Plane shock compression generators, utilizing convergence of conical shock waves

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Abstract. The results of experimental testing of shock wave generators, based on irregular Mach reflection of shock waves in a conical geometry, along with the results of numerical simulation is presented. The shock in a layered cylindrical central body was produced by an impact of a converging conical flyer plate. Conical flyer plate was originating from initially cylindrical cavity liner in a cylindrical HE charge that was launched by a sliding detonation. This approach led to device simplification, since manufacturing of conical parts from metal and explosive is not required. The sequential detonation of HE charge by a multi-point distributor was employed to vary the geometry of formed conical flyer. The dependence of parameters of shock wave in cylindrical Polymethylmethacrylate (PMMA) core on launch angle was investigated. It was found that launch angles below 10° lead to failure of the Mach reflection mode, while larger angles produced flat Mach disks that can be utilized in various shock experiments.

1. Introduction
An irregular mach reflection of conically converging shock waves was used to generate high shock pressures [1,2]. These devices utilized a single reflection mode, characterized by fast drop of pressure behind mach disk. Also, it consisted of conical parts, produced from metal and high explosive, making them complex and expensive. A competing double mach reflection (DMR) regime providing slow decay of pressure behind Mach disk. In [3] it was proposed, that DMR regime is achievable if a cylindrical contact boundary is introduced in layered “hard shell – soft core” cylindrical central body, although HE charge and liner remains conical.

In this study we proposed full rejection of conical parts. Conically converging flyer plate is forming from cylindrical liner, and the only complicated part is a multi-point detonation distributor, forming a conical detonation wave by sequential ignition of main charge.

2. Experimental device
General view of high-pressure generator is presented in figure 1. The main part of tested experimental devices was cylindrical charge (1) of high explosive (RDX-type, \( \rho_0 = 1.65 \) g/cc, detonation velocity \( D_1 = 8.0 \) km/s) with outer diameter 150 mm and length 150 mm. The charge was prepared by compression, its overall mass was 3.8 kg; charge was composed of 3 distinct pieces to reduce amount of HE in one compression cycle. The cylindrical hole at the axis of charge was lined by cylindrical steel shell (2) with outer diameter 50.5 mm. Central body, consisted of \( d = 20 \) mm stainless steel tube...
(3), filled with polymethylmethacrylate (PMMA) (4), was placed at the axis. Charge was surrounded by detonation distributor plates.

![Experimental device](image)

**Figure 1.** Experimental device.

2.1. Detonation distributor

Detonation distributor (DD) was the key part of proposed design (figures 1 and 2). It consisted of a set of 18 MDF fiberboard plates with 2 × 2 mm milled channels, filled with soft plastic-bonded explosive. From the upper side the plates were joined by single round plate, also contained milled channels, radiating from the center, with central hole to fix the detonator. All parts were precisely produced by CNC milling machine. Total amount of ignition points of was 234, 13 circles × 18 points.

![Scheme of detonation distributor](image)

**Figure 2.** Scheme of detonation distributor.

Geometry of the channels mesh of single distributor plate is presented in figure 2. The performance was defined by “DD angle” α. It’s well seen, that a plate with α = 45° provides simultaneous ignition of the surface of charge (limiting case of infinite V - velocity of distribution of detonation along charge), such a geometry was proposed in [2] for ignition of conical Mach device. If α < 45°, $V = D_2/(\cos \alpha - \sin \alpha)$, where $D_2$ is a detonation velocity in PBX, filling the channels (7.63 km/s in our case). The half-angle of conically converging detonation wave in main charge β is defined by relation: $\sin \beta/D_1 = V$. Experimentally tested devices were identical, α was varied from 32° to 20.5°. The DD parameters are presented in table 1.
2.2. Diagnostics

The well-known technique of flashing gaps, briefly described in [2,4] was used to measure mach disk velocities and overall dynamics of mach disk growth. As mentioned in section 2.1, the central body was made of steel tube, filled with a set of PMMA disks with optically clear surfaces. Small (50 μm) air gaps were introduced between disks, providing bright flashes during the shock wave passing. The slit of mechanical sweep camera with rotating mirror was aimed to the face of central body; image of the slit was resolved in time of photographic film. Example of experimental recordings is presented in figure 3.

![Figure 3](image_url)

**Figure 3.** Experimental records. (a) shot 18, $\alpha = 32.1^\circ$, $D = 26.5$ km/s; (b) shot 22, $\alpha = 29.7^\circ$, $D = 21.4$ km/s; (c) shot 17, $\alpha = 24.2^\circ$, $D = 16.7$ km/s.

