THE EFFECT OF SEPARATION DUE TO CAVITATION ON THE EXTINCTION OF WAVES IN A LIQUID WITH POROUS INTERLAYERS

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We present the results from an experimental and theoretical investigation into the extinction of plane waves in water by interlayers of a strongly compressed material. We examine the loads on a fixed solid barrier in their dependence on the wave parameters and the characteristics of the interlayer, situated at the surface of a barrier. It is demonstrated that as the wave interacts with the interlayer cavitation causes separation of adjacent layers of water. These layers impact against the interlayer, one after the other, as well as through the interlayer and against the barrier, leading to a rise in pressure. The pressure acting on the barrier may exceed the value calculated without cavitation by more than an order of magnitude.

1. The process of extinguishing waves by means of a porous interlayer can be described by the time over which the interlayer acts as a shock absorber:

$$t^* = \alpha_0 h_0 \rho a / 2p_m, \tag{1.1}$$

where α_0 is the original volume of the porous space within the interlayer; h_0 is the thickness of the interlayer (the subscript 0 corresponds to t = 0); ρ represents the density of the water; a is the speed of sound through the water; p_m is the amplitude of the pressure in the incident wave.

For a wave in the shape of an infinite step and with an interlayer out of a void (α_0 = 1) t^* is equal to the time required to fill the volume of the interlayer with water moving at the velocity $u = 2p_m/\rho a$ of the free surface. The pressure against the barrier behind the interlayer is $p^* = 0$ when $t < t^*$ and $p^* = 2p_m$ when $t \geq t^*$. If the interlayer is formed by an ideal gas, then the jump in pressure, as demonstrated by calculation [1], against the barrier is dissipated, but the nature of the phenomenon is retained.

It follows from experiments [2-5] that water under dynamic loads withstands tensile stresses σ no greater than σ_r. When $\sigma \geq \sigma_r$ the water breaks apart. Values ranging from 0.4 to 4 mPa have been obtained in various studies for σ_r. This scattering of values is explained by the difference in the time over which the tensile stress is effective, by the purity of the liquid, and by the differences in the surfaces of the vessels containing the liquid. In shock tubes we observe the propagation of a pulse of tensile stress without attenuation where the amplitude of $\sigma_m \leq 0.5$ mPa [3], and on reflection of compression waves of amplitude $p_m \geq 0.8$ mPa we note separation from the free surface [2], as well as the formation of secondary compression waves as the cavitational cavity implodes [4]. According to [5], $\sigma_r = 4\beta/3R^* - p_v$ (β is the coefficient of surface tension for the water, R^* is the critical radius of the vapor-gas bubbles, and p_v is the pressure of the saturated vapor).

In [6, 7] we find a calculation based on [8] of the interaction of a shock wave with the free surface, with provision made for the development of cavitation in the rarefaction wave. It turns out that the time for the existence of large tensile stresses in the cavitation zone is no greater than 0.1 μsec.

2. The experiments were conducted on a thick-walled shock tube 3.3 m in length, with a rectangular internal lateral cross section of 20 × 60 mm. The tube is mounted vertically and filled with tap water. A piston closes off the top of the tube, and the stroke of this piston is limited by means of a special device. The wave is generated by the impact of a load falling on the piston. The parameters of the wave are varied by changing the height through which the load falls, by changing the mass of the load, as well as by altering the piston stroke. A face plate closes off the bottom of the tube. Piezoceramic pressure sen-

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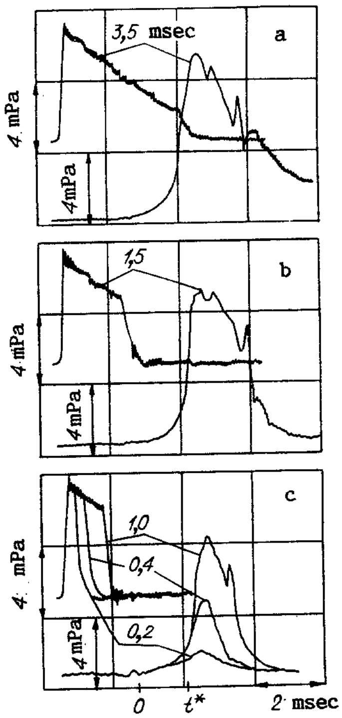

