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Attenuation of shock parameters in air and water

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Abstract. This paper describes the results of shock pressure measurements in the range of 1–25 MPa in water and in the range of 60–500 kPa in air. Pressure pulses were generated by exploding wire technique and measured with a quartz piezo-electric transducer. The attenuation with distance of shock overpressure, impulse and energy in shock front has been studied. Experimental data on shock attenuation in air is scarce and the results presented here confirm the attenuation behaviour derived from theoretical considerations.

Keywords. Exploding wire; shock overpressure; impulse; energy; piezo-electric transducer; attenuation; air; water.

1. Introduction

In nuclear safety analysis, it is required to evaluate the consequences of dynamic loading of structures resulting from a variety of phenomena such as (i) nuclear excursion (ii) thermal interactions due to accidental mixing of molten reactor fuel and coolant (iii) sodium water reactions in reactors using liquid sodium heated steam generators (iv) hydrogen explosions etc. Experiments carried out in the laboratory simulating these situations provide an insight into these phenomena and generate useful data for safety analysis. Determination of the degree of conversion of available energy in the shock front for doing mechanical work on structures, is an important objective of these experiments. The pressures in these experiments are invariably measured at some distance away from the zone of interaction. An understanding of the propagation of the pressure front in the medium is essential for extrapolation of the measured pressure profiles back to the zone of interaction. This paper presents the measured attenuation characteristics of shock pressure, impulse and energy, in air and water, using exploding wire technique to generate shock fronts.

A comparative review of available data on shock propagation in air, in the range 10 to 20 kPa has been made by Vortman (1970). It is seen that while considerable theoretical work has been carried out to determine shock attenuation characteristics in air in different pressure ranges, experimental data are rather scarce. Also the agreement between theory and experiment is not satisfactory.

Cole (1965) compared the empirical relationship between shock overpressure, distance and charge weight derived from theory and underwater experiments. The correlation for shock attenuation assumes a single expression to be valid over a range of pressures extending over almost three orders of magnitude from 3 to 3000 MPa.

Generation of experimental data on shock attenuation, in the low pressure range, with chemical explosives calls for use of small quantities of charge material with attendant problems of reproducibility. Alternatively, measurements can be made at relatively large distances from reasonably-sized charges, but in this case shock propagation is likely to be affected by environmental factors such as temperature, its gradient, windspeed and so on. In this context, the application of exploding wire sources for experimental determination of shock attenuation in air and water has the advantages of easy repeatability and good reproducibility.

2. Experimental set-up

The schematic of the experimental set-up is shown in figure 1. A 10 kV 190 μF condenser bank is used for the generation of shock waves by exploding a copper wire of 0·18 mm diameter and 5 mm length. The capacitor bank is resistively damped to avoid ringing and enable generation of a single shock pressure pulse. The wire explosion is initiated by a two-electrode spark gap, with switching time less than 500 nsec. A special wire holding assembly has been made with pinvices for holding the copper wires. The base of the wire holder assembly is so shaped as to prevent reflected shock fronts from reaching the gauge face. For underwater studies, the entire assembly was immersed in a water tank (400 × 400 × 700 mm). For experiments in air as well as underwater, the geometry and dimensions of the experimental set-up are so chosen that the reflected shock fronts reach the transducer only after the direct overpressure pulse seen by the transducer has decayed.

3. Instrumentation

Quartz piezoelectric transducers (Kistler model 603H) were used to measure the shock pressures. The transducers have a rise time of 1 μsec and sensitivity of 25 pC/kPa. The transducer resonant frequency is 500 kHz. Charge amplifier (model 504 of Sundstrand Data Inc, USA) with a flat frequency response up to 150 kHz was used for

