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INDUCTION METHOD OF CONTINUOUS RECORDING OF THE VELOCITY OF A CONDENSED MEDIUM IN SHOCK-WAVE PROCESSES

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Methods of continuous recording of the velocity of a medium in shock-wave processes can yield useful information in the investigation of complex phenomena occurring during shock compression of compressed media (elastic–plastic waves, phase transformations, etc.). A magnetoelectric method of continuous recording of the velocity of dielectric media [1] and a capacitive method of measuring the instantaneous velocity of a moving metal surface [2] are well recommended in a number of investigations. Unfortunately, quantitative measurements are practically impossible by using a magnetoelectric method for relatively high pressures produced by metal impactors because of the distortion of the initial magnetic field by the impactor motion. The capacitive method is quite responsive to interference and does not permit realization of measurements of the velocity of the metal–condensed dielectric interface because of changes in the dielectric permittivity of the medium filling the interelectrode spacing behind a strong shock front.

A method [3] without the above-mentioned constraints inherent to the magnetoelectic and capacitive methods, and permitting the realization of continuous recording of the velocity of the condensed medium at higher shock-compression pressures is considered in this paper. Methods of measuring the parameters of shock-compressed media, which are similar in the physical principles to the principle of the method proposed, are examined in [4, 5].

1. Principles of the Induction Method

Let a turn of radius R_1 with a negligibly small conductor section be connected to a stabilized dc current source and located in a condensed dielectric medium 1 (Fig. 1a) at a height h_0 above a conducting half space 2 with the electrical conductivity $\sigma \to \infty$, while there is a stationary magnetic field in all space. The magnetic permeability of the media are $\mu_1 = \mu_2 = \mu_0$, where μ_0 is the magnetic permeability of a vacuum. If a change in the magnetic field should occur in the dielectric medium 1 for any reason, an electromotive force (emf) of induction $\mathcal{E}_1$ will appear in the turn.

Let us trace the behavior of the induction emf in the turn of a plane shock whose front is parallel to the interface of the medium is propagated from bottom to top over the system. Although the wave front moves over the conductor, no induction emf originates in the turn. This deduction follows from [6, 7] in which it is shown

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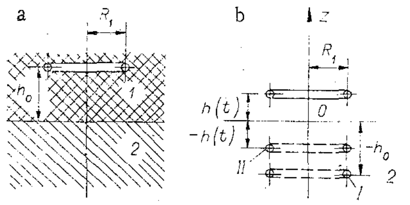

Fig. 1

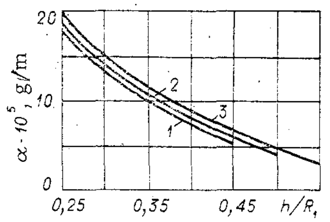

Fig. 2

that in an ideal conductor the field ahead of a shock front remains equal to its initial value. However, after the wave front has emerged on the interface at the time $t = 0$, the latter will be set in motion and concentric eddy currents will appear on the surface of the conducting medium. They evoke a change in the field in the upper half space and the appearance of the induction emf $\mathscr{E}_1$ dependent on the velocity of dielectric–conductor interface motion $u(t)$ in the turn. In order to establish the dependence of $\mathscr{E}_1$ on the velocity $u(t)$, we turn to a coordinate system coupled to the conductor surface. In this coordinate system, the action of eddy currents on the field in the upper half plane is equivalent to the action of two fictitious turns. The first fictitious turns I (Fig. 1b) is in the plane $z = -h_0$, is fixed ("frozen" in the conductor), has the same magnitude and the same direction of the current as there are in the true turn. The second fictional turn II is in the plane $z = -h(t)$, has the same value of the current as does the true turn but the current direction is opposite. Just as the true turn, it approaches the plane $z = 0$ at the velocity $u(t)$. For such a substitution scheme for the perfectly conducting half space, the induction emf $\mathscr{E}_1$ in the turn with dc current I_0 is related to the velocity $u(t)$ by the following:

