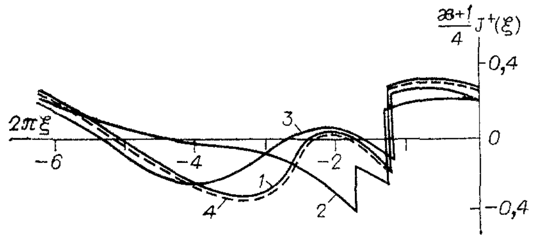

Fig. 3

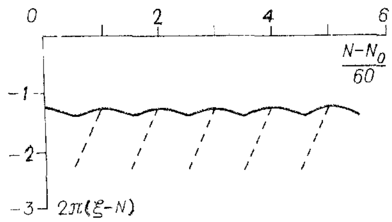

Fig. 4

A detailed analysis of the causes underlying the onset of the "long" modulation would be of independent interest and is not carried out in the present study.

The author is grateful to V. E. Fortov and S. I. Anisimov for their interest and encouragement.

LITERATURE CITED

1. J. J. Keller, "Nonlinear acoustic resonances in shock tubes with varying cross-sectional area," Z. Angew. Math. Phys., 28, No. 1, 107 (1977).
2. L. P. Gor'kov, "Nonlinear acoustic oscillations of a gas column in a closed tube," Inzh. Zh., 3, No. 2 (1963).
3. W. Chester, "Resonant oscillations in closed tubes," J. Fluid Mech., 18, Part 11 (1964).
4. A. N. Kraiko and A. L. Ni, "Nonlinear acoustics approximation in problems of gas oscillations in tubes," Prikl. Mat. Mekh., 44, No. 1 (1980).
5. A. L. Ni, "Nonlinear resonant oscillations of a gas in a tube under the action of a periodically varying pressure," Prikl. Mat. Mekh., 47, No. 4 (1983).
6. Sh. U. Galiev, N. A. Il'gamov and A. V. Sadykov, "Periodic shock waves in a gas," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 2 (1970).
7. M. P. Mortell and B. R. Seymour, "A finite-rate theory of quadratic resonance in a closed tube," J. Fluid Mech., 112, 411 (1981).

INTERACTION OF AIR SHOCK WAVES WITH POROUS COMPRESSIBLE MATERIALS

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UDC 532.593:532.529

Experimental studies of the process of interaction of air shock waves with porous compressible materials as a polyurethane foam and formed plastics have shown that such interaction has a number of unique features. Thus, it was shown in [1] that the maximum pressure on a wall beneath a layer of polyurethane foam can significantly exceed the value of pressure attained in normal reflection of a shock wave from a rigid wall. It was proposed in [1] that this effect could be explained by the solid phase being set in motion behind the entering shock wave. Intensification of an oblique shock wave upon incidence on a layer of porous compressible material was analyzed in [2]. Interaction of an air shock wave with a porous screen of polyurethane foam was studied in [3], where a significant reduction in peak pressure on the wall was recorded in the presence of an air gap between the wall and screen. The process observed in [3] was described theoretically in [4] by a computation technique first developed for gas dynamic flows with solid particles. Below we will present results of experimental studies of the interaction of a steady-state shock wave with a wall covered by layers of porous compressible material of various thicknesses.

The materials used for the experiment were PPU-3M-1 polyurethane foam and PKhV-1 foamed plastic; the densities of these materials are approximately the same (33 and 50 kg/m^3 respectively), while the rigidity of the foamed plastic is significantly higher. The loading for failure of this plastic is $(4-7)\cdot 10^5$ N/m^2 [5].

