ACCELERATION OF RIGID BODIES BY COHERENT JETS

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UDC 532.52

The jetting effect, which is an energy-concentrating process, is of considerable interest to physicists. One example is the formation of a coherent jet in connection with the detonation of a high-explosive (HE) charge with a metal-lined cavity. Using the fundamental relations of the hydrodynamic theory of jetting [1, 2] in the planar case (for a wedge-shaped cavity), we obtain

$$E_j/E_l = (1 + \cos\alpha)/2,\ m_j/m_l = (1 - \cos\alpha)/2,$$

where E_j, m_j and E_l, m_l are the kinetic energies and mass per unit length of the jet and liner, respectively, and 2α is the wedge vertex angle.

It follows from these relations that the fraction of energy transported by the coherent jet is close to unity for small impact angles, while the mass of the jet is exceedingly small. As a general rule, of course, the compressibility factor prevents the formation of a jet for small impact angles. However, experiments have shown that for impact angles such that solid coherent jets are formed their specific kinetic energy can exceed the specific energy of the HE by an order of magnitude. The main mass of the liner, on the other hand, is transformed into the low-velocity part of the flow or the so-called "slug." However, Titov [3] directs our attention to the possible existence of an "inverse" jetting regime, where the mass transmitted into the coherent jet is greater than the mass of the slug. This regime is possible for wedge or conical liners with a sufficiently large vertex angle. But his example of "inverse" jetting is not unique. A similar pattern emerges in the collapse of a hemispherical cavity. In this situation, at least in the early stages of the process, it is impossible to segregate the flow into a slug and a jet. Collapse of the liner is followed by the formation of a slightly conical column with a blunt vertex, the velocity of which decreases monotonically from the vertex to the base. For example, in the collapse of a Duralumin hemisphere with an outside diameter of 40 mm and thickness of 2 mm lining a hemispherical cavity in a 50/50 TNT-H (H = Hexogen) charge with a diameter of 50 mm and height of 36 mm, a body is formed with a configuration resembling a truncated cone. At a time of 22 μsec after detonation of the charge, it has a length of 48 mm, a base diameter of 15 mm, and a diameter at the vertex of 5 mm (an x-ray photograph is shown in Fig. 1; the direction of motion is indicated by an arrow). From the base to the vertex there is a void in the interior of the cone, extending to a depth of 17 mm and having a diameter of 4 or 5 mm. After another 4 μsec the length of this cone has grown to 65 mm, while the base and vertex have practically the same size (Fig. 2). At this time the velocity of the vertex is about 4.8 km/sec, the velocity at a distance of 35 mm from it is 3.7 km/sec (at the termination of the void), and the velocity of the base is 1.2 km/sec. This metal fragment at the head of the jet with a length of ~38 mm ($d_1 \approx 5$) mm, $d_2 \approx 10$ mm) and a mass of ~4.3 g has a kinetic energy of about 38 kJ (ε = 2.1 kcal/g). The same specific energy of the matter in the jet is attained in the "inverse" jetting regime.

The process of energy concentration can be continued by utilizing the coherent jet in a device such as a light-gas gun as a piston to compress the working gas for the acceleration of rigid bodies.

We consider the motion in a pipe of two pistons (Fig. 3) with masses M and m, separated by a gas layer with an initial pressure p_0 and adiabatic exponent γ. At the initial time t = 0 let the piston of mass M have velocity v_j and be situated at a distance x_0 from the stationary piston. Assuming that the compression of the gas is adiabatic and neglecting its mass, we write the equations of motion of the pistons:

$$m\frac{d^2X_p}{dt^2} = p_0 S x_0^\gamma (X_p - X_j)^{-\gamma},\quad M\frac{d^2X_j}{dt^2} = -p_0 S x_0^\gamma (X_p - X_j)^{-\gamma}, \tag{1}$$

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 5, pp. 145-149, September-October, 1980. Original article submitted April 7, 1980.

 0021-8944/80/2105-0696$07.50

where S is the cross section of the pipe, X_p is the path of the accelerated projectile (piston m), and X_j is the path of the coherent jet (piston M).

The process of acceleration of the projectile by the coherent jet in this device occurs in two distinct phases: 1) compression of the gas in time 0 to t_*; 2) expansion of the gas compressed between the pistons during time $t > t_*$ (Fig. 3). The jet in this case is continuously decelerated, while the projectile accelerates. The transition from the phase of compression of the working gas to the expansion phase is characterized by the condition of equality of the jet and projectile velocities:

$$\left.\frac{dX_p}{dt}\right|_{t=t_*} = \left.\frac{dX_j}{dt}\right|_{t=t_*}. \tag{2}$$