$$\mathscr{E}_1(t) = I_0\alpha_1(t)u(t), \tag{1.1}$$

where

$$\alpha_1(t) = \mu_0\left\{\frac{h}{R_1}k_1\left[\frac{2-k_1^2}{1-k_1^2}E(k_1^2) - 2K(k_1^2)\right] - \frac{h+h_0}{4R_1}k_2\left[\frac{2-k_2^2}{1-k_2^2}E(k_2^2) - 2K(k_2^2)\right]\right\},\ k_1^2 = \frac{1}{1+\left(\frac{h}{R_1}\right)^2},\ k_2^2 = \frac{1}{1+\left(\frac{h+h_0}{2R_1}\right)^2}, \tag{1.2}$$

$E(k_i^2)$ and $K(k_i^2)$ are complete elliptic integrals of the second and first kinds, respectively ($i = 1, 2$). It is seen from (1.2) that the coefficient α_1 is a function of not only the running distance $h(t)$ on the turn to the conductor surface, but also a function of the initial distance h_0. The nature of the dependence of the coefficient α_1 on the quantity h/R_1 for $h_0/R_1 = 0.45$, 0.50, 0.55 is seen in Fig. 2 (lines 1-3, respectively).

In contrast to an idealized scheme the dielectric medium acquires a noticeable electrical conductivity σ_* behind the shock front under actual experiment conditions (see Fig. 1a), and the perfectly conducting half space is a metal plate with limited size (thickness, diameter) and with finite electrical conductivity σ.

Let us estimate the value of the electrical conductivity of a shock compressed dielectric for which there is in interaction with the magnetic field of the turn with current. There is no such interaction in practice [8] if the magnetic Reynolds number is $\mathrm{Re_m} = \mu_0\sigma_* uR_1 \ll 1$, which is equivalent to the condition $\sigma_* \ll 10^2\ (\Omega\cdot\mathrm{cm})^{-1}$ for $u = 5$ km/sec. This latter condition is satisfied for many condensed dielectrics in a sufficiently broad range of shock compression pressures. For instance, the electrical conductivity of boron nitride is 0.37 $(\Omega\cdot\mathrm{cm})^{-1}$ under the shock compression pressure $p \simeq 50$ GPa, while the electrical conductivity of potassium chloride is 1.47 $(\Omega\cdot\mathrm{cm})^{-1}$ under the same pressure [9].

The influence of finiteness of the electrical conductivity of metals and the boundedness of the dimensions of their plates on the signal being recorded was experimentally investigated in this paper in one of the possible modifications for technical realization of the method.

2. Description of the Experimental Set-Up and the Measurement Technique

To increase the induction emf it is evidently expedient to utilize several rather than just one turn, i.e., an inductance coil. According to [10], a real inductance coil can result in the case of windings with negligibly small cross section. The equivalent parameters of a coil (sensor) are here determined as follows:

$$h_e = \bar{h},\ R_e = \bar{R}(1 + r^2/24\bar{R}^2).$$

Here $\bar{h}$ is the mean distance between the winding and the conducting surface; r, width of the winding, and $\bar{R}$, is mean radius. In conformity with the superposition principle of the fields of the turns of the equivalent inductance coil and the relationships (1.1) and (1.2), the induction emf is

$$\mathscr{E} = I_0\alpha u, \tag{2.1}$$

where

$$\alpha = \alpha_1 N^2;$$

N is the number of turns, and α_1 is a factor for the equivalent turn.

The sensor in this paper was fabricated from eight turns of insulated 1-mm-diameter copper wire with the values $R_e \simeq 16$ mm, $r \simeq 5$ mm, and winding thickness of 2.5 mm. Plane shocks were produced in the media being investigated by using cylindrical explosive charges of 120- or 200-mm diameter with nonsynchronization of the wave front motion on a 100-mm diameter not ordinarily exceeding 0.1 μsec. The duration of the process being investigated lasted 1-2 μsec. The explosion was realized 0.1 sec after feeding current to the sensor loop. Current in the sensor loop $I_0 \simeq 400$ A was produced by using batteries installed in a protected structure. A buffer inductance coil, placed 2-3 m from the site of the explosion in a closed container buried in the soil, was connected in series with the sensor supply loop to stabilize its current.

