

Propagation of spherical shock waves in water

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Abstract. The propagation and attenuation of spherical shock waves in water, produced by the explosion of spherical charge, is studied. Our results compare favourably with experimental data.

Keywords. Spherical shock; shock propagation; attenuation.

1. Introduction

The propagation and attenuation of shock waves in water is important in naval warfare and considerable research has been made on this subject (Kirkwood & Bethe 1942; Brinkley & Kirkwood 1947; Penny & Dasgupta 1942). The theory of Brinkley and Kirkwood has been extensively used in blast wave studies in air (Sachdev 1971).

Thomas (1957) devised an energy hypothesis and found a relation between jump in energy and the radius of shock wave in air. This method was later modified for cylindrical shocks by Bhutani (1966). In all these studies it was assumed that energy was released at a point. The detonation of a spherical charge of finite radius in water was studied by Singh (1976) and Singh & Bola (1976) and the energy hypothesis of Thomas for explosive charge of finite radius has been modified. Singh *et al* (1979) extended energy hypothesis for plane shock waves in aluminium. In this paper $U = a + bu_2$ has been used as the equation of state of water and the propagation and attenuation of spherical shock in it have been studied.

In the present studies we ignore the effect of gas bubble on the shock wave and assume that the energy is uniformly distributed in the shocked medium. The equation of state is determined experimentally for ordinary tap water at 17°C. The attenuation found by the energy hypothesis is compared with that found experimentally.

2. Formulation of the problem

Let a spherical charge of radius R_0 be detonated in water. We take the centre of the charge as the origin of reference. When this charge is exploded by some device, a spherical shock is produced which propagates in all directions. Let, at time t after the explosion, R be the radius of the shock front. Let U , P , ρ , E respectively be the shock velocity, pressure, density, and the internal energy per unit mass and

the subscripts 1 and 2 denote respectively the states behind and in front of the shock. The equation of state of water is given by,

$$U = a + bu_2 \quad (1)$$

Where u_2 is the particle velocity behind the shock and a, b are the constants of water. The jump conditions across the shock at time t are

$$p_2 = \frac{\rho_1 a^2 \delta (\delta - 1)}{\{b - \delta(b - 1)\}^2} \quad (2)$$

$$U = a\delta / \{b - \delta(b - 1)\}, \quad (3)$$

$$E_2^* = E_1^* + \left\{ \frac{(\delta - 1)a}{b - \delta(b - 1)} \right\}^2, \quad (4)$$

where $\delta = p_2 / p_1$, $E^* = E + \frac{1}{2}u^2$.

These are the three conditions relating the four unknown p_2 , U , δ and E_2^* . The fourth relation is obtained by using the energy hypothesis of Thomas (1957) where the jump in total energy E^* is given by the energy hypothesis as

$$[E^*] = \frac{3\alpha Q}{4\pi R^3 \rho_2} \quad (5)$$

where α is the constant of proportionality and Q is the total energy released by explosion. Now to evaluate α we have (Singh 1976)

$$\alpha = \lim_{R \rightarrow R_0} \frac{4\pi [E^*] \rho_2 R^3}{3JQ}, \quad (6)$$

where J is the Joules constant of mechanical equivalent of heat and R_0 is the radius of charge. Now if at the boundary $\delta = \delta^*$ we have from (4) and (6)

$$\alpha = \frac{4\pi R_0^3 \delta^* \rho_1}{3JQ} \left\{ \frac{a(\delta^* - 1)}{\delta^* - b(\delta^* - 1)} \right\}^2. \quad (7)$$

To find δ^* we use the mismatch method due to Buchanan & James (1959), i.e. at the water-explosive boundary we have

$$p_2/p_D = 2\rho_1 U / (\rho_D U_D + \rho_1 U), \quad (8)$$

where $p_D = \frac{1}{2}\rho_D U_D^2$ and U_D, ρ_D are the velocity of detonation and density of solid explosive. In (8) p_2, U are functions of δ^* and p_D, ρ_D, U_D are known quantities for the given explosive. Thus one can evaluate the value of δ^* from (8). In the

present case we have used the spherical charge of RDX/TNT (60 : 40), and the value of δ^* is 1.59525. Equation (5) can now be written as

$$\delta \left\{ \frac{a(\delta - 1)}{b - \delta(b - 1)} \right\}^2 = \frac{3a \bar{Q} J}{4\pi \rho_1 \bar{R}^3} \quad (9)$$

where $\bar{R} = R/R_0$, and \bar{Q} is the heat energy per unit volume released by the explosive. \bar{Q} is the known quantity for the explosive. Equation (9) enables us to determine δ as a function of \bar{R} and hence p_2 and U can also be determined from (2) and (4).

