS IN THIS
EXPANSION REGION
MAY BE IN ERROR BY
±2 UNITS

$\dfrac{U}{a_0} = 1.24$

$\xi = \dfrac{P_0}{P_1} = 0.614$

$\dfrac{\rho_1}{\rho_0} = 1.41$

$\theta = 30$

$P_0 = 748$

$n_1 = 10.6$

$\tau = 1.54$

THE NUMBERING OF
ISOPYCNICS IN THIS
EXPANSION REGION
MAY BE IN ERROR BY
± 2 UNITS

$\dfrac{U}{a_0} = 1.24$

$\xi_s \dfrac{p_0}{p_1} = 0.619$

$\dfrac{\rho_1}{\rho_0} = 1.40$

$\theta = 30$

$p_0 = 739$

$\eta_1 = 10.3$

$\tau = 2.42$

$$\frac{U}{a_0} = 1.24 \qquad \theta = 30$$
$$\xi = \frac{P_2}{P_1} = 0.615 \qquad P_0 = 739$$
$$\frac{A}{A_0} = 1.41 \qquad n_1 = 10.4$$
$$\tau = 3.85$$

$$\frac{U}{a_0} = 1.23$$

$$\xi = \frac{P_0}{P_1} = 0.622$$

$$\frac{\rho_1}{\rho_0} = 1.40$$

$$\theta = 15$$

$$P_0 = 735$$

$$n_1 = 10.0$$

$$\tau = 0.75$$

11.5

12.5

20.5
19.5
18.5
17.5
16.5
15.5
14.5
13.5

$\dfrac{U}{a_0} = 1.24$

$\xi = \dfrac{p_0}{p_i} = 0.618$

$\dfrac{p_i}{p_0} = 1.41$

$\theta = 15$

$P_0 = 735$

$n_1 = 10.1$

$\tau = 1.06$

10.5

15.5

20.5

21.5

21.5

20.5

19.5

18.5

17.5

16.5

15.5

14.5

13.5

13

12.5

12.5

THE NUMBERING OF
ISOPYCNICS IN THIS
EXPANSION REGION
MAY BE IN ERROR BY
±2 UNITS

$\frac{U}{a_o} = 1.24$

$\xi = \frac{p_o}{p_i} = 0.618$

$\frac{\rho_1}{\rho_0} = 1.41$

$\theta = 15$

$P_o = 735$

$n_1 = 10.1$

$\tau = 1.62$

SHOCK WAVE

SHOCK WAVE

$\frac{U}{a_o} = 1.24$

$\theta = 15$

$\xi = \frac{P_o}{P_1} = 0.615$

$P_o = 735$

$\frac{P_1}{A_o} = 1.41$

$n_1 = 10.4$

$\tau = 4.00$

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