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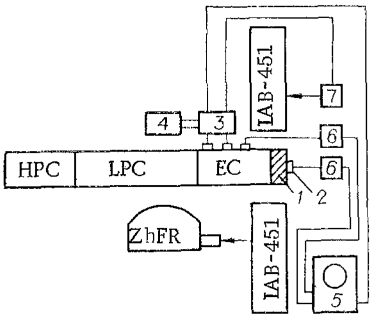

Fig. 1

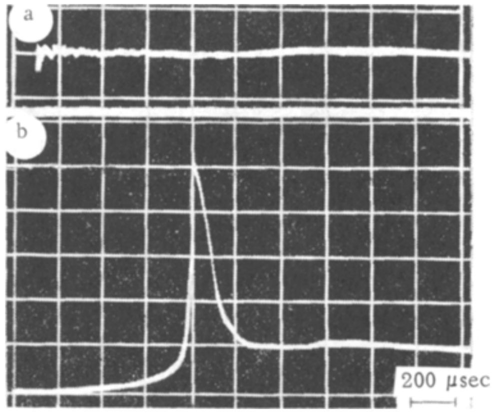

Fig. 2

We will note that the normal shock wave reflection pressure for a rigid wall was varied over the range $(1\text{-}15)\cdot 10^5$ Pa, which significantly exceeds the characteristic stress of $\sim 10^4$ N/m^2 required to deform polyurethane foam by 40% [5] and is comparable to the corresponding value for the foamed plastic. This allows clarification of the role of the acoustical pressure transfer mechanism through the rigid structure of the coating. The porosity coefficients of the materials studied were similar, 0.95-0.98.

A schematic diagram of the experimental arrangement is shown in Fig. 1. The studies were performed with a single diaphragm shock tube with 0.1×0.1 m square cross section. The lengths of the low pressure and experimental chambers (LPC, EC) with optical windows were 8 m, while the high pressure chamber (HPC) was 1.5 m long. Flat sheets 1 of various thickness of the materials to be studied were placed on the end face of the experimental chamber with pressure piezosensor, completely covering the channel section. The construction of the pressure piezosensors used 2 was described in [6]. Incident wave velocity measurements were performed with pressure piezosensors installed in the channel side walls, and special pulse shaper circuits 3 which trigger a ChZ3-33 digital frequency counter 4, and a Tektronix 453A oscilloscope 5. Voltage followers 6 based on an operational amplifier and pushpull transistor power amplifier were used to match the high output impedance of the piezosensors to the characteristic impedance of the connecting cables. The process of deformation of the porous material was visualized with the aid of a light pulse source 7, an IAB-451 shadow camera, and a ZhFR camera operating in the slit display mode. The working gas used was air at pressures of 10^3-10^5 Pa, with helium and nitrogen as driver gases. The incident wave Mach number was varied over the range 1.4-5.

Figure 2a, b shows oscillograms of the pressure recorded by the sensor on the endwall in the absence and presence of a 65-mm-thick polyurethane foam coating. The initial air pressure $p_0 = 10^3$ Pa, with incident wave Mach number $M_0 \simeq 4.5$. Analysis of these oscillograms indicates a significant transformation of the pressure wave as it passes through the obstacle. It is evident that in the presence of a layer of porous material the usual step-like pressure pulse is replaced by a pulse of complex form with maximum amplitude p_3 many times exceeding the amplitude of the sensor signal with no coating p_2.

Photographic displays of the compression process indicate the coincidence of the times corresponding to maximum compression of the layer and realization of the maximum pressure p_3. After the compression phase, an unloading phase commences and the pressure gradient approaches the value p_2 (if the charge of shock heated gas behind the incident wave is sufficiently extended).

Figure 3a shows superimposed oscillograms of the pressure obtained in experiments with polyurethane foam layers of various thickness. In the first series of experiments (Fig. 3a) the incident shock wave Mach number $M = 5$ at an initial air pressure $p_0 = 1.65\cdot 10^3$ Pa in the second series (Fig. 3b) $M = 2$ at $p_0 = 10^5$ Pa. In each series of experiments, with increase in layer thickness the maximum pulse amplitude initially increases, and at layer thicknesses $d \geqslant 80$ mm stabilizes at an approximately constant level, dependent on the type of material and initial conditions of the experiment. With increase in d the duration of the pressure pulse front increases somewhat, and it is possible to divide the front into two regions: In the first of these there is a slow increase in pressure; in the second there is a relatively

