Electronic mechanism of transport of sound pulses in a magnetic field

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We consider a new mechanism of transmitting sound signals in a metal. This mechanism is connected with formation of a system of sound-field spikes due to the deformation interaction and to the specific dynamics of the electrons in the magnetic field.

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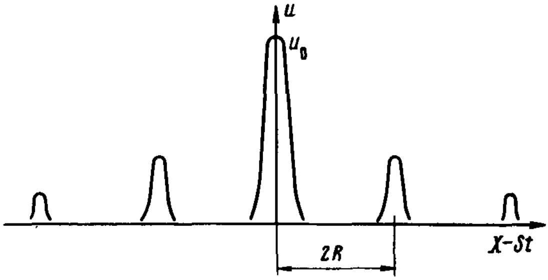
It is well known that the penetration of a high-frequency electromagnetic field into a metal can be stimulated by applying a magnetic field **H** parallel to the sample surface. The specific character of the dynamics of the electrons in the magnetic field leads to the appearance of the so-called anomalous penetration mechanism,[1] as a result of which characteristic field spikes are produced at depths that are multiples of double the cyclotron radius R. A similar effect takes place also for electronic transport of the field of a sound wave. Under stationary conditions, owing to the acoustic "transparency" of the metal, this effect leads only to small corrections against the background of the unperturbed sound waves.[1)] In the case of pulsed sound, it becomes possible to produce a dynamic spike picture in the sample. In this paper we present the theory of this phenomenon and propose its use for stimulated transmission of acoustic signals in conductors. Fil', Burma, and Bezuglyĭ[3] have observed an anomalous penetration, which appears to be connected with the effect discussed here, of a sound pulse in a metallic plate in a magnetic field.

A sound pulse moving in a metal is a qualitative analog of the skin layer characteristic of the high-frequency electromagnetic field, but moving into the interior of the metal with the speed of sound. Owing to the deformation interaction, the energy of the sound field is transported by the electron over circular orbits in a magnetic field, and the sound packet is reproduced in the form of spikes located at distances that are multiples of $2R$ away from the main pulse, and forming a system of "sound precursors," which propagate in synchronism with the main sound signal (see the figure). Thus, in a magnetic field parallel to the surface of the sample, a new mechanism is provided for the propagation a sound pulse over a chain of electron trajectories, with a characteristic ·locity of the order of the Fermi velocity.



The propagation of sound in a metal is described by the equations of elasti- ity, in the form[4] (we confine ourselves for simplicity to longitudinal scillations)

$$\ddot{u}(x, t) - s^2 u''(x, t) = \frac{1}{\rho} f(x, t). \quad (1)$$

'he x axis is directed into the interior of the metal ($x > 0$), f is a force that de- ends on **H** and is exerted by the electrons on the lattice

$$f(x, t) = -\int d\tau_{\mathbf{p}} \Lambda \frac{\partial f_0}{\partial \epsilon} \chi', \quad (2)$$

'here $\partial f_0/\partial\epsilon$ is the nonequilibrium increment to the distribution function of the lectrons, f_0 is the Fermi function, and Λ is the strain potential (we assume he strain potential to be isotropic, $\Lambda_{ik}(\mathbf{p}) = \Lambda(\mathbf{p})\delta_{ik}$, and the electron dispersion aw quadratic). The presence of the electron force f leads to the onset of a pecific law of dispersion of the sound oscillations in a magnetic field.[5] The 'electronic" renormalization of the elastic moduli, which does not depend on he magnetic field, is included in the speed of sound s.

Equation (1) should be supplemented by boundary conditions, which we choose n the form

$$u'(0, t) = g(t), \quad u(\infty, t) = 0; \quad u(-\infty, x > 0) = 0, \quad \dot{u}(-\infty, x > 0) = 0,$$
$$g(t) = u_0 \frac{\omega_0}{s} e^{-t^2/t_0^2} \left\{ \sin(\omega_0 t) + \frac{2}{\omega_0 t_0} \cos(\omega_0 t) \right\}. \quad (3)$$

