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TRANSMISSION OF A SHOCK LOAD BY BULK MEDIA

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The sliding of an air-borne shock wave (ASW) over the surface of a dust layer was studied in [1]. It was shown that the character of the change in pressure on the base in the presence of the layer differs significantly from the propagation of an ASW along a pure surface. In view of the practical importance of this phenomenon, here we conduct a detailed experimental investigation of the parameters of a compression wave acting on a rigid wall covered by layers of different bulk materials during shock loading. We examine both cases of normal incidence of the ASW on the layer and propagation of the ASW along the surface of the layer.

1. Normal Incidence of an ASW on the Layer. Experiments were performed on a vertical shock tube with an inside diameter of 50 mm and a length of 3 m. A diagram of the experimental unit is shown in Fig. 1a. The high-pressure chamber (HPC) 1, with a length of 1.5 m, was separated from the low-pressure chamber (LPC) 2 by a membrane 3. The LPC was equipped with piezoelectric pressure sensors 4-6. Layers of bulk materials were placed on the end of the LPC with a built-in sensor 6. Table 1 shows the characteristics of the test substances (ρ_p, ρ_n, φ, and d are respectively the density of the material of the particles, the bulk density and volume concentration of the solid phase, and the mean size of the particles). We used sized screens to scatter the particles. The piezoelectric sensors were of the LKh type. The diameter of the sensitive surface was 1 cm, which was much greater than d. The sensor 5 was placed near the surface of the layer, while the sensor 4 served as the triggering sensor. The HPC contained nitrogen or helium, while the LPC contained air at a pressure $p_0 = 0.1$ MPa. The signals from the sensors were recorded on S8-17 oscillographs. The excess pressure on the front of the incident SW's $\Delta p = p_1 - p_0$ (p_1 is the pressure behind the shock front) was varied within the range 0.05-1 MPa.

The experiments showed that in shock loading, the character of pressure on the end covered by the bulk material differs from the familiar case of the interaction of an ASW with a rigid wall. After reflection of the incident ASW from the free surface of the bulk medium, a pressure disturbance arrives at the end underneath the layer. This disturbance characterizes the surge at the front of the shock wave and the subsequent decrease in pressure – with rapidly decaying oscillations – to the pressure associated with reflection of the wave on the surface of the layer p. The duration of the surge in pressure is proportional to the height of the layer, while its amplitude may be several times greater than the "steady" value of p. The latter value is slightly (by 10-20%) less than the pressure associated with reflection on a rigid wall.

In isolated cases, we attempted to explain the nature of the above phenomenon by obtaining measurements using the scheme in Fig. 1b. This scheme allowed us to distinguish the effects of the solid and gas phases on the character of the pressure record. Two sensors were located at the end of the shock tube. Sensor 1 was placed in direct contact with the particles of the bulk medium (i.e. as sensor 6). The sensitive surface of sensor 2 was covered by a perforated barrier to exclude contact with the particles but permit penetration of the gas. Tests showed that the presence of the barrier did not affect the character of the pressure record if it was positioned near the sensitive surface of the sensor.

Figure 2a and b shows the pressure record in the experiments conducted by the scheme in Fig. 1b, with a layer of substance 3 (see Table 1) having a height h = 20 mm. The time scale

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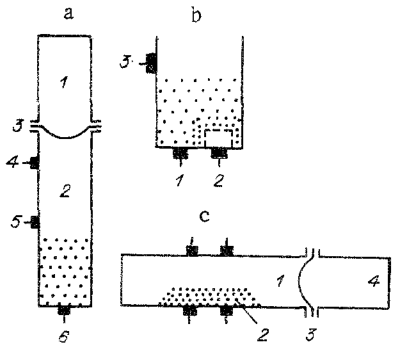

