magnetic field. The relaxation of the modulus to the equilibrium value occurs very slowly, with a characteristic frequency $\omega \sim \Delta/T\tau_\epsilon$. Therefore, a sharp peak appears at this frequency in the imaginary part of the kernel describing the coupling of the current with the potential. At a current of the order of the critical value, the imaginary part becomes of the same order as the real one. Upon further increase in the frequency, dispersion develops in the kernel at $\omega\tau_\epsilon \sim 1$, because the excitation distribution function relaxes to equilibrium with a characteristic frequency $\omega \sim \tau_\epsilon^{-1}$.

There is a kink in the absorption of the high frequency field at a frequency of $\omega = 2\Delta$. When the static current is turned on, a maximum is produced if the current is directed along the magnetic field of the wave. The maximum in the absorption near the frequency $\omega = 2\Delta$ is connected with the large density of states near the threshold of single-particle excitations. The width of the peak in the absorption at low current density is proportional to $\Delta(j/j_c)^{4/3}$.


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# Echo effect in metallic powders at low temperatures


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The response of metallic powder to two-pulse excitation by an RF field at low temperatures is investigated theoretically. The mechanism that produces the echo signals is assumed to be the anharmonicity of the sound oscillations generated by the electromagnetic field in the metal. The theoretical expressions derived for the echo-signal parameters are in good agreement with the experimental data of Kupca and Searle [Can J. Phys. 53, 2622 (1975)].



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Experimental observation of echo signals induced by a sequence of electromagnetic field pulses in powdered metallic samples in the presence of a constant external magnetic field has been reported in a number of papers.[1-3] A number of the properties of the observed signals (the presence of the effect only in a narrow interval of powder-particle dimensions, vanishing of the echo when the powder is placed in a viscous dielectric medium etc.) have made it possible for the authors of these papers to state that the echo is due to resonant excitation of acoustic oscillations in the metallic particles. However, no theoretical calculation was made of the echo response for such systems.

In the present paper we calculate theoretically the echo signals in powders of normal metals at low temperatures, i.e., in the case when $\omega_c\tau \gg 1$, where $\omega_c$ is the electron cyclotron frequency and $\tau$ is the electron free path time. The onset of the echo is attributed to nonlinearity of the acoustic oscillations generated in the metal by the external RF fields. This nonlinearity is assumed to be due to the lattice-vibration anharmonicity, which is described by the fourth-order terms of the expansion of the free energy in the ion displacements $\xi$. The calculations are performed in the "local" limit $qv_F/\omega_c \ll 1$, where $q$ is the wave vector of the sound wave and $v_F$ is the Fermi velocity.

The metallic powder is a set of particles of irregular shape passed through a sieve to make their linear dimensions distributed, about a certain characteristic $l_0$. The spectrum of the natural frequencies of the acoustic oscillations of each particles cannot be analytically predicted, since the particles are of irregular shape. For an aggregate of such particles, however, it can be assumed that the set of powder frequencies covers in continuous fashion an interval $\Delta\omega_l$ near some frequency $l_0$ which is connected with the dimension $l_0$. The electromagnetic field of the pulse, if its carrier frequency $\omega$ falls in the interval $\Delta\omega_l$, excites intense oscillations of those particles whose natural frequency coincides with $\omega$. The echo response produced in the powder by the natural vibrations of the particles after turning on the external RF pulse is therefore also concentrated near the frequency $\omega$.

The irregularity of the particle shapes makes it impossible to determine the analytic form of the vibrational modes, which is needed for the description of the echo. This makes it necessary to use a simple geometrical approximation of the powder particles. The metal powder will hereafter be regarded as an aggregate of parallelepipeds whose dimensions are randomly distributed about a characteristic dimension $l_0$.

The approximation of the vibrational modes of a real powder by the simplest modes of a set of parallelepipeds leads to numerical errors in the echo-signal amplitude. Fortunately, such errors are not substantial, since in echo experiments one does not determine the absolute magnitude of the signal, but only its functional dependence on the external parameters. An error of the same type is introduced also by the fact that no account is taken below of the dependence of the vibrational modes on the coordinates perpendicular to the wave vector.