Fig. 1

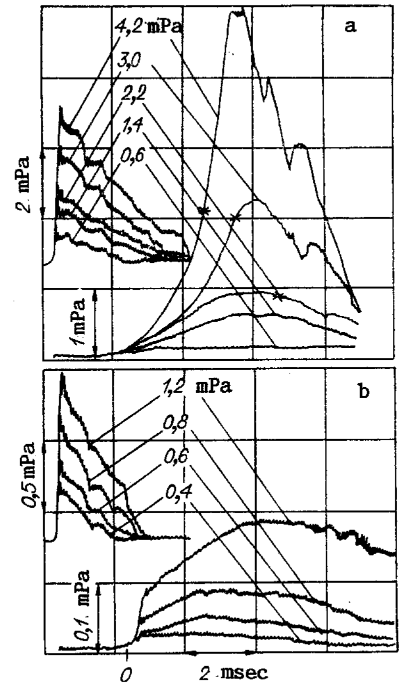

Fig. 2

sors are mounted flush with the inside surface of the tube and the face plate. A shock-absorbing interlayer made of porous rubber is attached with glue to the inside surface of the face plate. A needle-shaped tourmaline sensor is passed through the interlayer. Pressures measured along the tube, underneath the interlayer, and directly above it. The signals are recorded by means of a double-beam storage oscillograph. The intrinsic frequency of the sensors is >200 kHz. The volume of air contained in the interlayer is α_a = 0.68 (the subscript a refers to atmospheric pressure). The pore diameter is less than 0.5 mm. We also carried out experiments without any interlayer. In these experiments the wave was propagated through the water at a velocity of 1500 m/sec with insignificant distortions and on reflection from the face plate the pressure doubled. In the presence of an interlayer the pressure at the barrier and the pressure at the upper edge of the interlayer were virtually coincident. It is assumed in the following that the pressure through the entire volume of the interlayer is identical and is a function of the deformation of the latter.

Figures 1 and 2 show oscillograms taken in experiments with an interlayer with h_a = 18 mm. The upper trace corresponds to the sensor in the upper portion of the tube, some 3 m above the face plate, and the one at the bottom corresponds to the sensor at the plate underneath the interlayer. Figure 1c and Fig. 2a, b, which show several experiments, the fronts of the incident waves recorded by the uppermost sensor are to be seen. The scales of pressure and time are indicated in the figures. In the experiments reflected in Fig. 1, with constant amplitude for p_m = 6.4 mPa the duration θ was varied. The duration θ in Fig. 1a is at its highest, i.e., the stroke of the piston is unlimited; in Fig. 1b, c the value of θ is reduced by imposing a restriction on the piston stroke. In the experiments reflected in Fig. 2, the piston stroke is unlimited and the amplitude of p_m is varied. The wave is approximately triangular in shape. The duration θ is slightly reduced with a reduction in p_m as a consequence of the friction of the piston against the wall of the tube. Each pair of curves related to a given experiment is identified in Fig. 1 by the corresponding value of θ found on the basis of the upper curve, while in Fig. 2 it is identified through the value of p_m, also obtained from the upper curve. The arrival of the wave at the surface of the interlayer, denoted 0, was determined in the experiments without an interlayer. The effective shock-absorption time (1.1) is identified as t* in Fig. 1, while in Fig. 2, where t* is a function of p_m, it is identified within the body of the figure with an asterisk on the curve (on those oscillograms where t* falls within the limits of the recording time). We will describe the effectiveness of the interlayer by the coefficient of pressure transmission $\lambda = p_m^*/2p_m$ (p_m^* is the maximum pressure exerted against the barrier).

Let us examine Fig. 1. With $t < t^*$ the pressure p^* is insignificant and increases sharply in the vicinity of $t = t^*$; λ begins noticeably to diminish when $\theta < 1$ msec (for $\theta = 3.5$, 1.5, 1.0, 0.4, and 0.2 msec, $\lambda = 0.70$, 0.68, 0.58, 0.34, 0.11). The pressure against the barrier continues to increase with $t > \theta$ (Fig. 1c), at a time when the action of the incident wave itself has ceased. This is explained by the separation that is caused by the fact that so long as the interlayer has not been compressed, the wave reflected from the interlayer is a rarefaction wave. Exhibiting some velocity, the separated water layer compresses the interlayer when $t > \theta$. When $\theta \geq 1$ msec, the local maxima (spikes) are reproduced on the curves recorded by the sensor at the barrier. These are the secondary compression waves generated by the collapse of the cavitational cavities in the case of multiple separation. Figure 2 shows that with a reduction in p_m the coefficient λ diminishes, which corresponds to an increase in t^* with a reduction in p_m (for $p_m = 4.2$, 3.0, 2.2, 1.4, 1.2, 0.8, 0.6, and 0.4 mPa, $\lambda = 0.58$, 0.36, 0.21, 0.18, 0.08, 0.05, 0.04, and 0.02). With $p_m >$ 0.6 mPa the pressure at the barrier reaches a maximum when $t > \theta$, which bears out the fact of separation. With $p_m < 0.6$ mPa, no such effect is observed. When $p_m \geq 3$ mPa, we can see the spikes from the secondary compression wave.