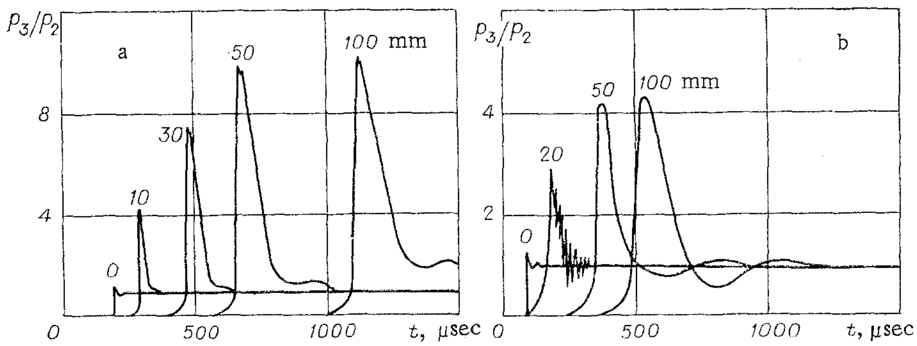

Fig. 3

abrupt increase in pressure, close to linear. The time at which the signal appears from the sensor covered by the material is noticeably delayed from the time at which an uncovered sensor produces a signal, with the delay increasing approximately in proportion to the coating thickness.

The maximum value of the pressure increase coefficient $R = p_3/p_2$ measured in the present experiments was ∿10 and occurred at $p_0 = 1.3 \cdot 10^3$ Pa, $M \simeq 5$. With decrease in p_0 to values lower than $(1-3) \cdot 10^2$ Pa at the same Mach number R decreases to 2-3. Pressure variation over wide limits at a Mach number of the order of five was impossible because of the particular construction tube. Figure 4 shows superimposed oscillograms of signals from pressure sensors coated with layers of foamed plastic of various thickness in the form of 30-mm-diameter disks at $p_0 = 1.65 \cdot 10^3$ Pa, M = 5. In this case, for all values of layer thickness d there is practically no delay in response, which indicates the relatively high speed of sound in the material $\geqslant$1 km/sec). The amplitude of the pressure on the wall is lower than for polyurethane (for similar initial conditions), but nevertheless is markedly greater than the signal for an uncovered sensor. Characteristic of this series of experiments is the oscillatory character of the pressure sensor signals, with the period of the oscillations being approximately proportional to the coating thickness. Figure 5 shows measurements of the time interval τ_m from the moment of arrival of the wave on the free surface of the material to the time at which maximum pressure is achieved on the wall as a function of layer thickness d. The time of arrival of the wave on the free surface of the material is determined from the coordinate of the free surface relative to the trigger sensor and the measured shock wave velocity near the free surface. Figure 5a shows the dependence of τ_m on d for polyurethane foam at $p_0 = 1.65 \cdot 10^3$ Pa, M = 5 (distribution 1) and $p_0 = 10^5$ Pa, M = 2 (distribution 2); results of τ_m measurements for the formed plastic at $p_0 = 1.65 \cdot 10^3$ Pa, M = 5 are shown in Fig. 5b. It is evident that the experimental point distributions are describable approximately by straight lines (the uncertainty in the velocity measurements was 5%), which indicates the constancy of the speed of propagation of intense perturbations within the material studied at specimen thicknesses up to 100-150 mm. The compression wave propagation velocity measured from the delay in the

