STUDY OF PRESSURE-PULSE PROPAGATION IN TUBES FILLED WITH WATER

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The results of studying pulsed pressure propagation in liquid-filled tubes are of considerable practical interest. The most complete reviews of theoretical and experimental works devoted to this question are given in [1, 2]. The theory of nonsteady movement of an ideal liquid worked out in [3] and developed in [4] is used in calculations for propagation of shock pulses in tubes with a liquid. In order to solve the problem of hydraulic shock in long pipelines a theory was developed in [1], taking account of liquid viscosity. The effect of elastoplastic deformation of the tube walls during propagation of a pressure pulse (PP) in a liquid was considered in [2]. For example, it was shown that the role of liquid viscosity is considerably reduced with tube deformation.

Elastic vibrations of the tube wall, propagating as a rule at a velocity greater than that of the PP in the liquid, may lead to erosion of the pulse front. It was demonstrated theoretically in [5] that at a length of approximately ten tube diameters the PP front is eroded and an acoustic compression wave propagates through the liquid.

The number of known experimental works is considerably less. A study was carried out in [6] of the wave field within a tube with water during explosion in it of small explosive charges. Empirical equations were obtained for the dependence of basic PP parameters on distance from the explosion location. Results were presented in [7] for experimental determination of PP propagation velocity in a liquid and in the tube walls, and also the amount of deformation for the walls of tubes of different materials. Excitation of a PP was accomplished by impact of a ball on the closed end of the tube. Results were given in [8] for an experimental study of PP attenuation along the length of a tube with water, and it was shown that with a curved PP front the results of calculations according to [3] do not agree with experimental data.

In the present work, experimental data are provided for propagation of a PP excited by an explosion in water-filled tube sections made of steel St3 and aluminum alloy D16T. A PP of transcendental shape with a curved leading front was formed in water filling a tube by means of the explosive loading device described in [9]. The amplitude and duration of the PP are determined by the density of the polystyrene foam, its thickness, and kinetic energy of the striker plate. Pressure was varied in the tests from 10 to 30 MPa, and duration from 100 to 300 μsec.

Experiments were carried out with tube sections of three types: 1) steel tubes with dimensions 40 × 4 mm (outer diameter, wall thickness), and length 1 and 3 m; 2) tubes of aluminum alloy D16T with dimensions 30 × 1.5 mm, length 0.6 m; 3) tubes of alloy D16T with dimensions 146 × 13 mm, length 0.8 m.

The PP parameters in water filling a tube were measured by piezoelectric pressure sensors PDD1 and PDD7 whose construction and calibration procedure are given in [10]. In tubes of the first and second types, sensors PDD7 recorded the pressure profile operating on the end stopper of the tube. From the difference in time for development of signals from a PDD1 sensor set up in the upper part of the tube and from a PDD7 sensor the average velocity of the leading PP front was determined. In tests with tubes of the third type, pressure in the incident and reflected wave was recorded by PDD7 sensors, and the deformation of the loaded surface of the tube was determined by strain gauges. The scheme for carrying out tests with a type-3 tube is given in Fig. 1a, where 1 is explosive loading device; 2, end stopper; D, pressure sensor; T, strain gauge for measuring tube axial deformation; R, strain gauge for measuring the radial deformation of the tube wall. Pressure sensors and strain gauges were also used as time markers in order to determine the average velocity of the PP front. Measurement error of PP amplitude and tube wall deformation did not exceed 15%, and the error of determining PP front velocity was not more than 8% with a confidence level of 95%.