The magnitude of the current I_0 at the time of the explosion was determined by the voltage drop recorded by a loop oscilloscope on a standard 1-mΩ resistor included in the sensor supply loop. The electrical resistivity of the sensor and the rest of the loop did not exceed 60 mΩ. Sensor signal distortions, due to the presence of the supply cables, were eliminated to a significant extent by using a 1-μF shunting capacitor in the container for the buffer inductance coil. The signal was taken off from the sensor by using a matched radio frequency cable about 50 m long and was adequate for recording by an electronic oscilloscope at velocities $u \gtrsim 0.5$ km/sec without application of intermediate amplification. No measures were taken to shield the measuring component.

Naturally, the signal being recorded in a real electrical loop will differ somewhat from the emf induced in the sensor. The equivalent circuit of a real loop for the variable current and voltage components is represented in Fig. 3, where L_1 is the sensor inductance, L_2 is the inductance of the buffer coil ($L_2 \gg L_1$), R_L is the load resistance, and C is the parasitic capacitance of the loop and the sensor. The induction electromotive force $\mathscr{E}(t)$ for such a circuit is connected to the voltage V(t) being recorded by the relationship

$$\mathscr{E} = (1 + L_1/L_2)V + \tau dV/dt + T^2 d^2V/dt^2, \tag{2.2}$$

where $\tau = L_1/R_L$, $T^2 = L_1C$. The loop parameters in this paper are: $L_1 = 2.5$ μH, $L_2 = 100$ μH, $R_L = 50$ Ω, $C \simeq 500$ pF. It is seen from (2.2) that C and L_1 must be diminished to diminish the difference between the voltage V(t) and the induction emf. The influence of the parasitic capacitance can be diminished if the signal is taken off the measuring coil coaxial with the coil that is the source of the magnetic field rather than the latter. In this case the formula for $\mathscr{E}(t)$ can be obtained if the substitution circuit for the perfectly conducting half space (see Fig. 1b) is used. Extreme diminution of L_1 is not desirable since the magnitude of the signal being recorded would here be diminished, which would reduce the interference-immunity of the method.

3. Results of Experimental Check Out of the Method

3.1. Influence of Finiteness of the Metal Electrical Conductivity. Let the conducting half space 2 (see Fig. 1a) have the finite electrical conductivity σ, and let its interface with the dielectric medium 1 acquire a constant velocity u behind the shock front. Obtaining an analytic expression for the induction emf $\mathscr{E}_\sigma$ in the case of finiteness of the electrical conductivity σ is a sufficiently complex problem. In this paper we limit ourselves to just the clarification of the functional connection between the induction emf $\mathscr{E}_c$ and the electrical conductivity σ. We assume the induction emf can be written in the form

$$\mathscr{E}_\sigma = f(I_0, \mu_0, u, R_1, t, \sigma, h_0) = I_0 \alpha_\sigma u. \tag{3.1}$$

Then from (3.1) and reasoning from dimensional analysis [11] there follows that

$$\alpha_\sigma = \mathscr{E}_\sigma / I_0 u = \mu_0 \varphi(h_0/R_1,\ ut/R_1,\ \mu_0 \sigma u R_1).$$

