Mathematical modeling of converging detonation waves at multipoint initiation

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Abstract. The methods of mathematical modeling based on the latest experimental data are proposed to conduct a study of the cylindrical detonation process and gas dynamics of the explosion products. The numerical simulation of converging cylindrical detonation waves at multipoint initiation for the recent experiments in IPCP RAS was conducted. The results of the numerical simulation and the experiment are compared.

1. Introduction
To achieve the extremely high physical properties in high energy density physics the explosive setups, based on the cylindrical, spherical or conical compression [1–4] are commonly used. They are devices such as ultra-high pressure generators, explosion generators and various kinds of cumulative setups. One of the most important requirements for such devices to achieve the desired effect is a simultaneous output of a detonation wave at a metal target having a cylindrical, spherical or conical shape. The cylindrical detonation wave and the movement of the cylindrical piston to the center are well investigated and presented in [5–9].

In the experimental studies conducted recently in IPCP RAS and in the results obtained in [10], the data on the output of the shock wave on the free surface of metal targets were obtained. The shock waves were the result of flat, cylindrical and conical detonation waves generated by the multipoint initiation. Thus some features of the gas-dynamic flow of the detonation products were detected. In the investigations different methods having a high temporal resolution (spectroscopy, pyrometry, probe technique) were applied. The experimental studies were carried out using high-speed cameras “Nanogeyt-22” and “Nanogeyt-4BP” of domestic production with the specifications at the level of world analogues.

We propose a mathematical model of a cylindrical detonation agreed with the results of the last experimental investigations [11]. The use of mathematical modeling of cylindrical detonation wave based on the kinetics of decomposition of the detonation products will significantly reduce the amount of costly explosion experiments. A combination of experimental investigations with the mathematical modeling allows observing adequately the process of the formation of different types of detonation waves (planar, cylindrical, conical, spherical) and detonation products flow under the multipoint initiation.
2. Numerical modelling
The simulations were fulfilled by the two-dimensional hydrodynamic computer code BIG2 [12]. This code is based on a Godunov type scheme that has a second order of accuracy in space. The curvilinear rectangular moving grids are used. The Mie–Grüneisen equation of state is used for description of the explosives and the products of explosion:

\[ p = p_c(V) + \frac{\Gamma(V)}{V}(E - E_c(V)), \]

where \( \Gamma(V) \) is Grüneisen coefficient, \( p \) is pressure, determined by the equation of state, \( E \) is specific internal energy, \( V \) is specific volume, \( \rho = 1/V \) is density, \( p_c(V) \) is cold pressure curve at zero temperature, \( E_c(V) = \int_{V_0}^{V} p_c(V) dV \) is cold energy curve, where \( V_0 \) satisfies \( p_c(V_0) = 0 \).

The phlegmatized RDX explosive model with the density of \( \rho_0 = 1.6 \text{ g/cm}^3 \) is taken in the simulation. The cold curves constant Grüneisen coefficient and kinetics constants are taken from [13].

For the explosive:

\[ p_c(V) = \frac{3}{2} \left( 13.2 \left( y^7 - y^5 \right) \left[ 1 - \frac{3}{4} (4 - 6.4) (y^2 - 1) \right] \right), \quad \Gamma = 2.4, \]

where \( y = (\rho/1.72)^{1/3} \).

For the products of explosion:

\[ p_c(V) = 896.16 \exp(-10.106V) + 3.98/V^2, \quad \Gamma = 0.3. \]

The decomposition of the explosive is described by equation:

\[ \frac{d\alpha}{dt} = \begin{cases} -6.25p\alpha^{0.3}(1 - \alpha)^{0.7}, & \text{if } p \geq 0.1, \\ 0, & \text{if } p < 0.1, \end{cases} \]

where \( \alpha \) is mass fracture of the explosive, \( p \) is pressure in GPa, \( t \) is time in \( 10^{-5} \text{ s.} \)
Figure 2. Experimental fields of the light intensity and the calculated field of specific internal energy for the relevant provisions of the detonation front for four time moments. The experimental pictures are located on the left side and the pictures from the simulation on the right side.
The initial data for the simulation correspond to the experiment [11]. The disc of explosives with a diameter of 150 mm is at the same time undermined in the twenty-four equidistant points on the cylindrical surface of the disk. The simulation is carried out in 2D plane across the axis of symmetry. Taking into account the symmetry of the problem, the numerical modelling is carried out on a rectangular grid, which is subsequently expanded by a quarter segment of the disk, bounded by rigid walls intersecting in the centre at right angles. Initially, the grid covers the cylindrical surface of the disc segment as a thin layer (see figure 1). In the process of simulation the grid is automatically extended and being completed.

The boundary conditions for the moving grid are: “front of perturbation”—the grid line is moving on to the substance with the sound speed or with the speed of detonation front; “free surface” is moving as a contact boundary; “rigid wall” corresponds to rigid wall boundary conditions. With the expansion of the boundaries the square covered by the grid grows. To maintain a given spatial resolution the number of grid cells automatically increases correspondingly.

3. Comparison of the numerical and the experimental results
The simulation was performed in the setup of the most relevant experiments. The speed of detonation front was tested in one-dimensional calculations. The initiation of the detonation process in the simulation was carried out at the points corresponding to the experiment with the initial pressure required for getting stationary detonation (figures 1, 2b).

Figure 2d shows the further evolution of the detonation front from the individual points of the initiation to the smooth spherical semicircles. A good agreement with the experiment (figure 2c) is observed.
A very interesting picture is presented in figure 2f, where a collision of detonation waves and the formation of Mach configuration were observed.

The more detailed picture is shown in figure 3. Two levels of specific internal energy behind the detonation front with multipoint initiation are represented. A blue line highlighted the specific internal energy in the picture directly on the front. The high level of specific internal energy and a correspondingly high level of light intensity behind the front arise from the intersection of two adjacent shock waves, and low energy levels occur behind the front of a single shock wave. This corresponds to the experimental data (figure 2e).

Due to this effect the detonation front on that stage of evolution looks like the consequence of bright and dark arcs. This stage of detonation front convergence one can see in figures 2e, 2f. The further evolution of the detonation process is shown in figures 2g, 2h. One can see that the main difference in the last pictures is the distortion of the symmetry of the converging front in the experiment.

4. Conclusion

The most important factor in symmetrical compression of metal targets of cylindrical, spherical, or other configurations is the symmetry of the detonation and consequently a shock wave impacting on the target. The presence of asymmetry may cause the hydrodynamic instabilities at compression and the formation of jets at the exit of the shock wave on the free surface of the target. The proposed mathematical model based on the experimental data adequately describes the formation and dynamics of the cylindrical detonation wave obtained by multipoint initiation. This technique can be used to study the flow of detonation products at multipoint initiation under the influence of different factors (asymmetry of initiation, change the detonation speed along the radius, non-uniform density, the formation of a three-wave Mach configuration, etc). That can substantially reduce the number of costly explosion experiments.

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