Another difference is that the natural frequencies of higher order in the parallelepiped are multiples of the fundamental frequency $\omega_0$ and excitation at the frequencies $2\omega_0$, $3\omega_0$, etc. is possible, whereas a particle of irregular shape cannot be resonantly excited at the multiple frequencies. This disparity does not influence the results of excitation if only the fundamental frequency is taken into account in the calculations.

Thus, one can hope that the proposed model, in which the calculations can be carried through to conclusion, yields a correct qualitative description of the echo phenomenon in metallic powder,[1] notwithstanding its crude character.

The echo signals were excited with RF field pulses $H_1(t)$ perpendicular to the constant magnetic field $\mathbf{H}_0$. From among the considered aggregated of parallelepipeds we separate those whose orientation corresponds to Fig. 1. In such a geometry there are excited in the metal transverse acoustic waves that propagate along the $z$ axis and are due to the echo effect.

2. The description of electromagnetic sound generation in metals is based on a simultaneous solution of Maxwell's equations and the elasticity-theory equations

$$\rho\frac{\partial^2}{\partial t^2}\xi_i=\lambda_{ijkm}\frac{\partial^2}{\partial x_j\partial x_k}\xi_m+f_i,$$
$$\operatorname{rot}\operatorname{rot}\mathbf{E}=-\frac{4\pi}{c^2}\frac{\partial}{\partial t}\mathbf{j}; \tag{1}$$

here $\rho$ is the density, $\xi_i$ are the components of the lattice-displacement vector, $\lambda_{ijkm}$ is the elasticity tensor, $\mathbf{f}$ is the force exerted on the lattice by the electrons, and $j$ is the current density. Expressions for the force $\mathbf{f}$ were obtained in [4,5]. In the "local" limit, for a sample whose orientation corresponds to Fig. 1, Eqa. (1) can be written in the form[6]

$$\frac{\partial^2}{\partial t^2}\xi_\pm=s^2\frac{\partial^2}{\partial z^2}\xi_\pm+\frac{Ze}{M}\left(1-\frac{\sigma_\mp}{\sigma_0}\right)E_\pm$$
$$-\left[\pm i\Omega_c+\frac{1}{\tau_{ph}}+\frac{Zm}{M\tau}\left(1-\frac{\sigma_\mp}{\sigma_0}\right)\right]\frac{\partial}{\partial t}\xi_\pm+\Phi, \tag{2}$$
$$\frac{c^2}{4\pi}\frac{\partial^2E_\pm}{\partial z^2}=\sigma_\mp\frac{\partial E_\pm}{\partial t}+\frac{m}{e\tau}(\sigma_0-\sigma_\mp)\frac{\partial^2}{\partial t^2}\xi_\pm,$$
$$\xi_\pm=\xi_x\pm i\xi_y.$$

Here $Ze$ and $M$ are the charge and mass of the ion, $s$ is the speed of sound, $\tau_{ph}$ is the non-electronic damping of the sound, $\Omega_c$ is the cyclotron frequency of the ion, $\sigma_\pm=\sigma_0/(1\pm i\omega_c\tau)$, and $\sigma_0=n_0e^2\tau/m$ is the conductivity of

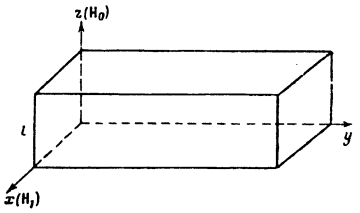


FIG. 1.

the metal. The quantity $\Phi$ introduced in (2) is given by

$$\Phi=\frac{D}{2M}\left[\frac{\partial^2\xi_\pm}{\partial z^2}\left(\frac{\partial\xi_\pm}{\partial z}\right)^2+2\frac{\partial\xi_\pm}{\partial z}\frac{\partial\xi_\mp}{\partial z}\frac{\partial^2\xi_\pm}{\partial z^2}\right], \tag{3}$$

where $D$ is the nonlinear modulus of elasticity and takes into account the anharmonicity of the lattice vibrations.

