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LONG-TERM SHOCK LOADING OF SOLIDS BY A COMBINED CHARGE WITH EXPLOSIVE INITIATION

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A method and results of calculation of parameters of long-term shock loading of solids, generated by a gas-dynamic former containing a combined charge with explosive initiation, are described. A calculation model based on the concepts of the hydrodynamic theory of detonation and on the theory of combustion of condensed substances is considered. The forcing pressure and the physical laws of combustion of the combined charge are determined in calculations and experiments. The dynamics of the process is studied by an example of calculation of parameters of the loaded solid acceleration pulse in the case of initiation and combustion of a charge consisting of two batches of high explosives: black powder and pyroxylin powder. The effect of the combined charge parameters and combustion-chamber size on the parameters of the shock loading pulse is studied.

Key words: *shock pulse, gas-dynamic former, explosive initiation, combined charge.*

Intense shock loading of massive objects is most successfully ensured by explosive-type experimental facilities. In this case, however, it is still rather difficult to form object acceleration pulses with a small duration of the leading front (as compared with the total pulse duration of the order of 5 msec and more). The present paper describes the technique and results of calculations of a gas-dynamic former of shock pulses with a combined charge with explosive initiation, which was proposed in [1].

Figure 1 shows the sketch of the gas-dynamic former of the shock pulse. The combined charge consists of two powder batches and a batch of a high explosive (HE) whose mass is within 2% of the total mass of the combined charge.

To determine the parameters of motion of the accelerated solid, we solve the problem of internal ballistics of the gas-dynamic former, using the calculation model for estimating the parameters of HE detonation processes, expansion of detonation products and ignition of the powder charge, and also for describing the processes of formation of powder gases owing to combustion of two types of powders in the combined charge and the process of conversion of the chemical energy of the charge to the kinetic energy of motion of the accelerated solid.

Thermodynamic Calculation Model. The complicated processes of transformations induced in the gas-dynamic former by the explosion can be divided into several stages.

The first stage includes HE detonation, expansion of detonation products, and ignition of the powder charge.

Detonation of the condensed HE is initiated by operation of the explosion-conducting bridge (see Fig. 1). The pressure $p_{\rm G}$ and the density $\rho_{\rm G}$ in the detonation wave (at the Jouguet point) are approximately determined by the formulas [2]

$$\rho_{\rm G} = \rho_0 (k + 1)/k; \tag{1}$$

$$p_{\rm G} = \rho_0 D^2/(k + 1), \tag{2}$$

where ρ_0 is the HE density, k is the ratio of specific heats at the Jouguet point, and D is the HE detonation velocity.

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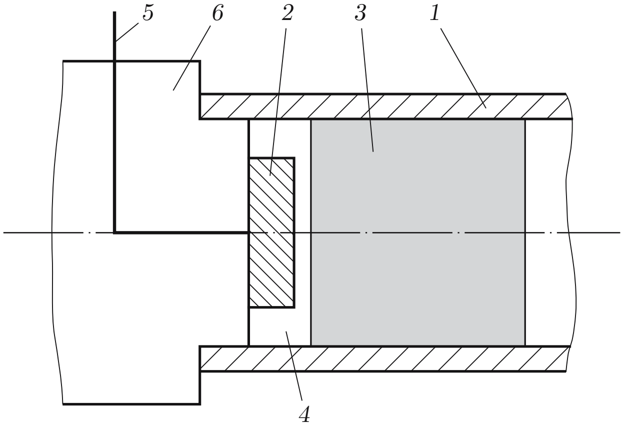

Fig. 1. Sketch of the gas-dynamic former: 1) casing; 2) combined charge; 3) loaded solid; 4) combustion chamber; 5) detonation bridge; 6) gate.

For the equation of state of detonation products $p = A\rho^k$ (A is a constant), we have $k = 3$, which is in reasonable agreement with experimental data [3–5]. Using Eqs. (1) and (2), we can determine the initial density and pressure of detonation products:

$$\rho_{D0} = 4\rho_0/3, \qquad p_{D0} = \rho_0 D^2/4.$$

When the HE detonation process is completed, the chamber (see Fig. 1) is filled by detonation products, which is accompanied by the formation of shock waves.