3. Experimental set-up

A streak camera (model 770 ns 10^{-9} s) was used to record the shock wave in water. This camera gives a continuous time resolution of the order of nanoseconds by abstracting a narrow segment of a fast moving event and sweeping the image of this segment by a rotating mirror, along a strip of photographic film (Sampooran Singh 1967, 1969). The streak camera record is purely a space time graph, from which the velocity of the fast event is easily determined.

In the present experiment, a spherical charge of RDX/TNT (60 : 40) of 5 cm in diameter was detonated in water. Ordinary tap water was used in the experiment at a temperature of 17°C. A suitable hole of 2.5 cm length was made in the charge, reaching its centre, for inserting the detonator in it for central initiation. We assume that the initiation is central and thus the shock wave produced is perfectly spherical. The charge was suspended in a wooden box, of which two opposite sides were made of glass to facilitate the recording by the camera (figure 1). An argon flash bomb with a plastic explosive and filled with argon gas was used as a back lighting source. This light and the event under study were synchronised to obtain a shadowgraphy record in the camera. The experimental set-up is shown in figure 1.

A typical record of the shock wave propagation in water is shown in figure 2 (plate 1). The innermost black strip is the expanding gas bubble and the curved line above and below it are the shock velocity in water, in the vertically downward and upward directions respectively.

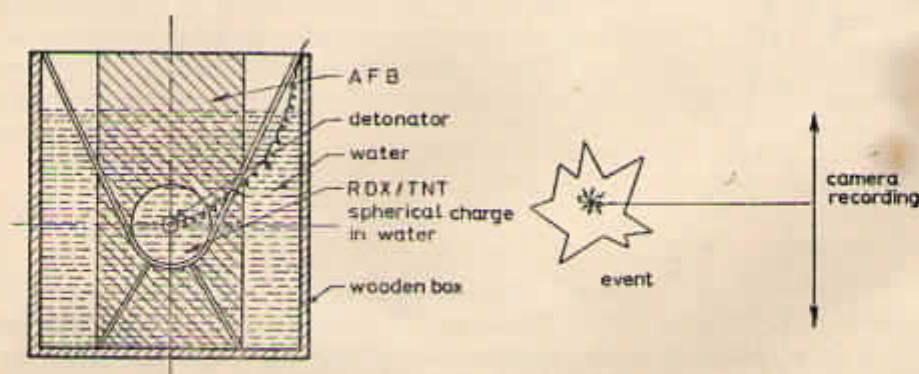


Figure 1. Experimental set-up before firing.

4. Comparison with the experiments

The following data was used for numerical computation.

$$a = 1.364 \times 10^9 \text{ cm/s at } 17^\circ\text{C},$$

$$b = 2.128,$$

$$\rho_D = 1.68 \text{ g/cc},$$

$$U_D = 7.8 \times 10^5 \text{ cm/s},$$

$$\bar{Q} = 2476 \text{ cal/cc},$$

and thus the value of

$$\delta^* = 1.59525,$$

$$\alpha = 0.94658.$$

Calculating the values of δ^* and α from (8) and (7) respectively, the variation of δ versus shock radius \bar{R} from equation (9) was studied and thus the shock velocity U versus R from (3) and is plotted in figure 3. To compare with experiments a