It is required to obtain the solution of the system (2) in the region $t>\tau_2+t_2$ under zero initial conditions at the instant $t=0$ and under boundary conditions corresponding to a pulsed alternating field:[2)]

$$H_y(0,t)=H_y(l,t)=0;$$
$$H_x(0,t)=H_x(l,t)=H_1\cos(\omega t+\psi);$$
$$\text{at } 0\leqslant t\leqslant t_1,\ \tau_2\leqslant t\leqslant\tau_2+t_2, \tag{4}$$
$$H_x(0,t)=H_x(l,t)=0 \text{ at other instants of time.}$$

In the foregoing equation, $\tau_2$ is the interval between the pulses, $t_1$ and $t_2$ are the pulse durations, and $\omega$ is the frequency of the alternating field, with $t_l\ll t_1$ and $t_2\ll\tau_2$, where $t_l=l/s$ is the time of passage of the wave through the sample. The system (2) will be solved by perturbation theory, with account taken of the smallness of the nonlinear terms $\Phi$.

3. We consider the linear approximation. The field $H_1(t)$ incident on the surface $z=0$ generates acoustic and helicon waves that propagate into the interior of the metal. The corresponding solutions of the system (2) will be obtained by the d'Alambert method. During the time intervals $0\leqslant t\leqslant t_l^*$, where $t_l^*$ is the minimal time of passage of the waves through the sample, the quantities $\xi(z,t)$ and $E(z,t)$ are proportional to $\exp\{i(\omega t+kz)\}$. The resultant dispersion equation has eight roots $k(\omega)$. Recognizing that the experimental external alternating-field frequency interval of interest to us lies far from the region of the helicon-phonon resonance, and retaining only those roots which correspond to waves that attenuate and propagate into the interior of the metal, we have

$$\xi_\pm(z,t)=A_\pm\exp\left[i\omega\left(t-\frac{z}{s}\right)-\frac{z}{\lambda}\right]+B_\pm\exp\left[i\omega\left(t-\frac{z}{s_*}\right)-\frac{z}{\lambda_*}\right]+\text{c.c.},$$
$$E_\pm(z,t)=\alpha_\pm A_\pm\exp\left[i\omega\left(t-\frac{z}{s}\right)-\frac{z}{\lambda}\right]+$$
$$+\beta_\pm B_\pm\exp\left[i\omega\left(t-\frac{z}{s_*}\right)-\frac{z}{\lambda_*}\right]+\text{c.c.},$$
$$\alpha_\pm=\left[s^2\left(-\frac{\omega}{s}+\frac{i}{\lambda}\right)^2-\omega^2+i\omega\Delta_\pm\right]\left[\frac{Ze}{M}\left(1-\frac{1}{1\mp i\omega_c\tau}\right)\right]^{-1}, \tag{5}$$
$$\beta_\pm=\left[s_*^2\left(-\frac{\omega}{s_*}+\frac{i}{\lambda_*}\right)^2-\omega^2-i\omega\Delta_\pm\right]\left[\frac{Ze}{M}\left(1-\frac{1}{1\mp i\omega_c\tau}\right)\right]^{-1},$$
$$\Delta_\pm=\pm i\Omega_c+\frac{1}{\tau_\Phi}+\frac{Zm}{M\tau}\left(1-\frac{1}{1\mp i\omega_c\tau}\right),\quad \lambda_*^{-1}=\frac{\omega}{2s_*\omega_c\tau},$$
$$\lambda^{-1}=\frac{1}{2s\tau_\Phi}+\frac{\Omega_c}{\omega}\frac{1}{2s\tau_\Phi}\frac{s_*^4}{s^4}\left(\frac{\omega\tau_\Phi}{\omega_c\tau}-\frac{s^2}{s_*^2}\right),$$

where $s_* = c(\omega_c\omega)^{1/2}/\omega_p$ and $\omega_p$ is the plasma frequency of the conduction electrons.

The amplitudes of the acoustic ($A$) and helicon ($B$) waves are determined by the boundary conditions

$$\frac{\partial}{\partial z}\xi_\pm(0,t)=0, \quad \frac{\partial}{\partial z}E_\pm(0,t)=\pm\frac{i}{c}\frac{\partial H_\pm(0,t)}{\partial t}. \tag{6}$$