3. Let us examine the solution of the wave problem. We will direct the x axis along the shock tube. We will position the nonmoving barrier shielded by the interlayer at $x = 0$. The conditions at the boundary separating the water from the interlayer will be related to $x = 0$. The initial interlayer pressure of $p_0 = 0.133$ mPa is composed of $p_a = 0.1$ mPa and the pressure of the column of water, while the instantaneous pressure within the water is made up of p_0 and $p(x, t)$, which arises in the interaction of the wave with the interlayer. The solution is obtained in Lagrange variables.

The pressure $p(x, t)$ satisfies the wave equation $\partial^2 p/\partial t^2 = a^2 \partial^2 p/\partial x^2$. At the initial instant of time we have an incident wave from infinity, the pressure within which wave has been given in one of the following variants:

$$p(x, 0) = \begin{cases} p_m & \text{when } 0 < x < x_1, \\ 0 & \text{when } x = 0, \quad x \geqslant x_1; \end{cases}$$

$$p(x, 0) = \begin{cases} p_m(1 - x/x_2) & \text{when } 0 < x < x_1 \quad (x_1 \leqslant x_2), \\ 0 & \text{when } x = 0, \quad x \geqslant x_1 \end{cases}$$

(x_1 is the length of the wave). The mass velocity $u(x, 0) = -p(x, 0)/\rho a$. The relationship between the pressure and the deformation of the interlayer has been obtained experimentally in the uniaxial quasistatic isothermal compression of the rubber specimen. The corresponding boundary condition

$$\frac{p(0, t) + p_0}{p_a} = \left[\frac{\alpha_a}{\alpha_a - \varepsilon(t)}\right]^\gamma + \frac{E\varepsilon(t)}{p_a},$$
$$u(0, t) = dh/dt = -h_a\, d\varepsilon/dt,$$

where $p(0, t)$ is the excess pressure in the interlayer; $E = 0.5$ mPa is the empirical coefficient governed by the resistance to compression on the part of the structure of the porous interlayer; $\varepsilon(t) = (h_a - h)/h_a$ represents the deformation of the interlayer: $\gamma = 1$ in the case of isothermal compression and $\gamma = 1.4$ in the case of adiabatic compression within the wave; $p(0, 0) = 0$; $\varepsilon(0) = 0.044$. The solution is achieved in the dimensionless variables $t^0 = ta/h_a$, $x^0 = x/h_a$ numerically, by the method of characteristics. The relationships on these characteristics are as follows: $dp = \pm \rho a du$ along $dx^0/dt^0 = \pm 1$.

In the calculation we compared the calculated value of $p(x, t)$ with $p_r = -0.6$ mPa. The point x_r, where $p(x, t) = p_r$, was taken as the discontinuity with the boundary condition $p(x_r, t) = 0$. We calculated the difference in the paths ΔS, covered by the particles to the right and to the left of the discontinuity: ΔS initially increased, and as the moving layers of the interlayer were decelerated, it diminished. With $\Delta S = 0$ the condition $p(x_r, t) = 0$ is removed; a secondary compression wave arises at the point x_r. We took into consideration as many as five such discontinuities.

4. Figure 3 shows the calculation corresponding to the experiments in Fig. 1b, c (h_a = 18 mm, $p_m = 6.4$ mPa, θ is shown in the figure). The pressure at the barrier, in the absence of an interlayer, is shown in the left-hand side of the figure only for $\theta = 0.2$ and 1.0 msec.