Solving Eqs. (1) simultaneously with the obvious initial conditions, we obtain for the compression phase $t \leqslant t_*$

$$\begin{gathered}\frac{dX_p}{dt} = \frac{M}{m+M}\left\{v_j - \sqrt{v_j^2 + \frac{2(m+M)}{mM}\frac{p_0 x_0 S}{(\gamma-1)}\left[1-\left(\frac{x_0}{X_p - X_j}\right)^{\gamma-1}\right]}\right\} = \frac{\mu}{m}\left\{v_j - \sqrt{v_j^2 + \frac{2\varepsilon_0}{\mu}\left[1-\left(\frac{x_0}{X_p - X_j}\right)^{\gamma-1}\right]}\right\},\\ \frac{dX_j}{dt} = \frac{M}{m+M}\left\{v_j + \frac{m}{M}\sqrt{v_j^2 + \frac{2(m+M)}{mM}\frac{p_0 x_0 S}{(\gamma-1)}\left[1-\left(\frac{x_0}{X_p - X_j}\right)^{\gamma-1}\right]}\right\}\\ = \frac{\mu}{m}\left\{v_j + \frac{m}{M}\sqrt{v_j^2 + \frac{2\varepsilon_0}{\mu}\left[1-\left(\frac{x_0}{X_p - X_j}\right)^{\gamma-1}\right]}\right\},\end{gathered} \tag{3}$$

where $\varepsilon_0 = p_0 x_0 S/(\gamma - 1)$, $\mu = mM/(m + M)$.

Using relations (3) and (2), we find the distance of closest approach of the pistons in the compression phase and the pressure of the compressed gas:

$$y_* = (X_p - X_j)_{t=t_*} = x_0\left[1 + \frac{(\gamma-1)\,mM}{p_0 S x_0 (m+M)} v_j^2\right]^{\frac{1}{1-\gamma}} = x_0\left(1 + \frac{E}{\varepsilon_0}\right)^{\frac{1}{1-\gamma}}; \tag{4}$$

$$p_* = p_0\left(\frac{x_0}{y_*}\right)^{\gamma} = p_0\left(1 + \frac{E}{\varepsilon_0}\right)^{\frac{\gamma}{\gamma-1}}, \tag{5}$$

where $E = \mu v_d^2/2$.

Finally, we obtain the velocity of the projectile from relations (1) with the initial conditions (2) and (4):

$$\begin{gathered}\frac{dX_p}{dt} = \frac{M}{m+M}\left\{v_j + \sqrt{\frac{2(m+M)}{mM}\frac{p_0 x_0 S}{(\gamma-1)}\left(y_*^{1-\gamma} - y^{1-\gamma}\right)}\right\},\\ y = X_p - X_j.\end{gathered} \tag{6}$$

The maximum velocity that the projectile can acquire in this accelerating device is deduced from relation (6) as $y \to \infty$:

$$v_{p\infty} = \frac{M}{m+M}\left\{v_j + \sqrt{v_j^2 + \frac{2p_0 x_0 S}{\mu(\gamma-1)}}\right\}. \tag{7}$$

This estimate shows that for a sufficient difference between the masses of the coherent jet and the projectile driven by it, $M > m$, the velocity of the projectile can exceed that of the jet.

To test this principle for the acceleration of rigid bodies we have conducted experiments with the device shown in Fig. 4. The above-described shaped charge 1 with a hemispherical liner is set up at a certain distance from the steel driver plate 2 at the entrance to the compression chamber 3, coaxially with it. The initial gas pressure in the compression chamber is varied from one to several tens of atmospheres. The steel projectile 4 has a bead with a thickness of about 0.5 mm. The projectile has a length of 4 mm, diameter of 3 mm, and a mass that varies from 0.25 to 0.3 g. Both the compression chamber and the barrel 5 are fabricated by drilling holes in a thick (diameter of 40-50 mm) steel cylinder. The length of the barrel does not exceed 60 mm, i.e., is a maximum of 20 diameters. The projectile velocity recorded in the experiments was about 3 km/sec or slightly higher. The velocity is determined from the volume of the crater in a steel target. Use is made of the relationship between the ratio of the crater volume of the mass of the projectile and the projectile velocity squared for steel barriers at impact velocities up to 5.5 km/sec [4]. In several tests the velocity, shape, and integrity of the projectile were determined by pulsed