Initially, the shock wave in PMMA body is conical, causing tilted traces from flashing gaps. Later, mach disk growth is started, causing the optical emission from shock-compressed PMMA, accompanied by bright flashes. Combining the measured time intervals and coordinates of gaps, it’s possible to calculate shock velocities, along with dimensions of mach disk. Mean shock velocity was obtained along last 4-5 gaps, where it reached stability. Typical thickness of disks was 10- to 15-mm, so the time resolution of mechanical camera was enough even for >20 km/s velocities.

3. Discussion

Two dimensional axisymmetric simulations of the experiments were performed, using Godunov technique [5] with adaptive mesh. Simulation included multi-point detonation ignition in experimental configurations, acceleration of liner by detonation products, and interaction of shock waves in central body. The results of simulation were compared with experimental data.

Typical pictures of mach disc growth are presented at figure 3. In case (c), the half-angle $\beta$ of detonation wave in main charge was big, mach disk had moderate velocity, but growing up rapidly and filled all the diameter of PMMA body. In case (b), $\beta$ was moderate, and the growth of mach disk was stopped at diameter 7 mm, although shock velocity was higher. Case (a) was a try to reach high (close to 25 km/s) shock velocity, but we got a failure of irregular reflection mode, and mach disk was not resolved by optical technique. The half-angle of impact of accelerated conical liner with central body was estimated as 9-10° for this case. The rapid increase of mach disk, accompanied by its deceleration is due to edge effect: the end of liner cannot be accelerated enough because of expansion of detonation products near the end of charge, so the angle of the liner is increasing while the velocity is decreasing.
A comparison of experimental registration of mach disk radius with simulation for 5 various DD geometries is presented in figure 4. We got satisfactory agreement for all experiments, except shot 18, where simulation offers growth of disk up to 4 mm, although no any was registered.

![Graph showing comparison of experimental and simulated mach disk growth.](image)

**Figure 4.** Comparison of dynamics of mach disk growth in experiment (dotted lines) and simulation (solid lines). X-coordinate is shifted: shot 17 + 2 cm, shot 19 + 4 cm, shot 22 + 6 cm, shot 18 + 8 cm.

To prove, if we got a DMR regime, the pressure profiles at the axis of central body along x-coordinate were plotted in figure 5a. Figure 5b is a picture of sound velocity $C_s$ distribution. Profiles were taken for moments of time, when mach disk roughly reached coordinate 11 and 13.5 cm. It can be seen, that only in shot 20, coordinate 13.5 cm, the pressure profile have obvious plateau, confirmed DMR mode. Simulation shows at that moment, that mach disk not only reached steel walls of central body, but interacts with them for 1.7 $\mu$s, 2.5 cm distance. Shot 22 provides considerably higher pressure (360 GPa vs. 160 GPa), but the diameter of mach disk was small, up to 7 mm. This configuration can also be utilized for experiments with modification – decreasing of diameter of PMMA core up to 6-7 mm.

![Graph showing pressure profiles.](image)

**Figure 5.** Simulation results. (a) Pressure distribution along the axis. (b) Corresponding simulation snapshots ($C_s$).
4. Conclusions
Fully cylindrical design of mach high-pressure generator was tested along with multi-point detonation distributor. Flat mach disk was obtained with velocity, defined by geometry of DD. Shock pressures in PMMA core up to 360 GPa were obtained; for lower pressure the DMR regime was reached. Effect of critical angle of incidence was experimentally confirmed. Good agreement with 2-D simulation was obtained.

Table 1. A slightly more complex table with a narrow caption.

| Shot | α     | β     | D\text{PMMA}_\text{experiment} | D\text{PMMA}_\text{simulation} | Remark                                      |
|------|-------|-------|---------------------------------|---------------------------------|--------------------------------------------|
| 18   | 32.07 | 19.4  | 26.5                            | 24.41                           | Mach disk growth failure                   |
| 22   | 29.7  | 23    | 21.4                            | 21.74                           | Mach disk growth stopped at \(d=7\text{mm}\) |
| 19   | 27.8  | 26    | 18.8                            | 20.23                           | Mach disk growth stopped at \(d=12\text{mm}\) |
| 21   | 27.8  | 26    | 19.8                            | 20.23                           | Mach disk growth stopped at \(d=12\text{mm}\) |
| 17   | 24.2  | 31.75 | 16.73                           | 18.05                           | Mach disk filled inner diameter            |
| 20   | 20.43 | 38    | 14.6                            | 16.38                           | Mach disk filled inner diameter            |

Acknowledgments
Work was supported by government contract H.4x.44.90.13.1112 and by program of presidium of RAS P-02

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