Fig. 1

TABLE 1

Serial number	Test substance	ρ_p, g/cm^3	ρ_n, g/cm^3	φ	d, mm
1	Plexiglas	1,18	0,34	0,29	0,01
2	Polystyrene 1	1,06	0,52	0,49	0,1
3	Polystyrene 2	1,06	0,50	0,48	0,2
4	Sand	2,45	1,78	0,73	0,3
5	Polyethylene	0,82	0,55	0,67	4,5

was 0.5 msec in the graduations of the horizontal scale for Fig. 2a and b and the pressure scale was 0.23 MPa in the division of the vertical scale for Fig. 2a and the upper beam in Fig. 2b. It was 0.3 MPa for the lower beam in Fig. 2b. Figure 2a shows the record of the reflection pressure on the surface of the sensor 3 (Fig. 1b). The excess pressure in the incident SW $\Delta p = 0.1$ MPa. The top beam in Fig. 2b is the record of pressure for sensor 1, while the bottom beam is the pressure record for sensor 2. It can be seen that the character of loading is quite different in each case. Then the sensitive surface of the sensor comes into contact with particles of the bulk medium, there is an appreciable pressure pulsation on the front. The amplitude of this pulsation is p_m. The pressure then decreases rapidly, with decaying oscillations, to the pressure on the surface of the layer p. In the absence of contact with the solid phase, the pressure on the end increases relatively slowly. This is evidently attributable to filtration of gas from the shock-compressed plug above the surface of the layer.

Despite the relative brevity of the pressure pulse (about 300 μsec for the experimental conditions in Fig. 2a and b), it may exert a mechanical effect in a number of cases. This was illustrated by the following control test. A membrane of copper foil 0.1 mm thick was secured to the end of the shock tube. An incident ASW with an excess pressure at the front of about 0.1 MPa did not rupture the membrane. A layer of substance 2 which was 20 mm high was placed on the membrane. In this case, a wave with the same parameters did rupture the membrane.

Let us analyze the dependence of the maximum excess pressure on the base p_m on the parameters of the layer of the bulk medium – the height of the layer h and the size and type of particles. We will characterize the increase in pressure through the maximum coefficient of the relative load δ_m. This coefficient is equal to the ratio of p_m to the excess pressure associated with reflection of the ASW on the surface of the layer: $\delta_m = p_m/p$. The top part of Fig. 3 shows the dependence of δ_m on the height of the layer for different bulk materials. The excess pressure in the incident SW was 0.1 MPa. The numbers of the curves correspond to the numbers of the substances in Table 1. It is evident that there is an "optimum" height h at which the load is maximal. The coefficient δ_m increases with a decrease in particle size. Comparison of curves 3 and 4 suggests that the parameters of the load depend directly on the material of the particles.

The initial state of the bulk medium before the test has a substantial effect on the load coefficient. It was found that δ_m decreases after preliminary compaction of the layer. Such compaction was done either mechanically or by repeated exposure to shock waves. For example, in an experiment with substance 1 with h = 20 mm, the volume fraction of the solid

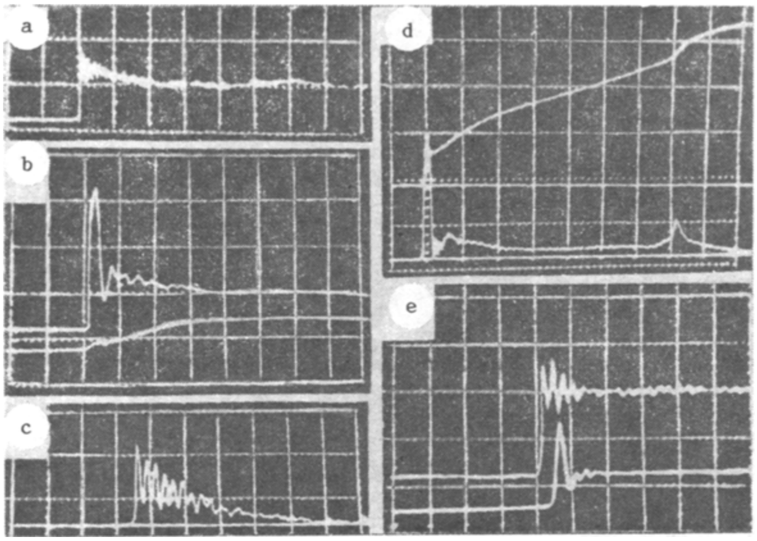

Fig. 2

phase in the mixture was increased from an initial value of 0.29 to 0.41 by mechanical compression. This increase caused the load coefficient δ_m to decrease by a factor of 2.5.

