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OPTIMUM CONDITIONS FOR EXCITATION OF ELASTIC VIBRATIONS IN SOLIDS BY PULSED IONIZING RADIATION

V. D. Volovik and S. I. Ivanov

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Investigations of elastic vibrations accompanying the interaction of pulsed ionizing radiation with solids have shown that mechanical stresses are produced by an unsteady thermoelastic body force $\mathbf{F}(\mathbf{r}, t)$ [1, 2]

$$\mathbf{F}(\mathbf{r}, t) = -\Gamma\nabla E(\mathbf{r}, t), \tag{1}$$

where Γ is the Grüneisen constant of the target material and $E(\mathbf{r}, t)$ is the energy absorbed from the beam of ionizing radiation per unit volume of target material.

Ordinarily nonstationary thermoelasticity problems require the simultaneous solution of the wave equation and the heat-conduction equation. If the duration of a pulse of charged particles τ_0 interacting with a solid target satisfies the condition

$$\tau_{ei} \ll \tau b \ll \tau_T \simeq r_b^2/\varkappa, \tag{2}$$

the propagation of heat does not have to be taken into account during a time on the order of magnitude of the pulse duration. Here τ_{ei} is the time to establish uniform temperature conditions in the electron and ion subsystems of the material, τ_T is the characteristic time for heat to diffuse from the region heated by a beam of radius r_0, and $\varkappa$ is the thermal diffusivity of the target material.

If condition (2) holds, and in addition $\tau_S = r_b/s \ll \tau_T$, the temperature of the region heated by the beam can be considered constant even for a time τ_S – the time for an acoustic wave propagating with velocity s to leave this region. In this case the problem of finding the displacement of elastic waves $\mathbf{u}$ excited by a pulsed beam of particles is reduced to the problem of solving the wave equation, which for an infinite target can be written in the form

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$$\ddot{\mathbf{u}} - s^2\Delta\mathbf{u} = (1/\rho)\mathbf{F}(\mathbf{r},\ t). \tag{3}$$

Equation (3) is solved in the long-wavelength approximation (low frequencies ω), i.e., for $\lambda = s/\omega \gg r_b$ [1] when the first term can be neglected and $|\nabla| \sim 1/r_b$. For this range of frequencies the experimental results [3] are in good agreement with theory.

However, for frequencies $\omega \lessgtr \omega_{max}$ which make the main contribution to the frequency spectrum of an excited acoustic pulse [4], the wave equation (3) is difficult to solve. Here the ω_{max} are the maximum recorded frequencies for which the condition of coherent reception

$$\omega_{max} = \min\{1/\tau_b,\ s/r_b\} \tag{4}$$

is satisfied. Therefore, the pressure of elastic waves in the wave zone

$$p \sim \rho s|\mathbf{u}|\omega\varphi(\mathbf{r},\ \tau_l)\Theta(R) \tag{5}$$

will be determined by the spectrum of frequencies present in the acoustic pulse, since for $\omega \leqslant \omega_{max}$, $|\mathbf{u}| = |\mathbf{u}|(\omega)$. Here ρ is the density of the medium, $\varphi(\mathbf{r},\ \tau_l)$ is the coherence factor which takes account of the interference pattern from the longitudinal τ_l and the transverse $\mathbf{r}$ dimensions of the radiation zone [when condition (4) is satisfied $\varphi(\mathbf{r},\ \tau_l) = 1$]; $\Theta(R)$ is a coefficient taking account of the spatial attenuation (at a distance R) of the pressure in the acoustic flux.

It was noted earlier that the spectrum of frequencies of the acoustic pulse is related to the conditions of excitation [4, 5]. It depends on the size of the region of interaction of the beam with the target, the duration of the current pulse of the accelerator, and the kind of target material.