This latter relationship acquires the form $\alpha_\sigma = \alpha_c(\xi\sigma u)$ for fixed values of h_0 and R_1, where $\xi = ut$ is the displacement of the conducting fluid and σu is a parameter dependent on the electrical conductivity of the metal and the loading conditions. In this paper, metals substantially distinctive in their electrical properties such as copper, lead, bismuth, were selected to obtain the experimental dependence $\alpha_\sigma(\xi)$. As is known, the specific electrical conductivity of copper is ≈10 times greater than the electrical conductivity of lead and 70 times greater than the electrical conductivity of bismuth. Two series of tests were performed. In the first series, a plane shock of rectangular profile was inserted from the aluminum screen 1 (Fig. 4a) of the explosive apparatus into the lead or bismuth specimen 2 and then into the organic glass specimen 3. The thicknesses (S) of specimens 2 and 3 were 5 and 6 mm, and their diameters were 100 mm. The signal was removed by using the sensor 4. The second series of tests (Fig. 4b) differed from the first in that a copper plate 5 of 100-

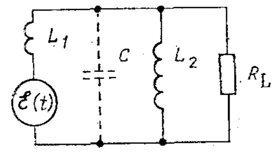

Fig. 3

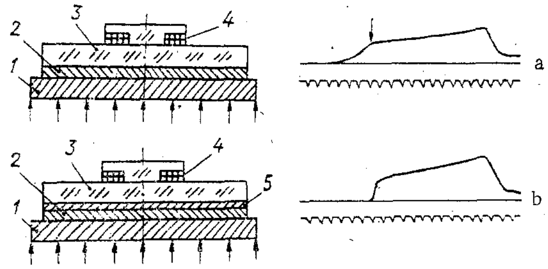

Fig. 4

mm diameter and 0.3-mm thickness was placed on the interfacial boundary between the lead (bismuth) and the dielectric, and acquired the velocity of this interface sufficiently rapidly. Two kinds of explosive apparatus I and II with known shock parameters behind the shock front in the screen 1 were used in the tests (u_e = 1.46 and 2.33 km/sec, respectively) to assure an initial pressure $p \simeq$ 40-80 GPa in the specimens 2.

Oscillograms of the first and second series of tests with bismuth performed on the explosive apparatus 1 are also presented in Figs. 4a and b. The timing marker frequency is f = 10 MHz. In the first series of tests with bismuth, the magnetic field perturbation leading the shock front, i.e., the appearance of the induction emf in the sensor in a time $\tau_* = 0.3$-$0.35\,\mu$sec before the arrival of the shock on the bismuth–dielectric interface, is determined. This time is shown by the arrow in Fig. 4a. It is determined by the duration of the pulse-corresponding to the oscillogram of the second test series (Fig. 4b) in which there is practically no magnetic field perturbation leading the shock. It is also not remarked in both series of tests with lead. The experimental value of τ_* for bismuth is in good agreement with that obtained in [6, 7] by the formula $\tau_* = 1/\mu_0 \sigma D^2$, where D is the velocity of the shock front in a metal. For lead and copper the computed values of τ_* do not exceed 0.05 and $0.005\,\mu$sec, respectively.

Experimental dependences $\alpha(\xi)$ for lead (curves 2 and 3) and bismuth (curves 4 and 5) are represented in Fig. 5a in comparison with the computed dependence $\alpha_\sigma(\xi) = \mathcal{E}_c/I_0 u$ for an ideal conductor (curve 1), the Roman letters I and II correspond to the numbers of the explosive devices. Values of the velocity u were determined from the known parameters of the explosive devices and the shock adiabats of aluminum, lead, and bismuth. It is seen that the dependences $\alpha_\sigma(\xi)$ for lead and bismuth are noticeably below the dependence $\alpha(\xi)$ for a perfect conductor. The magnitude of the relative deviation $\delta\alpha_\sigma = (\alpha - \alpha_\sigma)/\alpha$ here grows as the metal surface is displaced. For a ξ = 2 mm displacement the relative diminution of the quantity α_σ is approximately 10% for lead, and 20-30% for bismuth. The experimental dependences $\alpha_\sigma(\xi)$ for copper (second test series) turned out to be quite close to the dependence $\alpha(\xi)$ for a perfect conductor. The maximal magnitude of $\delta\alpha_0$ for copper for ξ = 2 mm, estimated from the data for lead and bismuth ($\delta\alpha_\sigma \sim 1/\sqrt{\sigma_0}$), is 3%.

