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FOCUSING OF SHOCK WAVES ON REFLECTION FROM CONCAVE CURVILINEAR SURFACES

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Results from a comparative analysis of experimental and numerical simulation of the processes of reflection of plane shock waves from concave axisymmetric and two-dimensional surfaces are presented.

The practical demands on a number of installations whose functioning involves the propagation of shock waves in channels with a complicated shape and also the interaction of shock-wave formations with curvilinear surfaces generated a need for a more detailed investigation of these processes [1, 2]. The developing shock-wave flow patterns turn out to be extremely complicated and require simultaneous use of both experimental techniques and the methods of numerical simulation for their analysis .

Even in the simplest (for the indicated installations) case of the reflection of plane shock waves from axisymmetric concave surfaces the available information [2, 3] does not permit one to draw an unambiguous conclusion about the character of the process of reflection and especially about the change in the gas parameters behind a reflected shock wave. Here, not only does the intensity of the incident shock wave appear to be important, but also the angular characteristics of the reflecting surface orientation.

In the present work we performed a comparative analysis of the results of experimental and numerical simulation for the processes of the reflection of plane shock waves from concave axisymmetric and two-dimensional surfaces.

The presence of shock waves and other parametric discontinuities in the field of calculations compels us to resort to the methods of "continuous calculation," in particular to the "large-particle" method (LPM) [4, 5]. Developed at the end of the 1960s in regard to the problems of supersonic gas dynamics, the LPM is widely used at present for investigating shock-wave and other unsteady-state processes in various areas of physical gasdynamics [4, 5].

In the present work, we carried out numerical simulation by a modified method of "large particles." A complete system of two-dimensional eddy equations of gasdynamics was solved for an inviscid nonconducting perfect gas. The system was written in the divergent form

$$\frac{\partial U}{\partial t} + \frac{\partial F(U)}{\partial x} + \frac{\partial G(U)}{\partial y} + H = 0$$

with the equation of state $P = (\gamma - 1)\rho\varepsilon$ and the vector functions

$$U = \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ \rho E \end{pmatrix}; \quad F(U) = \begin{pmatrix} \rho u \\ \rho u^2 + P \\ \rho v u \\ (\rho E + P)\, u \end{pmatrix};$$

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$$G(U) = \begin{pmatrix} \rho v \\ \rho v u \\ \rho v^2 + P \\ (\rho E + P) v \end{pmatrix}; \quad H = \frac{\nu}{y} \begin{pmatrix} \rho v \\ \rho v u \\ \rho v^2 \\ (\rho E + P) v \end{pmatrix};$$

where $E = \varepsilon + \dfrac{u^2 + v^2}{2}$.

Here $\nu = 1$ and 0 for the axisymmetric and plane case, respectively; $\gamma = 1.4$.

The method was modified by incorporating splitting with the coefficients $\kappa_1 = \kappa_2 = 0.5$ for the momentum and energy equations at the Euler stage and also by eliminating the errors of approximation when divergent terms are calculated at the Lagrange stage for the case of the "sink" and "source" cells as suggested in [4].

Calculations were made on cells with constant and equal steps in both coordinate directions. The time step did not change in the process of calculation and was assigned according to the requirement that the Courant number should remain within the range 0.3-0.1. This ensured a spatial resolution in physical units with the grid of 0.25 × 0.25 to 1 × 1 mm and a time resolution of 0.3 to 0.9 μsec. The maximum time of the simulation of the process development was usually limited to 4 msec. Due to the symmetry of the structure, which is a plane (cylindrical) channel terminating in a bottom with a concave surface of cylindrical (spherical) shape, we may consider only half the section. This makes it possible to substantially reduce the demands on the computer resources.

Our experiments with an axisymmetric model were carried out on a pulse gasdynamic rig whose main element was a two-diaphragm shock tube with nonstationary flow expansion [6]. The diameter of the low-pressure and intermediate sections was equal to 76 mm; the module under test, having a spherical recess of radius 35.7 mm and depth 28.7 mm, was placed at the face of the shock tube. The dynamics of the change in pressure in different sections was recorded by preliminarily calibrated piezoelectric pressure pickups with a spatial resolution of 2 mm. The gas parameters were calculated with the help of the Hugoniot curve on the basis of the shock wave velocity measured by the time lag in the signals from piezoelectric pressure pickups located on two different bases. Moreover, the pressure behind the incident and reflected shock waves in both the cavity itself and ahead of it was monitored by calibrated pressure pickups located in the end face spherical wall on the channel axis and in the side wall at a distance of 30 and 205 mm from the cavity outlet. The primary recording of signals was made by S9-8 digital oscilloscopes; the subsequent processing of the results of measurements and also the recording of the shock wave velocity and the calculation of the thermodynamic parameters of the medium were made with the use of an automated data acquisition and processing system built to the CAMAC standard on the basis of an Élektronika MS-1212 minicomputer connected with a central PC of IBM PC/AT-286 type.