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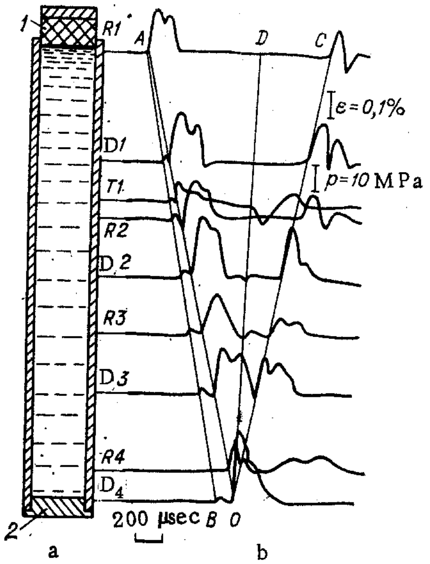

a b

Fig. 1

Shown in Fig. 1b are oscillograms of signals from the pressure sensors and strain gauges referred to the tube cross sections in which the measurements were carried out. The nature of the PP profile and tube wall deformation is satisfactorily reproduced from test to test, and analysis of the results obtained makes it possible to present a picture of PP propagation in liquid-filled tubes in the following way.

Ahead of the main PP front in the liquid there is a precursor (line AB in Fig. 1b) propagating with velocity ~1450 m/sec, which almost coincides with the velocity of sound in water (a similar phenomenon was observed in an aluminum rod [11]), and the amplitude of the precursor is an order of magnitude lower than that of the PP. The amplitude and curvature of the PP front during propagation in a liquid were almost unchanged in the tests. A PP reflected from the end of the tube has almost the same amplitude and front curvature.

The velocity of PP front propagation in the forward and reverse directions (lines AO and OC, respectively) is identical and equal to 1200 ± 40 m/sec, which is in good agreement with the value calculated by the Zhukovskii equation:

$$c = c_0(1 + Kd/hE)^{-1/2},$$

where c_0 is volumetric sound velocity; K is modulus of volumetric compression for the liquid; E, tube material Young's modulus; d and h, tube wall diameter and thickness. For tubes of type 3, c = 1230 m/sec.

Similar behavior of PP was also observed in using tubes of types 1 and 2; measured velocities for PP propagation agree satisfactorily with calculated values.

Measurements of tube-wall deformation in the axial and circumferential directions made it possible to connect the stressed state in the tube wall with the amplitude of the pressure pulse in the liquid. Tube-wall deformation measured in the axial direction is in good agreement with the value calculated by Hooke's law $\varepsilon_1 = p/E$, and the value for circumferential tube deformation agrees with that calculated with $\varepsilon_2 = pd/E2h$ [12], where ε_1 and ε_2 are tube axial and circumferential deformation; p is PP amplitude.

The method used for creating a PP in a liquid made it possible to avoid simultaneous loading of the tube wall in the axial direction. Strain gauges oriented in the axial direction only recorded deformation caused by passage of the PP. However, reflection of the pressure pulse from the closed end of the tube led to excitation of tensile stresses in the tube wall, and strain gauge T1 recorded a tensile wave propagating along the tube with velocity 5200 ± 200 m/sec, i.e., almost coinciding with the velocity of sound propagation in the walls of aluminum plates (~5300 m/sec), i.e., line OD.

The amplitude for deformation in the tensile wave is in good agreement with that estimated by Hooke's law $\varepsilon_3 = p_1S_1/(ES_2)$, where p_1 is pressure of the reflection at the tube end; S_1 and S_2 are area of the internal cross section and tube wall, respectively. No marked effect of the wave in the tube wall on pressure in the liquid was detected. No erosion of the PP front was noted in tests, at least within the limits of the resolving capacity of the recorder. This is possibly explained by the fact that a sound wave propagating through the wall of a metal tube ahead of the PP causes bending oscillations of very low amplitude, insufficient for marked excitation of the liquid and erosion of the PP front.

As follows from results in [6, 8], attenuation of the PP amplitude caused by the viscosity of water may only be detected for passage of a PP over several hundreds of tube diameters. In our tests, in which the maximum tube length did not exceed 100 diameters, attenuation of the PP amplitude was not detected, which points to the validity of the estimates made above. No effect was detected for PP amplitude on its propagation velocity in tubes of the same type with elastic tube-wall deformation.

Results of these experiments show that PP propagation through a liquid filling a tube is very complex in nature. In particular, it has been shown that ahead of the main PP, whose velocity is determined by the elastic characteristics of the liquid and tube material, a precursor with an amplitude an order of magnitude less than that of the PP propagates with the velocity of sound in the liquid.

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