All dosimetry problems which can be investigated by the methods of radiation acoustics can arbitrarily be divided into integral and differential types. Integral problems (determination of the total number of particles per pulse, the total energy absorbed in matter, etc.) are solved for $\omega \ll \omega_{max}$ [cf. (3)], and differential problems (determination of the spatial distribution of the energy absorbed in the target, the distribution of the density of particles in the beam, etc.) are solved for $\Delta\omega \sim \omega_{max}$ (they require solutions of the whole system of thermoelasticity equations). Therefore, to solve various kinds of physical and applied problems using acoustic waves excited by ionizing radiation it is necessary to find a parameter which determines the condition for their excitation and whose optimum value can be found for the problem being solved. The present paper reports on an experimental solution of this problem.

The form of the parameter was determined from the following considerations. The mechanical pressure excited (5) for constant dissipative energy losses of the beam in the target E_d determines the conversion factor k of energy E_d into energy of elastic vibrations E_m :

$$k = E_m/E_d \sim p^2/E_d. \tag{6}$$

The mechanical energy Φ transmitted through the surface $2\pi r_b h$ can be obtained by substituting into the equation for the Poynting vector averaged over a period the value of the effective acoustic pressure obtained from (1):

$$\Phi = (\pi\Gamma^2/\rho s)E^2(\mathbf{r},\ t)r_b h. \tag{7}$$

The determination of the total mechanical energy transported by the flux Φ is certainly correct only for frequencies $\omega \simeq \omega_{max}$ (4), since according to [4], $1/\omega_{max} < \tau_a$, where τ_a is the duration of the acoustic pulse excited. Therefore, for elastic vibrations of frequency $\omega \simeq \omega_{max}$, according to (6) and (7)

$$k \simeq \frac{\Phi}{\pi E(\mathbf{r},\ t)\, r_b^2 h}\tau = \frac{\Gamma^2}{\rho s}\frac{E(\mathbf{r},\ t)}{r_b\omega}. \tag{8}$$

Having determined the relative conversion factor η for the maximum frequency and frequencies close to it

$$\eta = \begin{cases} k(\tau_b)/k(r_b/s), & \tau_b > r_b/s, \\ k(r_b/s)/k(\tau_b), & \tau_b < r_b/s, \end{cases}$$

we obtain by using (8) and (4)

$$\eta = \begin{cases} \dfrac{\tau_b s}{r_b}, & \tau_b > r_b/s, \\ \left(\dfrac{\tau_b s}{r_b}\right)^{-1}, & \tau_b < r_b/s; \end{cases}$$

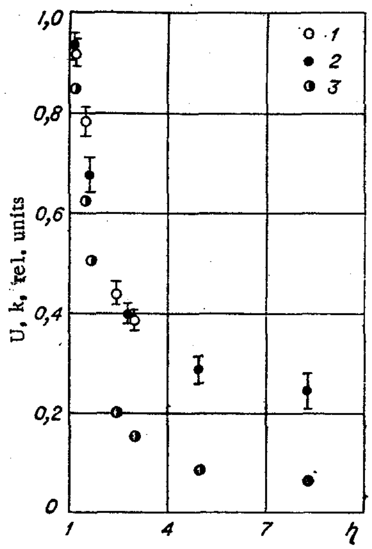

Fig. 1

i.e., for frequencies near and equal to ω_{max} the conversion factor depends on the ratio of τ_b to r_b/s.

Assuming the same relation also for frequencies characterizing the actual recorded pulse of mechanical pressure (5) [4] we chose η as the excitation parameter for experimental investigation.

A pulsed collimated electron beam from an IFP AN SSSR microtron excited elastic vibrations in an aluminum disk 9 cm in diameter and $h = 0.1$ cm thick. The initial energy of the electrons was 12 MeV and the average number per pulse was $\sim 10^{11}$. The vibrations excited were recorded by a nonresonant wide-band piezoelectric ceramic transducer ($\Delta\omega \simeq 1.5$ MHz). The longitudinal component of the zero Lamb wave was recorded in the experiment. The electric signal U from the detector (crest value) was transmitted through a preamplifier to an oscilloscope whose sweep was triggered by a synchronizing pulse from the accelerator. The pulsed beam current was measured with a Faraday cup placed after the disk-target. The parameter η was varied by varying r_b from 0.5 to 0.15 cm and τ_b over the range $(2.2\text{–}0.3) \cdot 10^{-6}$ sec. The dependence of $U \sim p$ on η was investigated in the experiment for a single value of the energy of dissipative losses of the beam.