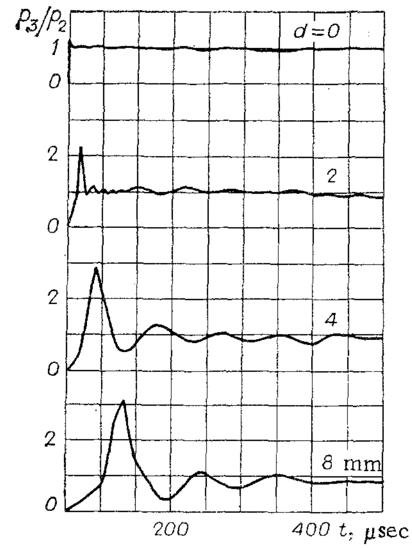

Fig. 4

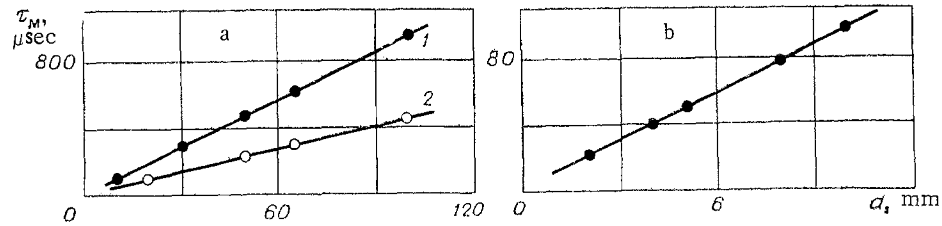

Fig. 5

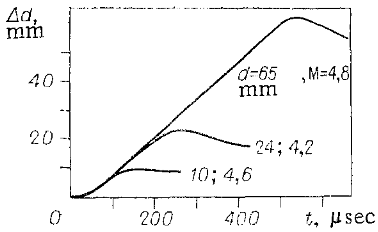

Fig. 6

pressure peak in polyurethane foam at $p_0 = 1.65\cdot10^3$ Pa ($M = 5$) and $p_0 = 10^5$ Pa ($M = 2$) was 110 and 215 m/sec, respectively, with 90 m/sec in the foamed plastic. However, we will note that the compression wave velocity in the polyurethane foam calculated from the delay in pressure response is significantly (1.2-1.5 times) higher than the values presented due to the presence of an extended "pedestal" in the pressure pulse. Generally speaking, the above statement regarding constancy of the compression wave propagation velocity in the materials studied is valid for sufficiently intense shock waves, since with reduction in incident wave intensity ($M \simeq 1.4$-1.6 at $p_0 = 10^5$ Pa) there is a marked reduction in pressure peak propagation velocity in the polyurethane to values of 100-200 m/sec, accompanied by a significant increase in duration of the front ($\tau_f \sim 300{=}400$ μsec) and decrease in the coefficient R to 2.5-3.

Figure 6 shows results of measurements of displacement of the polyurethane layer free surface as a function of time, obtained with slit photography ($p_0 = 1.65\cdot10^3$ Pa). As in the preceeding series of experiments, time was measured from the moment of incidence of the shock wave on the material. The measurements indicate the constancy of the velocity of displacement of the free surface over time (with the exception of the small initial segment), which for polyurethane is equal to ∿95 m/sec, and ∿75 m/sec for the foamed plastic. A polyurethane layer of initial thickness 65 mm was compressed by 3-5 mm, after which the unloading phase begins. No residual deformations were observed in polyurethane foam specimens subjected to shock wave action, although the structure of the material became more friable, and at low initial pressures the free surface was markedly darkened and partially carbonized. Analysis of the results confirms the conclusion of [1] that the mechanism responsible for the anamolously high pressure on a wall behind a layer of porous compressible material is the setting into motion of the solid phase behind the penetrating shock wave front. Direct calculation of the mechanical impulse transferred to the wall through coatings of various thickness indicates the absence of momentum loss. The mechanical moments of the air shock wave initially distributed through out the gas mass behind the front is partially localized in a relatively compact but quite dense mass of compressed porous material, the interaction of which with the wall leads to the appearance of a pressure peak. It can be proposed that in polyurethane, which is distinguished by high structural elasticity, the compression wave is a shock wave, while in the foamed plastic we have superposition of shock and acoustical waves (the latter propagating through the skeleton of the porous material). The division of the pressure pulses front into two segments referred to above can be qualitatively explained in the following manner. The permeable structure of the material leads to gas filtration ahead of the shock wave front, and thus to a slow increase in pressure. There then follows an abrupt increase in pressure, corresponding to the front of the shock wave formed in the porous medium, the thickness of which must be equal in order of magnitude to several material pore diameters.