Experiments with a two-dimensional concave reflecting surface were made on a single-diaphragm shock tube with a low-pressure chamber channel of cross section 45 × 90 mm, at the end of which a concave cylindrical cavity of radius 22.5 mm was installed. The recording system is similar to that described above. Moreover, using an IAB-451 shadowgraph matched with a high-speed photorecorder based on a ZhLV-2 driven time loop, we carried out the visualization of the process of plane shock wave reflection from a concave curvilinear surface in some characteristic regimes. For synchronized startup of the shock tube and also for eliminating the impeding effect of scraps of diaphragms, we used a diaphragm-free high-pressure chamber with a forced electropneumatic startup.

The procedure of numerical simulation was similar to a full-scale experiment. Comparison between the readings of the experimental and "numerical" pressure pickups made it possible to synchronize the development of the process, whereas the graphical representation of data for pressure, density, temperature, and local Mach numbers and also for the vector field of velocities with subsequent processing of them similar to the applied experimental methods of optical diagnostics made it possible to carry out not only qualitative but also quantitative analysis of flow patterns.

Comparison of the experimental and "numerical" recordings of pressure at the bottom of the spherical and cylindrical semiclosed cavities (Figs. 1 and 2) indicates that the developed theoretical model adequately describes the process of the reflection of a plane shock wave from concave curvilinear surfaces. This allows one to reconstruct

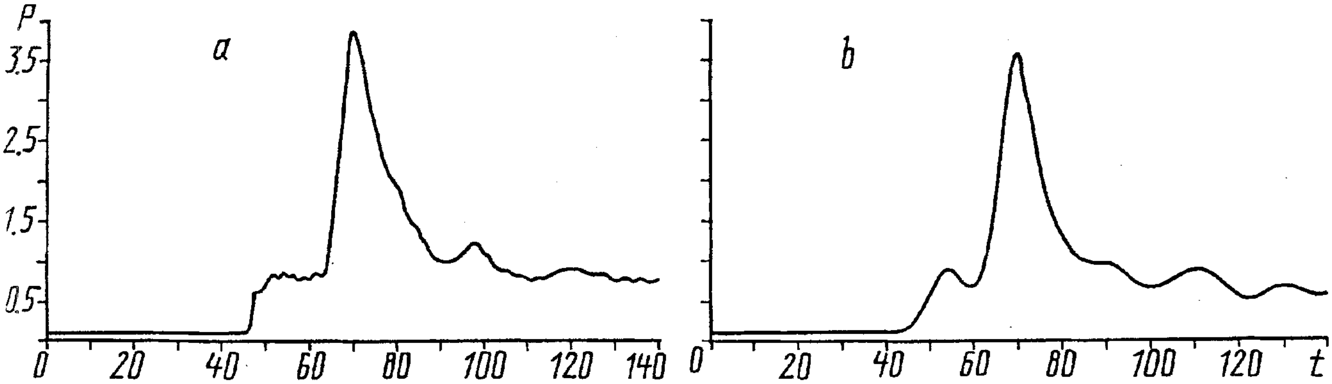

Fig. 1. Pressure recordings at the bottom of a spherical semiclosed cavity in air at the initial pressure $P_0 = 0.1$ MPa; the Mach number of an incident shock wave is M = 1.71; a) experiment; b) calculation. P, MPa; t, μsec.

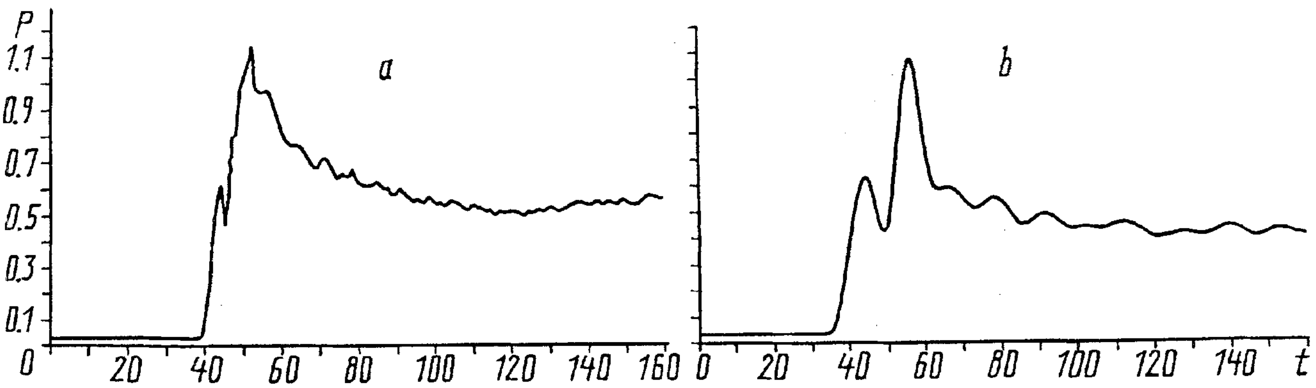

Fig. 2. Pressure recordings at the bottom of a cylindrical semiclosed cavity in air at the initial pressure $P_0 = 0.03$ MPa; the Mach number of the incident shock wave is M = 2.19: a) experiment; b) prediction.