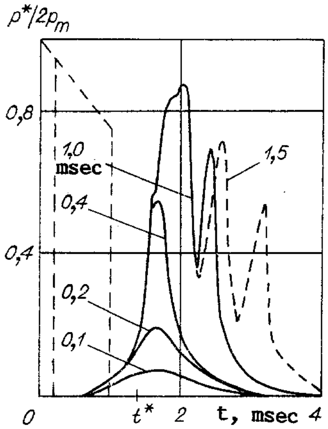

Fig. 3

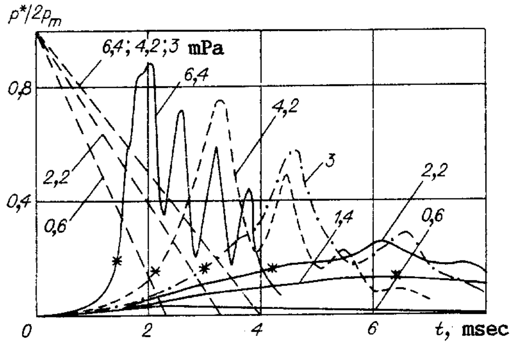

Fig. 4

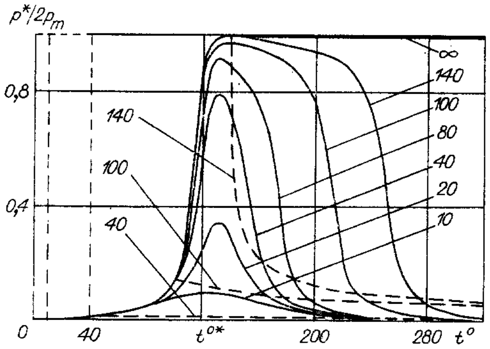

Fig. 5

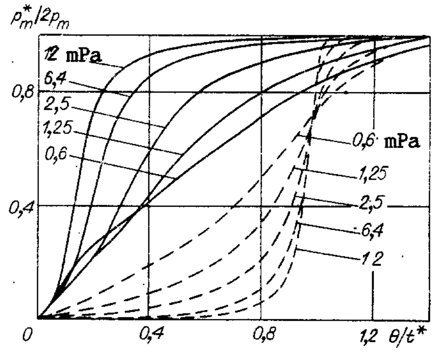

Fig. 6

The theoretical curves in Fig. 4 correspond to the experiments in Fig. 1a (curves 6.4 mPa) and in Fig. 2. The sloping straight lines represent the pressure at the barrier in the absence of an interlayer. In the calculation, based on the experiment, with a reduction in p_m the reduction in θ is specified. The thickness h_a = 18 mm, and p_m is shown in the figure.

In all of these cases the theoretical and experimental curves are found to be in satisfactory agreement. The position and magnitude of the local maxima, there where they exist, are almost coincident, although in the calculation it is the reduction in the pressure between them that stands out most clearly.

Similar experiments and calculations in a range of pressures p_m from 0.2 to 6.4 mPa and a duration θ from 0.1 to 5 msec were carried out with interlayers exhibiting thicknesses of h_a = 4.5, 9, 18, and 36 mm. The pressure p_r was varied in the calculation. With p_r = −0.6 mPa the agreement between calculation and experiment is best both with respect to the position and magnitude of the local maxima, as well as with respect to the value of the transmission factor λ. The agreement between the theoretical and experimental values of λ within limits of 10-20% confirms the suitability of the proposed calculation.

Figure 5 shows a comparison of the calculated pressure at the barrier, determined without consideration of cavitation according to [9] and with consideration of cavitation (the dashed and solid lines). The incident wave is specified in the form of a step having a duration θ^0 and an amplitude for p_m = 6.4 mPa. The values of $\theta^0 = \theta a/h_a$ are shown at the lines. The pressure at the barrier without an interlayer is shown for θ^0 = 10 and 40. With and without consideration of cavitation, the pressure at the barrier coincides with the arrival of the trailing front of the incident wave. Subsequent to this, the pressure calculated without consideration of cavitation diminishes; with consideration of cavitation, it continues to increase (with θ^0 = 140 the pressure diminishes in both cases, but in different fashion).

Figure 6 shows $\lambda = p_m^*/2p_m$ as a function of θ/t^*: where cavitation is taken into consideration, we have the solid lines, while the dashed lines represent the situation without consideration of cavitation. The calculation has been carried out for waves in the form of a step with duration θ for five amplitudes of p_m (their values are indicated at the lines). The dashed lines simultaneously describe the dimensionless pressure $p^*/2p_m$ at the barrier as a function of the dimensionless time t/t^* in the case of an incident wave in the form of an infinite step. For $\theta > t^*$, with and without consideration of cavitation, $\lambda \to 1$, i.e., the interlayer does not reduce the maximum pressure. For $\theta < t^*$ consideration of cavitation yields a significantly higher value for λ and in this case the λ has been calculated without consideration of cavitation and it diminishes as p_m increases. Consideration of cavitation shows that λ with increasing p_m, as a rule, increases sharply; consequently, with an increase in p_m the error generated by the failure to take cavitation into consideration increases, amounting, for example, in the case of p_m = 12 mPa and $\theta = 0.2\text{-}0.4t^*$, approximately to two orders of magnitude. A condition for the significant reduction in pressure at the barrier is $\theta \ll t^*$. Thus, cavitation must necessarily be taken into consideration in the reflection from a porous interlayer of a wave of amplitude $p_m > |p_r|$ and duration $\theta < t^*$.

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