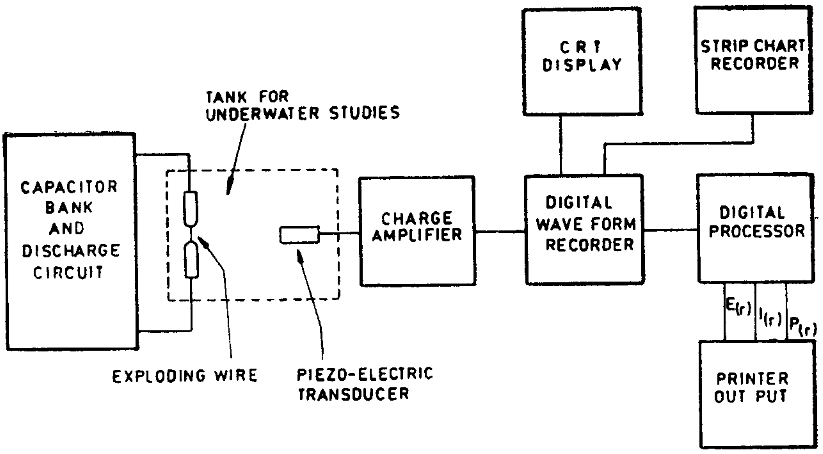


Figure 1. Experimental set-up for shock wave generation and measurement of shock parameters.

processing the pressure signals from the transducer. During the wire explosion, very high surge current of the order of 15 kA flows through the discharge circuit. The heavy electromagnetic field produced as a result was observed to induce an overriding noise in the signal lines. To provide the necessary shielding, charge amplifier and recording instruments were housed in a fully closed aluminium cabin. Double-shielded signal cables were used with the outer shield terminated at the cabin wall. The inner shield which is the common line for the signal was connected to the laboratory ground. The amplifier and the recording systems were separately connected to the laboratory ground. This type of grounding was found to be quite effective and reduced the noise due to the electromagnetic pick-up. During underwater measurements, the current flow path through water between the high voltage terminal and the transducer body was effectively blocked by electrically isolating the latter with a coat of insulating paint. To avoid leakage of water into the cable connectors and to isolate the connectors from water, the entire connector portion was wax moulded.

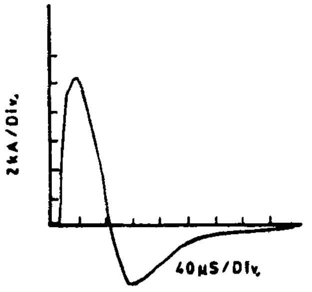
4. Recording devices

Pressure signals were recorded by a digital waveform recorder (Biomation 805) and read with 1% accuracy. A microprocessor-controlled digital interface connected to the waveform recorder was used to determine the peak pressure, impulse and energy flow.

5. Measurements

Keeping the wire material, length and diameter fixed, the distance of the transducer from the wire was varied for each of different capacitor voltages. Pressure measurements were repeated thrice for each setting and a reproducibility within 5% was observed. Figure 2 shows a typical waveform of the current through the exploding wire obtained in the present experimental set-up.

A typical pressure pulse produced in underwater wire explosion is given in figure 3. A rise time of 2 μsec and a pulse duration of 6 μsec was observed. However in the case of exploding wire in air, while the pressure signals had a similar rise time of 2 μsec, the pulse duration was observed to be longer, namely 40–50 μsec.



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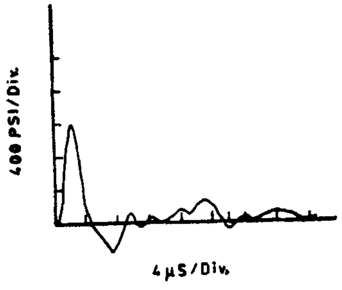

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Figure 2. Typical current pulse through the exploding wire.

Figure 3. Pressure signal in underwater wire explosion.

The impulse at distance r from the source is defined by the relation

$$I(r)=\int_0^{t_0} P(r,t)\,\mathrm{d}t, \tag{1}$$

where t_0 is the duration of the positive phase of the pressure pulse and $P(r,t)$ represents the variation of pressure with time behind the shock front. Impulse was evaluated by numerical integration of the pressure signal in the waveform recorder using the digital processor.

Assuming a spherical shock front the work done on a surface of radius r is given by

$$w(r)=\int_0^{t_0} 4\pi r^2 P(r,t)\,u_p(r)\,\mathrm{d}t, \tag{2}$$

where $u_p(r)$ is the particle velocity behind the shock front. From the conservation equations for mass and momentum we have

$$u_p=P/\rho_0\,u_s, \tag{3}$$

whence
$$w(r)=\int_0^{t_0} 4\pi r^2\frac{P^2(r,t)}{\rho_0\,u_s(r)}. \tag{4}$$

For the measured range of shock overpressures in water, the shock velocity u_s differs from the sonic velocity by just about 2% (table 2·2 of Cole 1965). This permits the replacement of the product $\rho_0\,u_s$ by the acoustic impedance $\rho_0\,c$. The energy flow per unit area associated with the propagation of the shock front in water is therefore given by