the gas flow velocity field as well as the pressure, temperature, and density fields of the medium (Fig. 3) in the region being studied.

The combination of investigations carried out allows us to describe the general structure of flow in this process which differs substantially from one-dimensional.

It was found that the reflection of a plane primary shock wave propagating along the channel starts at the time of the change in the channel section and is characterized by the local angle of shock wave incidence at a given Mach number of the wave and specific-heat ratio of the gas [1, 2, 7]. For small incidence angles one observes a smooth bending of the incident shock wave front near the surface of the wall with the formation of a reflected shock wave of compression [7]. Then the compression wave increases in strength and on exceeding a certain characteristic angle forms a reflected shock wave. A cusp appears on the incident wave front, forming a configuration with a "Mach leg," which ensures the turning of the flow behind the primary shock wave toward the axis. In this case, the intensity, Mach number, and orientation of the "Mach leg" relative to the axis are determined by both the change in the surface shape and the parameters of the primary shock wave. For a cylindrical (spherical) surface in the studied range of the Mach numbers for the primary shock wave (from 1 to 3) the "Mach leg" disappears before reaching the cavity bottom, and reflection occurs in a regular way. At this instant the pressure pickups record the first pressure maximum at the bottom of the cavity (Fig. 4a).

After reflection of the first shock wave from the cavity bottom, the process of the formation of a reverse flow behind the reflected wave begins. The pickups at the cavity bottom first record a jump with a subsequent relief of pressure behind the reflected wave and then again an increase in the pressure at the cavity bottom with extremal parameters.

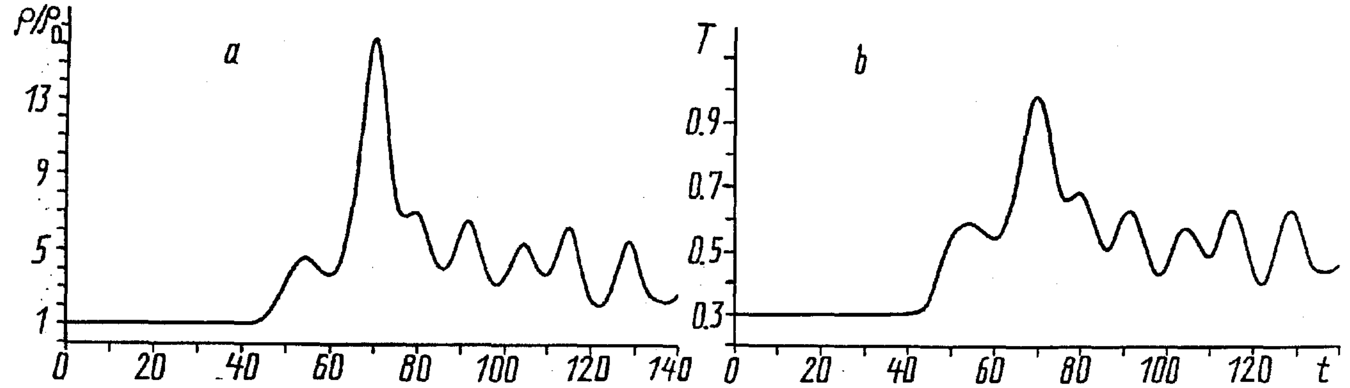

Fig. 3. Predicted relationships for the relative density (a) and temperature (b) at the bottom of a spherical semiclosed cavity in air at the initial pressure $P_0 = 0.1$ MPa with the Mach number of the incident shock wave M = 1.7. T, kK.