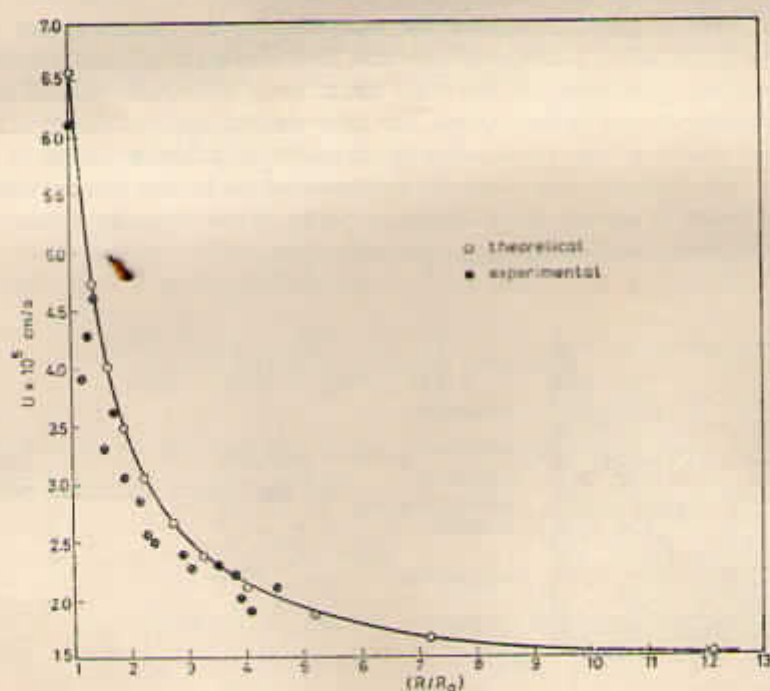


Figure 3. Attenuation of shock velocity versus distance.

spherical charge of RDX/TNT (60 : 40) was detonated in water. The velocity of detonation of this charge was 7.8×10^5 cm/s and the density over 1.68 g/cc. These were the known parameters of this explosive. In figure 2 (plate 1), it can be seen that the shock starts from the surface of the spherical charge (parallel strips) and the gradient of the c curve gives the velocity of the shock. The scale factor for the time axis is $0.606 \mu\text{s}$ and for the space axis it is 7.21 mm. The crossed points in figure 3 are experimental points. A good matching between theoretical and experimental values of the shock velocity is obtained.

5. Discussion and conclusion

In the theoretical model we assume that the energy of explosion is released instantaneously and is confined within the shock surface. Also the effect of the gas bubble is not considered. Therefore the shock velocity obtained theoretically is a little higher than that obtained experimentally for the same value of distance. It appears that the energy of explosion is being dissipated and also that part of the energy is used in gas bubble expansion.

It can be concluded that if we take the effect of the gas bubble also into account, the results can be brought nearer to the experimental values. Further studies taking the effect of the gas bubble into account are being carried out.

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Plate 1

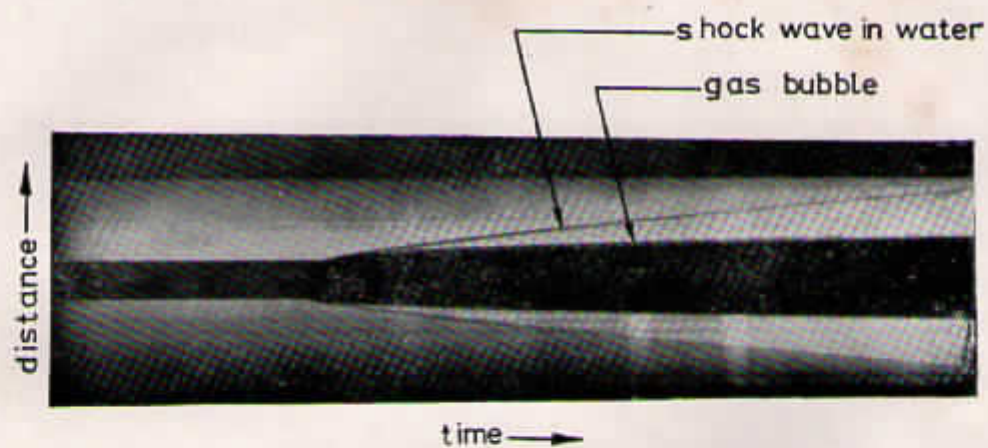


Figure 2. A typical streak record showing shock velocity and gas bubble velocity.