As the chemical transformations due to HE detonation and expansion of detonation products occur within a small time period (several microseconds) as compared with the duration of powder-charge combustion (several milliseconds), they do not exert any significant influence on the parameters of the shock pulse acting on a massive loaded body, which is assumed to be a solid in the problem considered. In this case, it is sufficient to determine the steady values of pressure and density of detonation products at the moment when the first stage is finalized. Based on this reasoning, we assume that the loaded solid is affected after HE initiation by a force generated by volume-averaged pressure, while the effect of the wave processes on solid acceleration can be neglected. The validity of using this assumption for estimating the parameters of the shock pulse of solid acceleration was validated in experiments.

The pressure p_0 established in the combustion chamber after HE detonation is considered in the present calculation model as the forcing pressure, i.e., the pressure acting on the frontal face of the loaded solid at the moment when the latter starts moving.

If brisant HEs are used in such facilities, the pressure p_0 is determined on the basis of experimental data [6–8]. The maximum pressure in the chamber is thereby assumed to be proportional to the ratio of the HE mass m_0 to the initial volume of the chamber W_0:

$$p_0 = \varphi_1 m_0/W_0 \tag{3}$$

(φ_1 is the proportionality coefficient determined in experiments and depending on the charge density ρ_L). The dependence $\varphi_1(\rho_L)$ can be presented as follows [7]:

$$\varphi_1 = (0.88 + 0.0045\rho_L) \cdot 10^6. \tag{4}$$

Calculations performed for a gas-dynamic former containing a combined charge with explosive initiation on the basis of Eqs. (3) and (4) show that the forcing pressure is lower than the pressure obtained in experiments in a gas-dynamic facility. To obtain calculated values of p_0 closer to experimental data, we use the power dependence

$$p_0 = A_P\Big(\frac{m_0}{W_0 - W_S}\Big)^{n_P}, \tag{5}$$

where A_P and n_P are the coefficient and the powder index determined experimentally and W_S is the volume occupied by the powder batches.

An analysis of data obtained in experiments in a gas-dynamic facility shows that the coefficient A_P depends on HE density and pressure of detonation products and is described by the formula

$$A_P = p_{D0}/\rho_{D0}^{n_P}. \tag{6}$$

The action of detonation products on the combined charge leads to its ignition. Allowance for the specific features of ignition of the combined charge in the case of its explosive initiation unduly complicated the problem and increases the calculation errors; hence, the kinetics of the ignition process is ignored in the calculation model proposed.

The use of Eq. (5) (with allowance for the volume occupied by the powder batches), which differs from Eq. (3) by the presence of the power index n_P, allows us to take into account the influence of ignition of the combined powder charge on the forcing pressure. The effectiveness of using Eqs. (5) and (6) was validated by results of numerous numerical experiments consistent with experimental data.

The second stage includes the processes of combustion of the combined charge and motion of the loaded solid.

In our calculation model of combined charge combustion, we use the following basic assumptions typical for thermodynamic models: the pressure in the combustion chamber is uniform; the velocities and other characteristics of powder combustion are averaged over the charge; the force and covolume of combustion products of each powder in the combined charge are constant. The assumptions that refer to the motion of the loaded solid are commonly known [9].

To take into account the combustion of the combined charge consisting of two types of powder batches, we re-formulate the classical system of equations of internal ballistics. Analytical dependences that describe the processes of powder combustion and formation of powder gases are not known in advance. The amount of gases being formed is found in the calculation model by the formula

$$\psi_i = \varkappa_i z_i (1 + \lambda_i z_i + \mu_i z_i^2), \tag{7}$$

where the subscripts $i = 1$ and 2 refer to the first and second batches of powder, respectively, $\varkappa_i$, λ_i, and μ_i are the characteristics of the powder shape, $z_i = e_i/e_{1i}$ is the relative thickness of the burned powder layer, e_i is the thickness of the burned powder layer, and e_{1i} is the initial thickness of the powder layer. The variation of the burning rate of the combined charge is defined by a system of equations with the use of power and linear functions:

$$\frac{de_i}{dt} = A_{i1} p^{\nu_i} \quad \text{at} \quad p \leqslant p_{Ji}; \tag{8}$$

$$\frac{de_i}{dt} = A_{i2} p \quad \text{at} \quad p > p_{Ji}. \tag{9}$$

Here A_{i1} and A_{i2} are the coefficients depending on the powder type and test conditions, p is the pressure in the combustion chamber of the gas-dynamic former, ν_i is the power index depending on the powder type and test conditions, and p_{Ji} is the pressure corresponding to the transition from the power function of the burning rate to the linear function and depending on the powder type.