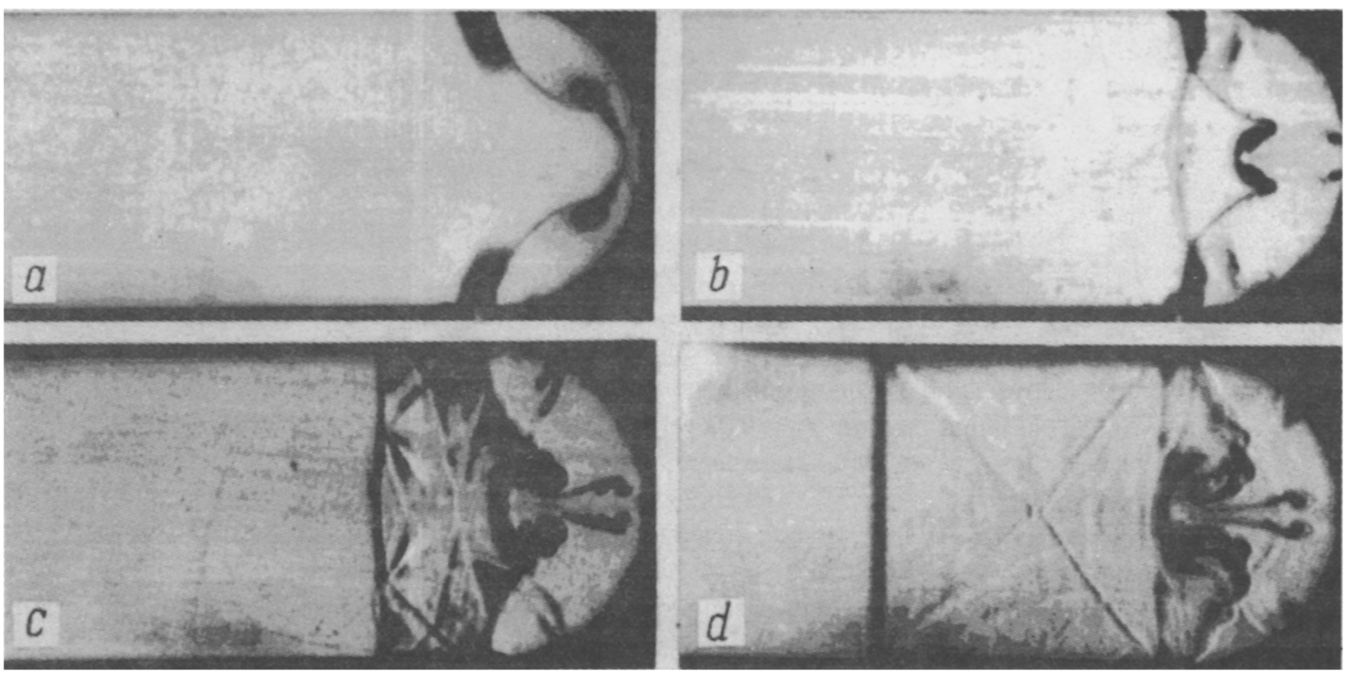

Fig. 4. Straight shadowgraphs of the process of reflection of a shock wave from a concave cylindrical cavity in air. Initial pressure is $P_0 = 0.03$ MPa; Mach number of the incident shock wave is M = 2.19.

Analysis of the experimental and numerical patterns of the flow has shown that the secondary increase in pressure can be explained by the inflow of gas, which moves along the cavity surface after the reflection of the primary shock wave at the periphery, into the volume near the axis behind the reflected wave. This motion occurs with acceleration and leads to intense compression of a certain gas volume near the cavity bottom. Within this volume, at a point called a focus, the parameters attain their maximum values. This point is offset from both the cavity bottom and the symmetry axis, thus providing the compensation of eddy motion. The volume expansion generates an unloading shock wave (Fig. 4b), which ultimately forms a reflected shock wave. Thereafter the very process of the formation of the shock wave reflected from the cavity begins. The unloading shock wave interacts with elements of the primary reflected shock wave at the cavity periphery, generating contact discontinuity and retarding and entraining the gas near the cavity surface into reverse motion. After entering the channel, the curvilinear unloading wave front acquires a plane shape at a distance of two diameters.

Apart from the unloading wave, the gas volume near the focus with extremal parameters also generates a mushroom-shaped subsonic pulse flow. In addition, the contact discontinuity appearing earlier separates the medium near the cavity surface from that behind the primary shock wave, which did not interact with the reflected shock wave (Fig. 4c). The dimensions of the expanding gas volume increase up to the cavity dimensions with a subsequent one-dimensional escape of the medium from the cavity into the channel (Fig. 4d).

Analysis of flow patterns on the basis of experimental data and numerical simulation shows that plane primary shock waves reflected from cylindrical and spherical cavities have an identical qualitative structure and differ mainly by quantitative data that characterize the extremal values of the parameters. For the spherical cavity these values are noticeably higher. This seems to be attributable to a higher compression of the medium during the inflow into the cavity at the first stage of reflection. Moreover, the "Mach legs" form a cylindrical converging shock wave after the reflection of the primary wave from the cavity bottom. This also contributes to a noticeable increase in the gas parameters at the gasdynamic focus.

NOTATION

E, total energy; P, pressure; u, velocity component in the x direction; v, velocity component in the y direction; t, time; ε, internal energy; γ, specific-heat ratio; ρ, density.

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