The results obtained are shown in Fig. 1 where points 1 correspond to $\tau_b s/r_b < 1$ and points 2 to $\tau_b s/r_b > 1$. Analysis of the experimental results shows that points 1 and 2 lie on a single branch of the graph; i.e., the quantities τ_b and r_b/s make equivalent contributions to the parameter η. Using this and the fact that the form of the parameter η was obtained from a consideration of the conversion factor k, points 3 show the relation $U^2(\eta) \sim k(\eta)$ obtained by taking account of (6).

The experimental results confirm the dependence of the recorded pressure of the ultrasonic waves excited in solids by pulsed ionizing radiation on the excitation conditions chosen. For wide-band recording of the excited acoustic pulse the optimum condition (condition of maximum response) is $\eta = 1$ (differential problems of radiation-acoustic dosimetry).

In the measurement of certain characteristics of solids by comparing the amplitudes of the acoustic pulses excited in them by beams of ionizing radiation [2], the optimum condition [condition for the amplitude to be independent of the beam parameters (Fig. 1)] is $\eta > 5$ (integral problems of radiation-acoustic dosimetry). The same inequality must be satisfied in using an acoustic signal to investigate various effects [6] of the interaction of beams of particles with thick targets (the amplitude of an acoustic pulse for wide-band recording does not depend on the change of the transverse dimensions of the beam as it leaves the target).

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UPPER EVALUATION OF POWER OF SURFACE FORCES WITH DEFORMATION OF A MEDIUM WITH A LIMITED INTENSITY OF TANGENTIAL STRESSES

G. V. Ivanov

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We consider a medium in which the intensity of the tangential stresses cannot exceed a given value. In other respects, the medium is arbitrary: The connection between the stresses and the deformations can be arbitrary; specifically, the deformation can be accompanied by a breakdown of the continuity (fracture). With the deformation of such a medium, the power of the forces at that part of the surface where the velocities are given can be evaluated from above [1]. In the present article a more general evaluation is proposed, based on the use of the kinematically possible field of the velocity and a model of an inhomogeneous viscous incompressible liquid. If the viscosity coefficient is determined from the condition of a minimum of the evaluation, it coincides with the known value [1]. The use of the proposed evaluation makes it possible to obtain simple evaluations of the power of the surfaces and to calculate by successive approximations the minimal evaluation in a given class of kinematically possible velocities.

§ 1. Upper Evaluation of Power of Surface Forces

Let σ_{ij}^* be any stresses, in the region Ω, satisfying the equilibrium equations

$$\sigma_{ij,j}^* + f_i = 0, \quad i = 1, 2, 3, \tag{1.1}$$

the inequality

$$\sigma_{ij}'^*\sigma_{ij}'^* \leqslant 2\tau^2, \quad \sigma_{ij}'^* = \sigma_{ij}^* - \delta_{ij}\sigma^*, \quad \sigma^* = \frac{1}{3}\delta_{ij}\sigma_{ij}^*, \tag{1.2}$$

and, in the part S_σ of the boundary S of the region Ω, the conditions

$$\sigma_{ij}^*\nu_j = p_i, \quad i = 1, 2, 3. \tag{1.3}$$

In (1.1)-(1.3) and in what follows a Cartesian system of coordinates is used; f_i, p_i are given functions; τ is a constant; ν_i are the components of an external unit normal to the surface S.

Let u_i^* be the components of the vector of the velocity, given at S_u; $S_u = S - S_\sigma$; u_i is some kinematically possible field of the velocities, i.e., a field of the velocities satisfying the condition of incompressibility in Ω

$$\delta_{ij}u_{i,j} = 0 \tag{1.4}$$

and the condition at S_u

$$(u_i - u_i^*)\nu_i = 0. \tag{1.5}$$

The velocities u_i can have tangential discontinuities at some surfaces S_k, k = 1, 2, ..., m.

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