Equations (8) and (9) yield an isentropic dependence of the burning rate of the combined charge on the pressure in the combustion chamber, which allows the coefficients A_{i1} and A_{i2} to be chosen so that the calculation results agree with experimentally obtained pressures with sufficient accuracy.

If black powder is used in the combined charge, the rate of the gas income can be calculated by the empirical dependence [10]

$$\frac{d\psi_i}{dt} = \alpha_{bi}(1 - \psi_i) p \exp\,[\beta_{bi}(T_0 - 288)],$$

where t is the time, α_{bi} and β_{bi} are the temperature coefficients of the powder burning rate, and T_0 is the initial temperature of powder.

As the durations of powder combustion in the powder batches of the combined charge are different, the second stage includes two phases of combustion: 1) simultaneous combustion of two powder batches, which is finalized when the condition $\psi_2 = 1$ is satisfied (it should be taken into account that the powder of the second batch burns out faster); 2) combustion of one powder batch, which is finalized when the condition $\psi_1 = 1$ is satisfied.

Using the Rezal equation [9] and the Dalton law for the sum of partial pressures, we determine the pressure of powder gases in the case of combustion of the combined charge:

$$p = \frac{K_2}{s(l_\psi + l)}\Big(f_1\omega_1\psi_1 + f_2\omega_2\psi_2 - \frac{1}{2}\,\frac{\theta_1\omega_1 + \theta_2\omega_2}{\omega_1 + \omega_2}\,\varphi m v^2 + p_0 l_{\psi 0} s\Big). \tag{10}$$

Here K_2 is the coefficient of additional energy losses, depending on the structure of the gas-dynamic former and on test conditions, f_i and ω_i are the force and weight of powder (see [9, pp. 116, 314–319]), θ_i is the proportionality coefficient, φ is the coefficient of mass fictitiousness, m is the mass of the loaded solid, l is the distance covered by the loaded solid, $v = dl/dt$ is the velocity of motion of the loaded solid, $l_{\psi 0}$ is the initial reduced length of the free volume of the combustion chamber, s is the cross-sectional area of the combustion chamber, and l_ψ is the reduced length of the free volume of the combustion chamber.

Taking into account that there are two batches of powder in the powder charge, we obtain the following expressions for the reduced length l_ψ and the coefficient φ:

$$l_\psi = \frac{1}{s}\Big(W_0 - \frac{\omega_1}{\delta_1}\,(1 - \psi_1) - \alpha_1\omega_1\psi_1 - \frac{\omega_2}{\delta_2}\,(1 - \psi_2) - \alpha_2\omega_2\psi_2\Big); \tag{11}$$

$$\varphi = K + \frac{\omega_1 + \omega_2}{3q}\,\Big(1 - \frac{l_0^3}{(l_0 + l_E)^3}\Big). \tag{12}$$

Here δ_i is the powder density, α_i is the covolume of powder gases, K is the coefficient depending on the structure of the combustion chamber and on test conditions [9], l_0 is the reduced length of the combustion chamber, l_E is the length of the gas-dynamic former, and q is the weight of the loaded solid.

Translational motion of the loaded solid is described by the equation

$$\frac{dv}{dt} = \frac{ps}{\varphi m}. \tag{13}$$

The generalized conditions of the end of the second stage, which is finalized when the entire combined powder charge burns out, are the relations $\psi_1 = 1$ and $\psi_2 = 1$.

The third stage includes adiabatic expansion of the gases formed. The heat loss can be neglected, because the time of motion of the loaded solid in the gas-dynamic former is extremely short. As the combustion of the combined charge forms a certain mixture of gases, we can write the relation for the pressure in the combustion chamber as

$$p = K_2 p_B\Big(\frac{l_1 + l_B}{l_1 + l}\Big)^{1 + (\theta_1\omega_1 + \theta_2\omega_2)/(\omega_1 + \omega_2)}, \tag{14}$$

where p_B and l_B are the pressure and displacement of the loaded solid at the moment when powder combustion ceases, and l_1 is the value of the function l_ψ at the end of the second stage.