One of the parameters which determines the destructive force of a shock wave is the impulse of the compression phase. To establish the character of transformation of the impulse of the bulk medium, we conducted tests with an ASW of finite duration on a unit similar to that shown in Fig. 1a. The only difference was that the HPC was 1 cm long and was filled with helium. The pressure rupturing the membrane in the HPC was about 5 MPa. Given these parameters for the HPC, a wave of triangular profile with $\Delta p \approx 0.1$ MPa and a compression phase lasting 1.2-1.4 msec struck the end of the LPC. For greater convenience in analyzing the test results, we augmented the technique of directly calculating the area from the pressure oscillogram by using an electronic integrator for the signal from the end sensor. It was found for substances 4 and 5 (Table 1) that the maximum impulse transmitted by the base was 15-20% greater than the impulse transmitted in the absence of the bulk medium. A larger difference between impulses was seen for substances 1-3. Figure 2c and d shows typical records of pressure in a test with substance 3 at h = 20 mm. Figure 2c corresponds to the record of the signal from the sensor located near the surface of the layer and represents a reflected compression wave of triangular profile (the time scale was 0.2 msec for the horizontal scale graduation, on the pressure scale was 0.2 MPa for the vertical scale graduation). The lower beam in Fig. 2d corresponds to the pressure record of the end sensor, while the upper beam corresponds to the impulse record obtained by means of the integrator. Here, the time scale is 0.5 msec in the horizontal scale graduation, while the impulse scale (top beam) is 115 Pa·sec and the pressure scale (bottom beam) 0.3 MPa in the vertical scale graduation. It is evident that while there is almost no pressure on the surface of the layer, the end continues to be subjected to the action of a load. The impulse increases accordingly in this case and may appreciably exceed the impulse in the wave reflected from the surface of the layer. Microscopic examination of particles of Plexiglas and polystyrene showed that, in contrast to the sand and polyethylene granules, the surfaces of these particles were quite rough. During the interaction of such particles among each other and with the surface of the tube, substantial adhesive forces may develop. These forces may cause irreversible compression of the bulk medium and thus result in residual loading of the base.

2. Propagation of an ASW along the Surface of a Layer. In the general case, the interaction of an ASW from an external source with volumes partially filled with a bulk medium may occur with an arbitrary angle of incidence of the ASW on the layer. In connection with this, we studied the propagation of an SW along the surface of a layer. The experimental unit is illustrated in Fig. 1c. Layers of the test substance 2 of different heights were placed in the LPC 1 of a horizontal shock tube with a length of 2 m and a square cross section measuring 40 × 40 mm. The length of the layer was about 40 cm. The distance from the membrane 3 to the beginning of the layer was 45 cm. The HPC 4, 0.5 m long, contained nitrogen or helium. The LPC contained air at p_0 = 0.1 MPa. The pressure sensors were arranged in pairs — above

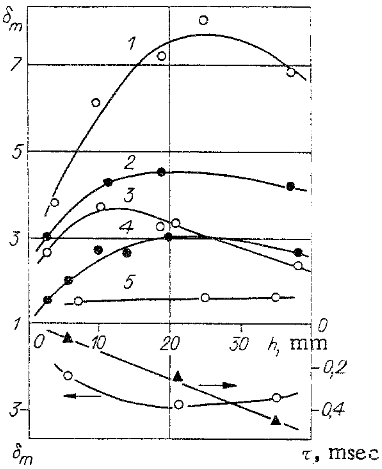

Fig. 3

and below the layer. This allowed us to fix the pressure in the gas and on the base at the same time. The distance between the sensors was 20 cm.

Figure 2e shows the pressure record in a test with a layer of sand having a height h = 6 mm. The time scale was 0.2 msec on the horizontal axis, while the pressure scale was 0.07 MPa for the top beam and 0.2 MPa for the bottom beam on the vertical axis. The top beam corresponds the pressure record in the gas, while the bottom beam corresponds to the record of the load on the wall under the layer in at the same location in the tube. The character of the change in pressure on the base is similar to the case of normal incidence of the ASW (compare with the top beam in Fig. 2b). One feature of the process is the fact that a disturbance reaching the base is delayed relative to the disturbance in the gas by the time τ, which is proportional to the height of the layer. The same result was obtained in [1]. We should note that τ also corresponds to the duration of the pressure jump. As in the case of normal incidence of an ASW on the layer, we introduce the coefficient δ_m, equal to the ratio of the maximum excess pressure on the substrate to the excess pressure on the wave front in the gas. The lower part of Fig. 3 shows the dependence of δ_m and τ on the height of the layer for sand. The excess pressure on the front of an ASW propagating above the layer Δp = 0.15-0.2 MPa. The dependence of the maximum coefficient of the relative load on the height of the layer is similar to that found for normal incidence of an ASW. It is reasonable to suggest that the mechanism of intensification of the shock load is the same in both cases.