$$E(r)=\frac{1}{\rho_0\,c}\int_0^{t_0} P^2(r,t)\,\mathrm{d}t. \tag{5}$$

$E(r)$ was computed by the digital processor from the pressure time history. Recalling that the governing equation for shock propagation in air is (Zeldovich and Raizer 1966),

$$u_s^2/c^2=\left[1+\frac{6}{7}\frac{P}{P_0}\right], \tag{6}$$

it is obvious that the shock front attains velocities much higher than sonic velocity even for moderate overpressures encountered in the present experiments. Consequently the flow of shock energy in air takes the form

$$E(r)=\frac{1}{\rho_0\,c}\int_0^{t_0}\frac{P^2(r,t)\,\mathrm{d}t}{[1+(6/7)\,[P(r,t)/P_0]]^{1/2}}. \tag{7}$$

To evaluate the integral in (7) it is necessary to know the functional form of the variation of pressure with time behind the shock front. As sugested by Leonard (1962) a relationship of the form

$$P(t)=P_m\left[\exp(-bt)\frac{\cos(\Omega t+\phi)}{\cos\phi}\right], \tag{8}$$

where $b=1/2t_0$, $\Omega=(\frac{1}{2}\pi-\phi)/t_0$, $\phi=23{\cdot}22°$,

has been used in the present studies. The pressure profile computed using (8) is given in figure 4. The profile matched fairly well with the typical pressure trace obtained with experiments. Shock impulse and energy flow per unit area in air were computed using (8) in (1) and (7). The impulse (equation (1)) is obtained by direct integration and leads to the result, $I=0{\cdot}3943\,P_m t_0$. To determine the energy integral, the integration was carried out using eighth order Gaussian quadrature.

6. Results and discussion

The impulse values for air computed by direct integration were in good agreement with the values obtained from the digital processor. The variation of the shock parameters with distance studied for water as well as air is presented in figures 5 to 10. It is observed that for a given capacitor bank voltage the attenuation with distance of shock overpressure, impulse and energy flow with respect to distance r obeys the well-known power law

$$P(r)=K_1\,r^{-\alpha_1},$$

$$I(r)=K_2\,r^{-\alpha_2},$$

$$E(r)=K_3\,r^{-\alpha_3}.$$

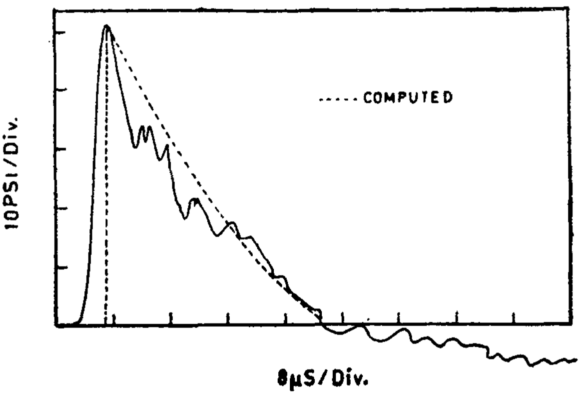
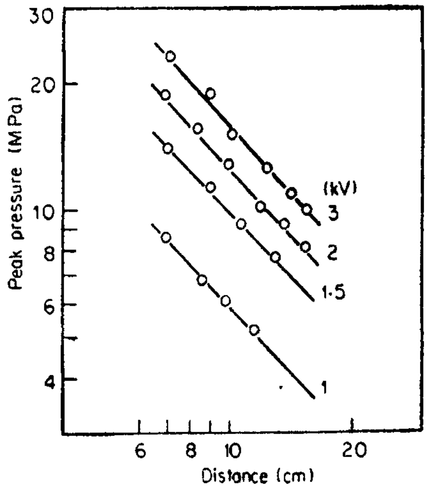
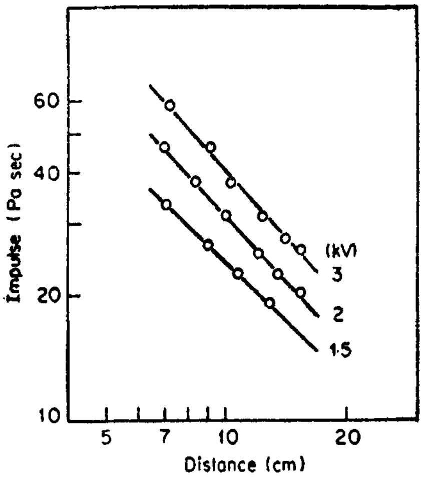


Figure 4. Actual and computed pressure profiles in air.