Conditions at the end of the second stage are the initial conditions for the third stage, which is finalized when the loaded solid leaves the gas-dynamic former, i.e., at $l = l_E$.

As systems (7)–(13) and (13), (14) are nonlinear, the basic problem of internal ballistics was solved numerically by the technique described above.

Calculation Results and Comparison with Experimental Data. Using the above-described technique, we studied the internal ballistics of a barrel-type acceleration test facility with a combined charge with explosive initiation. The loading combined charge consisted of pyroxylin and black powder batches with masses m_1 and m_2, respectively, and an initiating batch of a condensed HE with a mass m_0.

The results calculated for tests with different charge conditions are summarized in Table 1. It is seen that the difference of the maximum accelerations $a_{\max}$ of the loaded solid determined with identical values of the coefficients A_{i1} and A_{i2} in Eqs. (8) and (9) from experimental values is within the measurement error. This agreement confirms the validity of the proposed model of the process and the technique for determining the coefficients of the physical laws of combustion of the combined powder charge, which take into account the real processes that occur in the facility considered.

Figure 2 shows the results of numerical modeling of test No. 3 (see Table 1). An analysis of the calculated and experimental dependences $p(t)$ allows us to obtain information about the processes in experimental facilities and to evaluate the calculation accuracy. It is seen in Fig. 2 that the calculated results and experimental data are in good agreement.

TABLE 1

Dimensionless Maximum Accelerations of the Loaded Solid in Experiments with Different Charge Conditions

Test number	Charge conditions				$a_{\max}/a_n$	
	m_1, kg	m_2, kg	m_0, kg	l_0, m	Calculation	Experiment
1	4.5	0.25	0.034	0.075	22.3	20.8
2	6.0	0.25	0.033	0.075	34.9	32.0
3	7.2	0.47	0.090	0.075	70.7	70.5
4	5.5	0.25	0.033	0.080	27.7	29.1
5	8.0	0.25	0.030	0.080	56.6	56.0
6	6.0	0.25	0.033	0.080	31.9	31.0
7	8.6	0.25	0.030	0.077	70.5	68.0

Note. a_n is the level of acceleration used for normalization.

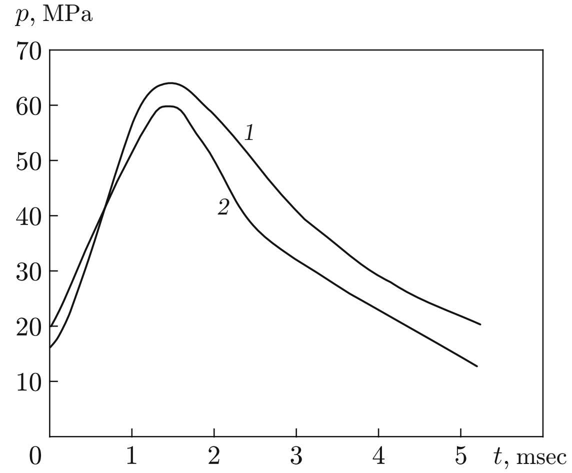

Fig. 2. Gas pressure versus time: calculated results (1) and experimental data (2).

Characteristic Dependences of Shock-Pulse Parameters. The present study was aimed at obtaining the dependences of the parameters of shock pulses on the parameters of the gas-dynamic former with a combined charge with explosive initiation (Figs. 3 and 4). It should be noted that the curves of the loaded solid acceleration as functions of the charge conditions are similar to the curves of pressure versus the charge conditions (see Fig. 3).

Effect of the Pyroxylin Powder Mass. A change in the pyroxylin powder mass m_1 exerts the most significant influence on the maximum pressure in the chamber and on the acceleration of the loaded solid. If the pyroxylin powder mass is substantially increased, the charge density of the combustion chamber increased, which affects the processes of powder-charge combustion: the burning rates of black and pyroxylin powders also increase.