3. Discussion of Results. Analysis of the data obtained shows that the shock loading of a surface covered by a layer loose material has the same features as the interaction of an ASW with a wall faced with a compressible porous material such as polyurethane foam with a moderate density of 30-50 kg/m^3 [2, 3]. The studies [4, 5] attempted to describe this phenomenon by using a model consisting of a porous compressible material by an equivalent gas with "equilibrium" parameters. Attempts to apply this approach to calculations for bulk media were unsuccessful for several reasons. It was shown in [6] that the use of "equilibrium" parameters to describe bulk media is valid only when the particle size is less than 20 μm. Also, it is not yet clear how it is possible to describe the dependence of the height of the layer on the basis of representations regarding an equivalent gas. We will examine a model of the phenomenon which is different from that used in [4, 5] and which is based on analysis of the motion of a bulk medium as an integral whole under the influence of a suddenly applied load.

As was shown above (Fig. 2b), the solid phase, consisting of the bulk medium makes the main contribution to the impulsive pressure on the front of the disturbance. In accordance with this, the essential nature of the phenomenon is explained as follows. As long as the layer of bulk material is under the pressure of the ASW, the individual particles are held in equilibrium by frictional forces. When the ASW is reflected from the interface between the gas and the bulk medium, the layer is instantaneously loaded by a gas piston with the excess pressure p. Under the influence of this pressure, the particles are displaced from their equilibrium positions are moved closer to each other. This requires relatively little pressure, and according to [7] it is true for substances such as sand, etc. During subsequent deformation, the resistance of the bulk medium increases in accordance with a law determined mainly by the elastic properties of the particle material.

Following the above scheme, we will take a column of mass m and of unit cross-sectional area, "cut out" in a layer of a bulk medium of the height h, and we will represent this column by an equivalent mechanical system with one degree of freedom consisting of a weight of mass m and a combination of an ideally plastic Coulomb element with a zero restoring force (section 1 in Fig. 4a) and an elastic element with an elasticity k and a deformation c (section 2). Let us examine the motion of the mass m under the influence of a suddenly applied constant load p. On section 1, the body acquires the velocity v_0. The subsequent motion of the weight is described by the equation

$$m\ddot{x} + c\dot{x} + kx = p \tag{3.1}$$

with the initial conditions

$$x(0) = 0,\ \dot{x}(0) = v_0. \tag{3.2}$$

With different relations between c and c_0 ($c_0 = 2(km)^{1/2}$ is the critical damping factor), it is possible to distinguish three classes of solutions of Eq. (3.1). The solution at $c < c_0$ is characteristic of the problem being examined. The load on a rigid base at an arbitrary moment of time $t > 0$ is $R = kx$. With allowance for (3.2), the solution of Eq. (3.1) for the coefficient $\delta = Rp^{-1}$ has the form

$$\delta = \exp(-\alpha t)[(\gamma - \alpha)\beta^{-1}\sin\beta t - \cos\beta t] + 1, \tag{3.3}$$

where $\alpha = c(2m)^{-1}$; $\beta = (km^{-1} - \alpha^2)^{1/2}$; $\gamma = kv_0p^{-1}$. The maximum value of the coefficient δ_m is reached at the moment of time $t_m = \beta^{-1}\mathrm{arctg}\{\beta\gamma[(\gamma - \alpha)\alpha - \beta^2]^{-1}\}$.