(5) (6)

Figure 5. Pressure variation with distance in underwater wire explosion.

Figure 6. Impulse ($\int P(t)\,dt$) variation with distance in underwater wire explosion

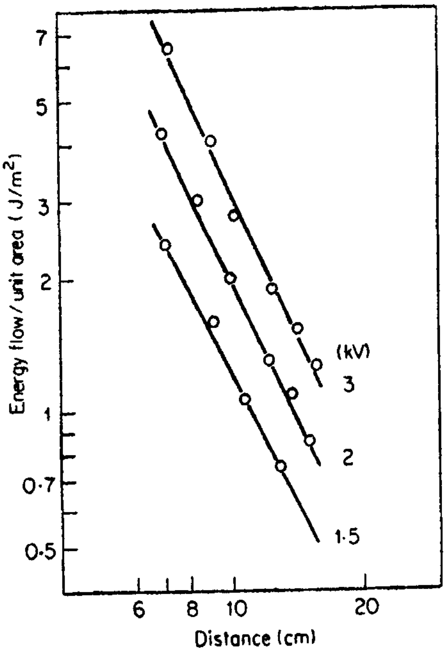


Figure 7. Energy flow ($\int P^2(t)\,dt/\rho c$) variation with distance in underwater wire explosion.

The values of the exponents a_i and coefficients K_i were determined for each of the capacitor bank voltages and are presented in table 1. Shock overpressures generated in water, in these experiments, should be regarded as close to the acoustic range since the corresponding shock velocities differ from the sonic velocity by about 2% only.

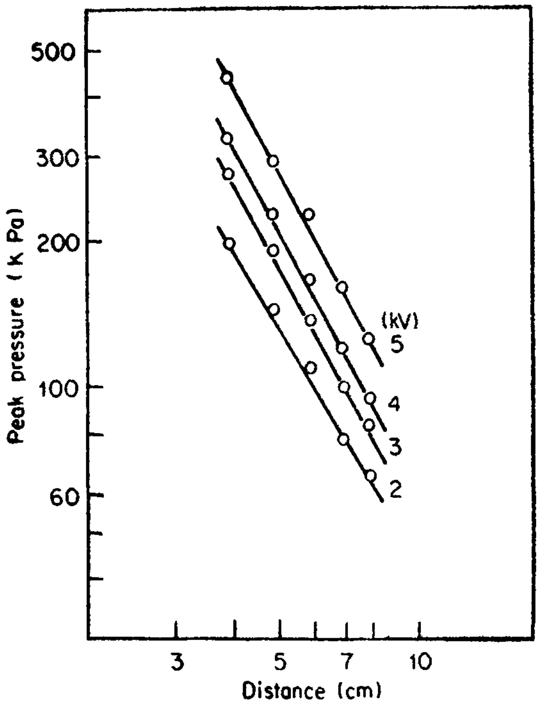


Figure 8. Pressure variation with distance in wire explosion in air.

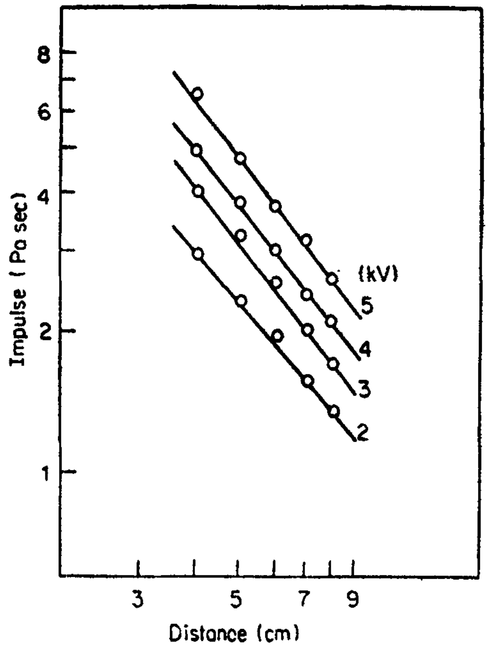


Figure 9. Impulse ($\int P(t)\,dt$) variation with distance in wire explosion in air.