The first of the conditions (6) follows from the continuity of the Maxwell stress tensor, while $H_\pm(0,t)$ is given by expression (4). Since the characteristic time intervals between the pulses in echo experiments ($\sim 10^{-5}$ sec) greatly exceed the helicon damping time ($\lambda_*/s_* \sim 10^{-6}$), the contribution of the helicon waves to the effects generated by the joint action of the two pulses can be neglected. We shall consider hereafter only the acoustic oscillations:

$$\xi_\pm(z,t)=A\cos[\omega(t-z/s)+\psi]e^{-z/\lambda}, \tag{7}$$

where

$$A=H_1(0)\frac{Zec\omega_c}{M\omega_p^2\omega s}.$$

The wave excited by the field $H(l,t)=H(0,t)$ incident on the surface $z=l$ are described by the expression (7), taken with a minus sign, in which $z$ is replaced by $l-z$. Actually, the equality $H(l,t)=H(0,t)$ is approximate, since a phase difference $\sim\omega l_0/c$ should be present. However, we neglect this difference, since $\omega l_0/c \sim 10^{-5}$. Thus, in experiments on metallic powders the bilateral sound excitation in the particle corresponds to the solution

$$\xi_\pm^{(0)}(z,t)=A\left\{e^{-z/\lambda}\cos\left[\omega\left(t-\frac{z}{s}\right)+\psi\right]-e^{-(l-z)/\lambda}\cos\left[\omega\left(t-\frac{l-z}{s}\right)+\psi\right]\right\}. \tag{8}$$

The superscript (0) indicates that the solution (8) pertains to the time interval $0\le t\le t_1=l/s$.

For times $t>t_1$, the solution of the system (2) is a superposition of multiply reflected waves (8):

$$\xi_\pm(z,t)=\sum_{k=0}^{\infty}\theta(t-kt_l-\varphi_k(z))\xi_\pm^k(z,t),$$

$$\xi_\pm^k(z,t)=\Gamma^k\xi_\pm^{(0)}(\varphi_k(z),t-kt_l-\varphi_k(z)), \tag{9}$$

$$\Gamma=\gamma e^{-l/\lambda}, \quad \varphi_k(z)=\frac{z}{s}\frac{1+(-1)^k}{2}+\frac{l-z}{s}\frac{1-(-1)^k}{2},$$

$$\theta(x)=\begin{cases}1, & x>0\\ 0, & x\le 0\end{cases},$$

where $\gamma$ is the coefficient of reflection of the acoustic wave from the surface of the metal, and $\varphi_k(z)$ is the phase of the wave after the $k$-th reflection.

When the alternating field is turned off at $t=t_1$, energy ceases to flow into the sample, and the only oscillations that continue to propagate in it are those produced during the time of action of the field. This circumstance is taken into account by the fact that the solution $\xi$ at $t>t_1$ is constructed in the form of a difference:

$$\xi_\pm(z,t;t_1)=\sum_{k=0}^{\infty}\xi_\pm^k(z,t)[\theta(t-kt_l-\varphi_k(z))-\theta(t-t_1-kt_l-\varphi_k(z))]. \tag{10}$$

The action of several RF pulses on the metal particle is described in the linear approximation by a sum of the solutions (10):

$$\xi_\pm(z,t)=\sum_\alpha\xi_\pm(z,t-\tau_\alpha;t_\alpha), \tag{11}$$

where $\tau_\alpha$ and $t_\alpha$ are the start and duration of the $\alpha$-th pulse.

The linear solution (11) makes it possible to determine with the aid of expressions (2) and (3) the electric field $E(z,t)$ inside the metal for the time interval $t>\tau_\alpha+t_\alpha$ with allowance for the nonlinear increment $\Phi$.

4. The echo signals are determined by the magnetic field $H(T)=\sum_i H_i(t)$ produced by all the powder particles after the second pulse of the external alternating field is turned off. The integral form of Maxwell's equations make it possible to connect the field $H_i(t)$ of an individual powder particle with the value of $E(z,t)$ on its surface. This circumstance makes it possible, if the solution (9) is represented in the form

$$\xi_\pm(z,t)=\sum_{k=0}^{n_i-1}\xi_\pm^k(z,t)+\theta(t-n_it_i-\varphi_{n_i}(z))\xi_\pm^{n_i}(z,t), \tag{12}$$

where $n_i=[t/t_i]$ is the integer part of the ratio $t/t_i$, to take into account only the sum, since the last term makes no contribution to the field on the surface.