Effect of the Black Powder Mass. An increase in the black powder mass m_2 enhances the burning rate of pyroxylin powder; moreover, an increase in the maximum pressure and maximum acceleration of the loaded solid is observed, while the duration of the leading front of the loading pulse decreases.

Effect of the HE Mass. An increase in the HE mass m_0 leads to an increase in the initial pressure in the combustion chamber; for this reason, the powder-charge combustion processes are intensified, and the maximum pressure in the combustion chamber increases. As a result, the duration of the leading front of the loading pulse decreases, and its maximum value, vice versa, increases.

Effect of the Initial Length of the Combustion Chamber of the Gas-Dynamic Former. A decrease in the initial length of the combustion chamber l_0 leads to a decrease in the initial volume of the chamber. This fact exerts a significant effect on all processes after powder-charge initiation: the initial pressure in the combustion chamber and the powder-charge combustion intensity increase, the maximum pressure in the chamber and the maximum acceleration of the loaded solid also increase, and the duration of the leading front of the loading pulse decreases.

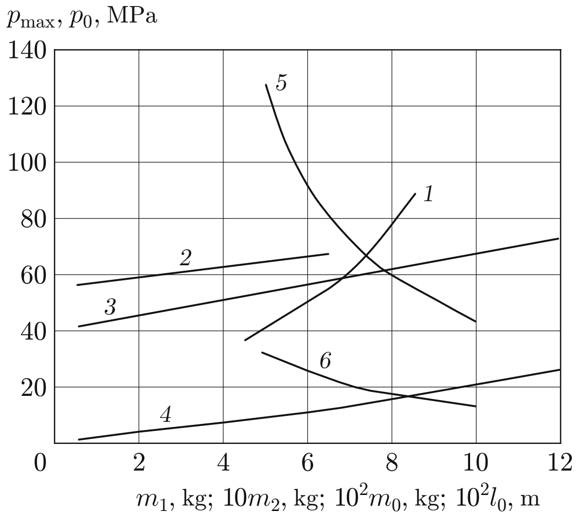

Fig. 3

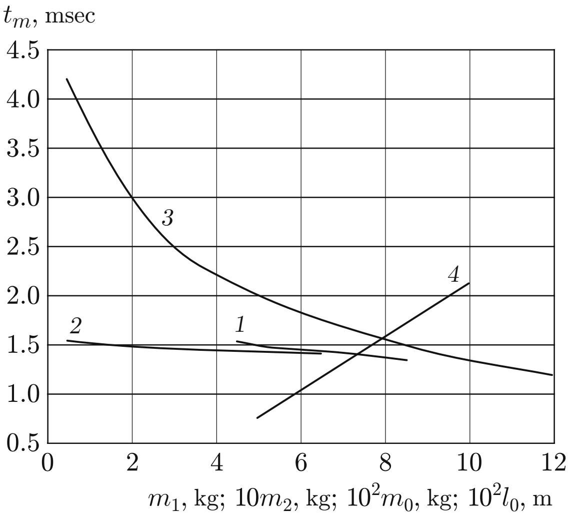

Fig. 4

Fig. 3. Initial and maximum pressures versus the charge conditions: $p_{\max}(m_1)$ (1), $p_{\max}(m_2)$ (2), $p_{\max}(m_0)$ (3), $p_0(m_0)$ (4), $p_{\max}(l_0)$ (5), and $p_0(l_0)$ (6).

Fig. 4. Duration of the leading front of the loading pulse versus the charge conditions: $t_m(m_1)$ (1), $t_m(m_2)$ (2), $t_m(m_0)$ (3), and $t_m(l_0)$ (4).

Conclusions. A technique is developed for calculating the parameters of long-term shock loads generated by a gas-dynamic former containing a combined charge with explosive initiation. This technique involves analytical dependences that describe the processes of combustion of the combined charge and that were derived with the use of the Rezal equation and Dalton law. Semi-empirical dependences for determining the forcing pressure in the case of explosive initiation are obtained. The effectiveness of using the proposed laws of combined charge combustion is validated by experiments.

Dependences obtained in the present calculation study of the influence of the charge conditions and the size of the combustion chamber of the gas-dynamic former containing the combined charge with explosive initiation allow prediction and correction of parameters of long-term loading of massive objects.

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