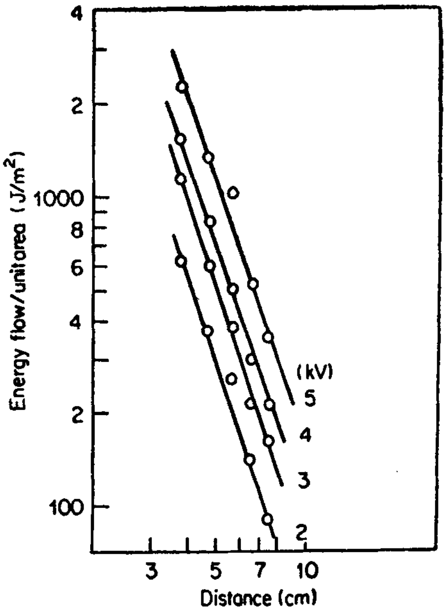


Figure 10. Energy flow ($\int P^2(t)\,dt/\rho c$) variation with distance in wire explosion in air.

Table 1. Values of constants K_i and a_i in the expressions for pressure, impulse and energy.

Capacitor voltage (kV)	Pressure		Impulse		Energy	
	K_1 (MPa)	a_1	K_2 (Pasec)	a_2	K_3 (j/m^2) (× 10^{-3})	a_3
Water						
3	1·250	1·100	3·27	1.090	19·9	2·195
2	1·170	1·040	2·98	1·026	18·0	2·048
1·5	0·942	1·032	2·78	1·023	12·2	2·012
1	0·637	1·023	—	—	—	—
Air						
5	1·264	1.82	9·64	1·30	0·504	2.630
4	0·910	1.82	8·57	1·26	0·148	2·880
3	0·894	1·78	6·95	1·27	0·117	2·850
2	0·878	1·69	7·36	1·15	0·092	2·760

It is known that spherical pressure waves tend towards $1/r$ behaviour as the acoustic range is approached. The observed values of the exponent for the spatial profiles of shock overpressure in water (namely $1{\cdot}023 < a_i < 1{\cdot}1$) are generally in accordance with this behaviour. However, at greater shock intensities shock overpressures tend to fall off with distance more rapidly.

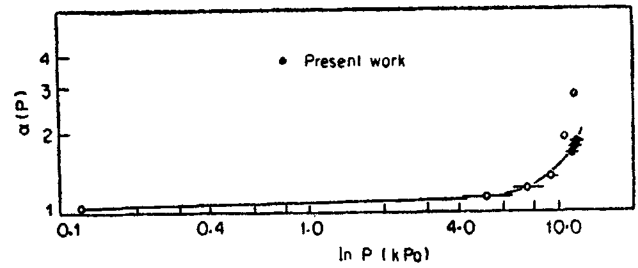


Figure 11. Variation with pressure of the exponent of the law $P \propto r^{-\alpha}$.

Table 2. Variation of shock overpressure with distance in air.

Overpressure (kPa)	Exponent of decay law	Reference
0·00113	1·0575	Lehto and Larson (1969)
0·06894–0·138	1·12	Whitaker (1970)
0·06894–0·6894	1·126	Lehto and Larson (1969)
0·06894–0·6894	1·35*	Kingery (1966)
0·6894–6·894	1·22	Lehto and Larson (1969)
2·757–6·894	1·2	Bethe *et al* (1955)
6·894–20·68	1·35	Kirkwood and Brinkley (1945)
49	1·9	Taylor (1950)
147	2·8	Taylor (1950)
60–195	1·69*	Present work
80–274	1·77*	Present work
92–324	1·82*	Present work

*Experimental.

The decay characteristics of shock overpressures in air observed in the present experiments (in the pressure range 60–320 kPa) are given in table 2 for comparison together with those reported in Taylor (1950) and Vortman (1970) for other pressure ranges. It may be noted that the attenuation characteristics are largely derived from theoretical considerations. From a plot of the variation of the exponent α against shock overpressure (figure 11) it is seen that the present results although restricted to a small range of pressures, confirm the theoretical estimate.

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