The experimental dependences u(t) extracted from the V(t) oscillograms in the second test series with Bi and Pb by using (2.1) and (2.2) with a small empirical correction for the finiteness of the electrical conductivity of copper taken into account are represented in Fig. 5b. The operation of extracting u(t) from the V(t) oscillograms offers no special difficulties when using an electronic computer. As noted above, a shock with constant pressure (velocity) behind the front was produced in the specimen under investigation. The experimental dependences obtained for u(t) actually have a practically rectangular profile and the velocity values agree to ± 2% accuracy with the velocities determined by the known shock adiabats of the metals and the parameters of the explosive devices I and II.

3.2. Influence of the Metal Plate Thickness. The copper plate thickness was just 0.3 mm in the tests, but as has been shown above, this turned out to be sufficient for considering such a plate a perfectly conducting half space with a good approximation. It is evident that if the plate (foil) thickness is diminished to values less than the thickness of the surface current layer in copper, then the effect of magnetic field diffusion through it starts to appear, which will naturally result in distortion of the signal being recorded. The influence of this effect on the signal was studied in a special test series in two metals, copper and aluminum. The foil thickness (not less than 100 mm for its diameter) varied between 0.01 and 0.3 mm. The dielectric medium in which the foil was placed was subjected to loading by a plane shock of rectangular profile. It is found that the signal is practically independent of the foil thickness for a pressure of $p \simeq$ 20 GPa in the dielectric if its magnitude is

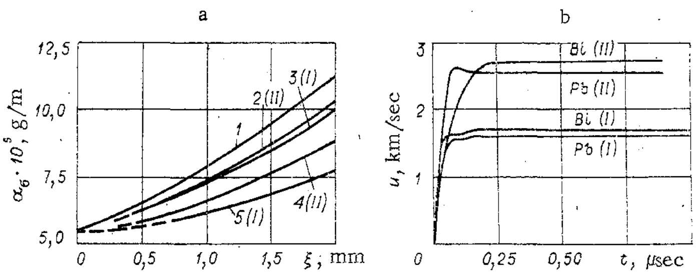

Fig. 5

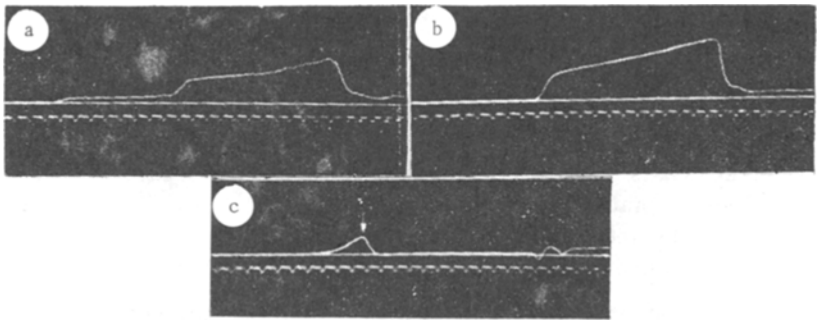

Fig. 6

not less than 0.1 mm for copper and 0.2 mm for aluminum. For a p ≃ 60 GPa pressure in the dielectric, the critical thicknesses of the copper and aluminum foils are 0.2 and 0.3 mm, respectively.

3.3. Influence of the Conducting Surface Diameter. For a correct formulation of the experiment information is necessary about the effective diameter of the conducting surface that assures a practically complete contribution to the signal being recorded. In order to obtain such information, a series of tests was performed to investigate the dependence of the magnitude of the signal on the diameter of a hole in 0.3-mm-thick aluminum foil mounted in the dielectric. It is established that a conducting surface of $5R_1$ and $5.7R_1$ diameter for $h_0/R_1 = 0.45$ and 0.7, respectively, assures a practically total contribution (99%) to the signal. For the $R_1 \simeq$ 16 mm sensor radius, used in this paper, the effective diameter of the conducting surface is 80-90 mm for $h_0 = 7$-11 mm.