At low initial pressure heads on the front of the shock wave formed in the polyurethane foam (which corresponds to the case of a low intensity air shock wave) the relative increase in density of the material in the discontinuity is not great, so that the effect of gas filtration from the charge into the unperturbed region ahead of the discontinuity becomes quite significant. Since the shock wave velocity in the medium D depends on the pressure head across the front, gas filtration encourages a progressive decrease in the quantity D and an increase in the duration of the front, as was noted in experiment. The pressure behind the shock wave front in the material was not measured, however, in view of the equality of pressures on both sides of the wave constant surface, which in the given case is the free surface of the material, the pressure in the wave may be equated to the normal reflection pressure p_{21} of an air shock wave from a free surface. Measurement of p_{21} over a wide range of initial parameters revealed that in the majority of cases the difference of p_{21} from p_2 is small ($p_{21}p_2^{-1} = 0.6$-0.9). This explains the relatively low velocity of the motion of the material free surface (in view of the significant initial density) as compared to the velocity of the reflected air shock wave.

Reduction in the coefficient R with decrease in initial pressure p_0 to $(1-3)\cdot 10^2$ Pa can be interpreted as a result of reduction in p_{21} to values close to the value of the porous material skeleton elastic force and intensification of the effect of gas filtration at low initial pressures.

LITERATURE CITED

1. B. E. Gel'fand, S. A. Gubin, et al., "Study of pressure wave propagation and reflection in a porous medium," Zh. Prikl. Mekh. Tekh. Fiz., No. 6 (1975).
2. N. A. Kostyukov, "Criterion for intensification of an oblique shock wave with a porous material layer," Fiz. Goreniya Vzryva, 16, No. 5 (1980).
3. B. E. Gel'fand, A. V. Gubanov, and E. I. Timofeev, "Interaction of air shock waves with a porous screen," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 4 (1983).
4. G. Rudinger, "Effect of the finite volume occupied by particles on the dynamics of a mixture of gas and particles," Raketn. Tekh. Kosmonavt., 3, No. 7 (1965).
5. V. M. Kataev, V. A. Popov, and B. I. Sazhin (eds.), Handbook of Plastics [in Russian], Khimiya, Moscow (1975).
6. L. G. Gvozdeva and Yu. V. Zhilin, "Piezoelectric pressure sensor," Prob. Tekh. Eksp., No. 5 (1978).

OBSERVATION OF A NEW TYPE OF SOLITARY WAVES IN A ONE-DIMENSIONAL GRANULAR MEDIUM

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A new type of solitary waves has been found by numerical calculations of a string of particles interacting according to Hertz's law [1]. The author's analysis of the differential equation representing the long-wave approximation for this system also demonstrated the existence of steady-state solitary waves under definite conditions, consistent with the numerical calculations of a discrete string of particles. The nonlinear equation obtained in [1] is more general than the Korteweg–de Vries (KdV) equation, which includes nonlinear and dispersion effects in the first approximation for a broad class of physical systems [2].

The investigated system of particles has the distinctive feature that the law of interaction between them does not contain a linear component, even in the zeroth approximation. The given interaction of a one-dimensional string or for simple cubic packing corresponds to an equation of state of the medium (for uniaxial static compression) in the form

$$\sigma = E\varepsilon^{3/2}/[3(1-\nu^2)],$$

where σ is the stress, ε is the strain, and E and ν are the Young's modulus and Poisson ratio of the material of the particles. It is seen at once that the long-wave sound velocity in a medium described by this equation of state is

$$c_0^2 = \frac{1}{\rho}\frac{\partial\sigma}{\partial\varepsilon} = \frac{E\varepsilon^{1/2}}{2\rho(1-\nu^2)}$$

(ρ is the density of the medium). For $\varepsilon = 0$, i.e., in a string of particles not subjected to an external force, $c_0 = 0$. Consequently, the standard wave equation cannot be used to describe perturbations of arbitrary amplitude in the case of zero initial strain.

It is reasonable to except on the basis of the customary approach in this case, e.g., in impact created by a piston with any velocity in such a system, that a shock wave will be generated in it if dissipative processes are present. However, the numerical calculations in [1] have shown that when a triangular pulse acts on one end of the given string of particles, the initial disturbance decays into a train of solitary pulses.

For comparison with experiment it is more convenient to consider the given system driven by the impact of a piston of finite mass. The parameter determined in the numerical analysis and then compared with experiment in this case was the reaction to a rigid wall, on which

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