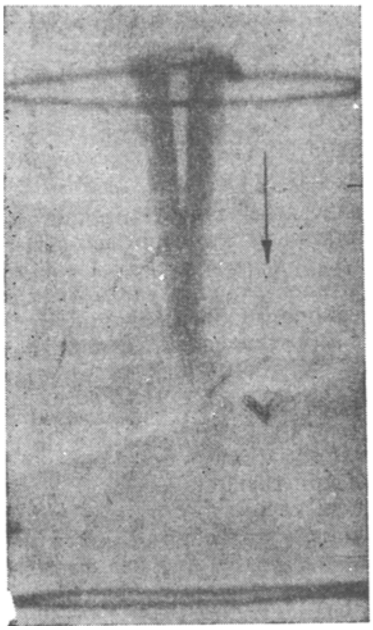

Fig. 1

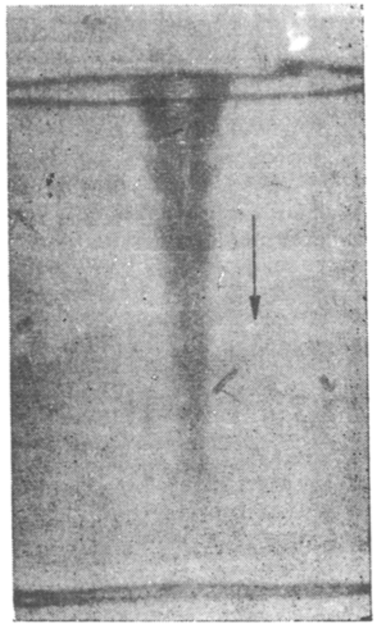

Fig. 2

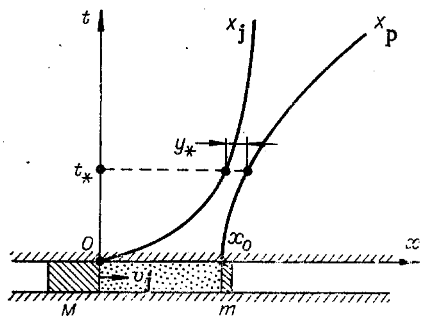

Fig. 3

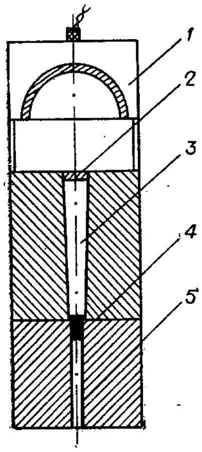

Fig. 4

x-ray photography. It was found to be equal to 2.3-2.5 km/sec, which is also lower than the estimated velocity obtained for the model of adiabatic compression of the gas (7). It follows from relation (7) that for $m \ll M$ and for the given experimental situation $v_j^2 \gg [2p_0x_0S/\mu(\gamma - 1)]$, the projectile velocity can attain a value $v_p \approx 2v_j$. However, the experimentally attained velocity of the projectile is even lower than the initial jet velocity v_j. The main reason for this result is clearly the insufficient length of the barrel. Thus, for a projectile of mass 0.3 g and diameter of 3 mm an average pressure of $\sim 3 \cdot 10^4$ atm is required, which over a path of 60 mm imparts a velocity of 3 km/sec to the projectile. Substituting the value found for the pressure into expressions (5) and (4), we find that the projectile leaves the barrel still in the compression phase.

In the case of actual light-gas guns, the barrel channel has a length of the order of 300 diameters, with a minimum of 200 diameters [5].

Chou et al. [6] give improved criteria for jet formation in the explosion of shaped charges with conical and wedge liners, along with criteria pertinent to the quality of the jet, i.e., solid coherent or dispersed incoherent jets are formed under definite impact conditions. For the formation of solid coherent jets it is necessary that the velocity of the impinging jets be smaller than the sound velocity in the material of the jet in a coordinate system where the oblique impact pattern of the plates is stationary. In the laboratory system, where the velocity of the impacting plates U is directed along the normal to their surfaces, this condition is written in the form

$$\tan\alpha = U/c_0.$$

Making use of the fundamental relation of the hydrodynamic theory of jetting, relating the coherent jet velocity to the impact parameters, we obtain

$$v_j = \frac{U}{\tan\alpha}\left(1 + \sqrt{1+\tan^2\alpha}\right) = c_0 + \sqrt{c_0^2 + U^2}.$$

Thus, the velocity of a solid coherent jet is more than twice the sound velocity of the jet material. In principle, therefore, a gun that uses a coherent jet as a piston is capable of accelerating firing pins to more than four times the sound velocity in the jet material under standard conditions.

It is essential to note that this hybrid of a light-gas gun and explosive accelerators consolidates the advantages of both driving techniques. In contrast with the gas-jetting shaped charges used to accelerate rigid bodies [7], the weight of the HE charge in the coherent-jet gun is an order of magnitude smaller.

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DISTRIBUTION OF TIMES TO FRACTURE UNDER RANDOM LOADING

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UDC 539.2:539.4

Predicting the times for a structural element to attain a certain hazardous state (such as fracture) is important both from the standpoint of new structural designs and from the standpoint of monitoring the instantaneous state of structures in service. In the latter case the prediction results are used to solve the problem of the advisability or safety of continued service of the particular structure, necessary preventive measures, etc. From the vantage point of mechanics, time-to-fracture prediction poses a complex problem, which includes describing the defect accumulation process and the development of macroscopic cracks in the structure, as well as estimating the loss of bearing capacity of a defective structure and its life expectancy under the conditions of loading, which is generally of a random nature and is specified by certain a priori distribution functions. In this article we develop a defect-accumulation model for structural elements, which is conditionally separable into two stages: 1) incubation; 2) propagation of arterial cracks. In this connection a relationship is postulated between a phenomenological measure of the defective state, which depends on the loading process, and the expectation value of the number of macroscopic cracks nucleating in a certain reference volume. Another significant aspect of the approach developed here is the application of the central limit theorem for asymptotic estimation of the distribution functions of nonstationary random processes to characterize the accumulation of defects in the structural element and its residual bearing capacity.

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 5, pp. 149-158, September-October, 1980. Original article submitted March 26, 1980.

0021-8944/80/2105-0699$07.50