The main problem in using a "mechanical" model to describe the transmission of a shock load by a bulk medium consists of the definition of k, c, and v_0. Sample values of k, c, and v_0 were obtained on the basis of one of the experiments (sand, h = 14 mm, p = 0.32 MPa) and Eq. (3.3). The dashed line in Fig. 4b corresponds to this experiment, while the solid line corresponds to calculation of the relation $\delta = \delta(t)$ from (3.3) with $k = 3.3\cdot10^{10}$ N/m^3, $c = 0.2c_0$, and $v_0 = 0.6$ m/sec. Figure 5a and b shows the results of tests (dashed lines) and calculations (solid lines) for sand at p = 0.32 MPa and h = 20 and 5 mm, respectively. We performed the calculations with values of k, c, and v_0 found from the experiment with h = 14 mm. It can be seen that the calculated results are in good agreement with the test data and correctly describe the amplitude–frequency characteristics of the processes.

If we suppose that the mass m (Fig. 4a) is originally located at the center of mass of the initial column of the bulk medium, then the maximum velocity of the free boundary is equal to $2v_0$. Moreover, if we know the value of v_0, we can determine the distance over which the free boundary is moved before the beginning of elastic compression, i.e. we can determine the length of section 1 in Fig. 4a. We will use ϵ to denote the ratio of the length of section 1 to the height h of the initial column. The velocity v_0 is described by the expression $v_0 = (\varepsilon p\rho_n^{-1})^{1/2}$ and, as can be seen, is independent of the height of the layer. For the conditions of the experiment in Fig. 4b, the calculated value $\epsilon \approx 0.0025$, i.e. the displacement of the boundary of the layer of sand under the influence of pressure p = 0.32 MPa is no greater than 1%. Using an FK-1M high-speed camera, we arranged for visualization of the movement of the boundary of the bulk medium by the ASW for the case being discussed. We did not detect any changes in the position of the boundary.

It should be noted that the proposed "mechanical" model is based on very simple assumptions regarding the character of motion of the bulk medium under the influence of an ASW. In particular, the model is limited by the fact it correctly describes the dependence of δ_m on the height of the layer only for relatively small values of h (h ≈ 20-25 mm). To refine the governing relations, it will be necessary to more fully account for the specifics of the given medium. For example, in the case of large h, the capacity of the bulk medium to be compacted under its own weight should be taken into consideration. Here, the value of ϵ decreases, which in turn leads to a reduction in the coefficient δ_m.

It can be seen from Eq. (3.3) that the maximum value of the load coefficient decreases with an increase in pressure. However, as was shown in [8, 9], the loading of a porous layer by powerful shock waves (pressure above 10 GPa) may be associated with intensification of the effect of the wave due to the dynamic stiffness of the medium and its particular strength characteristics.

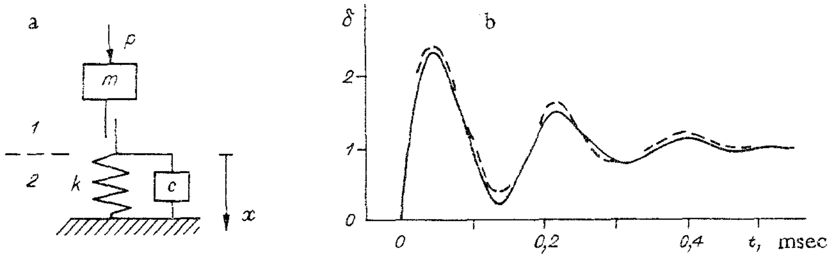

Fig. 4

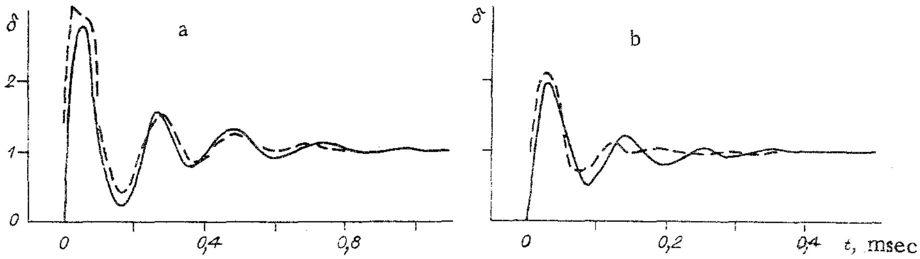

Fig. 5

Thus, there is a change in the character of loading in the action of a shock wave of moderate intensity on a rigid wall covered by a layer of loose material. Whereas the base is loaded quasistatically in the absence of a layer, the presence of a layer leads to the manifestation of an impulsive component. This component must be accounted for in a number of cases when calculating strength.

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