4. Possibilities of the Method and Examples of Its Application

It is established in an experimental checkout of the induction method that the behavior of copper in shocks is close to the behavior of a perfect conductor. By application of the relationships obtained for perfect conductors in Secs. 1 and 2, this fact permits realization of continuous recording of the velocity of the metal–dielectric interface with a sufficiently good approximation, when the magnitude of the electrical conductivity of the metal is close to the electrical conductivity of copper. To record the velocity of an interface between a dielectric and a conductor with low electrical conductivity (bismuth, graphite, etc.) or the velocity of a dielectric medium, a thin, in the gasdynamic sense, but sufficiently thick, in the electromagnetic sense, copper or aluminum foil (from 0.1-0.3 mm in thickness depending on the foil material and the shock compression pressure) must be placed in the interface or in the dielectric. In the particular case when the dielectric is air, the method permits realization of continuous recording of the free surface velocity of the substance under investigation. When it is necessary to eliminate a small systematic reduction in the velocity associated with the finiteness of the electrical conductivity of the copper (aluminum) and not exceeding 3% ordinarily, a correction induces changes in the results, and is determined by computational means or in special calibration tests. Tests performed up to now by using an induction method (under conditions known beforehand from other measurements) show that the experimental values of the velocities with the correction for the finiteness of the electrical conductivity of copper (aluminum) taken into account do not differ by more than ±3-4% from those expected. As is shown, the magnetoelectric and capacitive methods possess analogous accuracy characteristics.

Since the induction method permits realization of continuous recording of the velocity of a condensed medium, it can be applied to investigate complex shock processes, for instance: elastic–plastic waves, phase transformations, artificially produced load, expansion, waves, etc. As an illustration of the application of the method, an oscillogram is represented in Fig. 6a of a test to record the separation of elastic and plastic waves in quartzite of 2.65 g/cm^3 density which is in contact with an explosive charge (diameter and length are 200 mm) comprised of TG 50/50 after an elastic wave has traversed a 55-mm path. The induction emf in this test is due to the motion induced by a 0.2-mm-thick aluminum foil in quartzite for S = 55 mm. As is seen from Fig. 6a, the elastic wave leads the plastic by 0.8 μsec. The quartzite mass flow rate in the elastic predecessor increases from 0.3 km/sec on its front to 0.45 km/sec ahead of the plastic wave front, behind its front u = 1.35 km/sec.

A specific peculiarity of the induction method and the methods in [4, 5] is the possibility of graphic observation of the phase transformations in shocks associated with a substantial change in the electrical properties of the materials being investigated, i.e., transformations of the dielectric–metal or metal–dielectric types. An example of the realization of this peculiarity of the method might be the recording of the graphite–diamond transformation. As is known, diamond is a dielectric.

A test oscillogram in which the velocity of the interface between graphite (S = 10 mm) and fluoroplastic (S = 7 mm) specimens was measured by using a 0.2-mm-thick aluminum foil is presented in Fig. 6b. The density of the graphite in the test was 2.10 g/cm^3 and the density of the fluoroplastic was 2.21 g/cm^3. The velocity u = 2.3 km/sec, corresponding to the pressure $p \simeq 30$ GPa, was determined. It is known [12] that the transformation of graphite into diamond starts under shock compression at a pressure of $p \simeq 20$ GPa and is almost completed for $p \simeq 40$ GPa.

An oscillogram of a test performed under the same loading conditions ($p \simeq 30$ GPa) but without the aluminum foil at the graphite–fluoroplastic interface is represented in Fig. 6c. As in the test with bismuth (see Fig. 4a), it is seen that the leading magnetic field perturbations precedes the exit of the shock from the conductor at its interface with the dielectric. In the test with graphite, however, the induction emf vanishes at the time of shock emergence on the interface (noted by the arrow in Fig. 6c), which is a graphic indication of the shock compressed graphite becoming a dielectric, i.e., the transformation of at least a part of it into diamond.

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