If the electron force f is equal to zero, then the solution of the problem (1), 3) takes the form

$$u(x, t) = u_0 \cos(kx - \omega_0 t) e^{-\frac{(kx - \omega_0 t)^2}{(\omega_0 t_0)^2}} \quad (4)$$

where st_0 has the meaning of the spatial width of the sound pulse, and ω_0 the meaning of the oscillation frequency. At $f \neq 0$, the form of the solution depends on the relation between the parameters ω_0, t_0, and Ω ($\Omega = eH/mc$). We consider the case when

$$\omega_o t_o >> 1, \quad \Omega t_o >> 1. \qquad (5)$$

The first inequality of (5) corresponds to the case when the width of the pulse is much larger than the wavelength of the sound, while the second corresponds to the condition when the change of the pulse amplitude during the time of evolution of the electron in the magnetic field is small. The solution $u(x,t)$ can be represented in the form

$$u(x, t) = \sum_n u_n(x, t), \qquad kR >> 1 \qquad (6)$$

which constitutes, at $\Omega\tau \gg 1$, an expansion in powers of the parameter $\Omega\tau/(kR)^{1/2}$ ($\omega_0 = sk$, τ is the electron relaxation time), which we assume to be sma[ll]. $U_n(x,t)$ has the meaning of a sound spike located at a distance $2nR$ from the main signal. The expression for the first spike in the case $t > 2R/s$ is (far fron[m] the acoustic cyclotron resonance[6] $|\omega_0 - \eta\Omega| \gg \tau^{-1}$):

$$u_1 = -\frac{\sqrt{\pi}}{8} u_o\left(\frac{\Lambda}{\epsilon_F}\right)^2 \frac{s}{v_F} \frac{\sin^{-1}(\pi\omega_o/\Omega)}{\sqrt{kR}} [F_1(x - 2R) - F_2(x + 2R)],$$

$$F_{1,2}(z) = e^{-\lambda\frac{z}{R}} \exp\left[-\frac{(st - z)^2}{(st_o)^2}\right] A_{1,2}(z)\cos(\omega_o t - kz + \phi_{1,2}),$$

$$\lambda = \frac{\pi\omega_o}{\Omega^2\tau}\sin^{-2}(\pi\omega_o/\Omega); \quad A_1(z) = \sqrt{(8kz)^2 + 1}, \quad A_2(z) = 8kz, \qquad (7)$$

$$\phi_1 = \arccos\frac{8kz + 1}{\sqrt{2[(8kz)^2 + 1]}} \qquad \phi_2 = \pi/4.$$

The distribution of the acoustic field in the interior of the metal $x \gg 2R$, in a coordinate system connected with the main pulse, is shown schematically in the figure. We note that the amplitudes of the spikes increase linearly with time, this being due to the transfer of energy from the main pulse to the spike. At $t \gtrsim R/\lambda s$, the dissipative processes in the electronic system become significant and the growth of the amplitude gives way to exponential damping. The ratio of the maximum amplitude of the precursor to the main signal is determined by the strain potential Λ_0 at the point $p_z = 0$, $v_x = 0$

$$\frac{u_{1max}}{u_o} \sim \left(\frac{\Lambda_o}{\epsilon_F}\right)^2 \frac{\Omega\tau}{\sqrt{kR}} \left|\sin\left(\frac{\pi\omega_o}{\Omega}\right)\right|, \qquad (8)$$

which makes it possible in principle to determine experimentally the local values of $\Lambda(\mathbf{p})$ by measuring the considered effect.

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[1]We note that the acoustic analog of the electromagnetic skin layer are Rayleig[h]

und waves localized near the surface of the metal. The anomalous penetra- ›n of the calculations of this type in a magnetic field was considered by ·ishin and Lyubimov.[2]

[. Ya. Azbel', Zh. Eksp. Teor. Fiz. **39**, 400 (1960) [Sov. Phys.-JETP **12**, 83 (1961)]; É. A. Kaner and V. F. Gantmakher, Usp. Fiz. Nauk **94**, 193 1968) [Sov. Phys. Usp. **11**, 81 (1968)].

. M. Grishin and O. I. Lyubimov, Pis'ma Zh. Eksp. Teor. Fiz. **12**, 489 1970) [JETP Lett. **12**, 342 (1970)].

. D. Fil', N. G. Burma, and P. A. Bezuglyĭ, this issue, p. 387.

. A. Kaner and V. G. Scobov, Advances in Physics **17**, 607 (1968).

O. Kulik, Zh. Eksp. Teor. Fiz. **47**, 107 (1964) [Sov. Phys.-JETP **20**, 73 1965)].

. A. Kaner, Zh. Eksp. Teor. Fiz. **43**, 216 (1962) [Sov. Phys.-JETP **16**, 54 (1963)].