Summing over $k$ in (12) we obtain for two pulses of duration $t_1$ and $t_2$ separated by an interval $\tau_2$,

$$\xi_\pm(z,t)=Y_{t_1}(z,t)+Y_{t_2}(z,t-\tau_2),$$
$$Y_{t_i}(z,t)=Ae^{i(\omega t+\psi)}\left[\exp\left(-\frac{z}{\lambda}+i\omega\frac{z}{s}\right)-\exp\left(-\frac{l-z}{\lambda}+i\omega\frac{l-z}{s}\right)\right]\frac{(-\varkappa)^{n_{t-t_i}}-(-\varkappa)^{n_t}}{1+\varkappa}+\text{c.c.}, \tag{13}$$

where $\varkappa=\Gamma\exp(-i\omega t_i)$. From (3) and (13) we get the nonlinear increment to the field $H_i(t)$. Retaining only the terms that determine the echo at $t=2\tau_2$, we have

$$H_{iy}(t)=\frac{2E_x(0,t)}{l}=\frac{12D}{Ml}A^3\frac{\omega^4}{s^4}\left|1-\exp\left(-\frac{l}{\lambda}+i\omega t_i\right)\right|^2\times\left\{\mathcal{H}\exp[i\omega(t-2\tau_2)]\left[1-\exp\left(-\frac{l}{\lambda}+i\omega t_i\right)\right]+\text{c.c.}\right\}, \tag{14}$$

$$\mathcal{H}=\frac{(-\varkappa^*)^{n_t}(-\varkappa)^{2n_{t-\tau_2}}}{|1+\varkappa|^2(1+\varkappa)}[1-(-\varkappa)^{n_{t-\tau_2-n_{t-\tau_2-t_2}}}]^2[1-(-\varkappa^*)^{n_{t-n_{t-t_1}}}]$$
$$\approx(-\varkappa^*)^{n_t}(-\varkappa)^{2n_{t-\tau_2}}\left\{\frac{1-(-\varkappa)^{n_{t_2}}}{|1+\varkappa|}\right\}^2\left\{\frac{1-(-\varkappa^*)^{n_{t_1}}}{1+\varkappa}\right\}.$$

The approximate equality in the expression for $\mathcal{H}$ in (14) is valid at $n_{t-t_1}\gg 1$ and $n_{t-\tau_2-t_2}\gg 1$, as is assumed by us. The expressions in the curly brackets describe the action of the alternating-field pulses, and those in front of the curly brackets characterize the damping of the oscillations excited in the metal by these pulses.

Formula (14) is the response of a single powder particle to monochromatic action. The response of the entire powder is given by

$$H_v(t)=\int G(\omega)\,d\omega\int g(l)\,dl\,H_v(t,\omega,l), \tag{15}$$

where $G(\omega)$ is the wave packet of the alternating-field pulse, $g(l)$ is the distribution function of the linear dimensions of the particle. The distribution $g(l)$, which depends on the sample preparation method, is generally speaking not known. For example, the experimental situation in[1] is sufficiently well described by the rectangular distribution

$$g(l)=\frac{1}{l_0}[\theta(l-l_1)-\theta(l-l_2)], \tag{16}$$

where $l_0=l_2-l_1$, and $l_1$ and $l_2$ are the smallest and largest metal particle dimensions. To integrate in (15) it must be recognized that the function (14) has a resonant behavior near the values $\omega t_i=(2n+1)\pi$, where $n$ is an integer (see the Appendix). For reasonable values of the powder-particle dimensions (in [1], e.g., $l_1=10^{-3}$ cm and $l_2=10^{-2}$ cm) and of the pulse frequency-spectrum width, we can confine ourselves to one value, $n=0$. Then (14) takes the form

$$H_v(t)=\frac{24\sqrt{2}}{\pi l_0}\frac{D}{M}\left(\frac{Zec\omega_c}{M\omega_p^2}\right)^3\frac{\omega}{s^7}H_1(0)n_{t_1}H_2^2(0)n_{t_2}^2 \times(1-\Gamma)\Gamma^{2n_{t_1}-t_2+n_t}\cos[\omega(t-2\tau_2)+\psi]\delta\left(l-\frac{\pi s}{\omega}\right). \tag{17}$$

Substituting (17) in the integral if (15) and assuming that the frequency spectrum of the pulse is described by a normal distribution with a mean value $\omega_0$ (the carrier frequency of the external alternating field) and with a second moment $t_i^{-2}$, we get

$$H_v(t)=\frac{24\sqrt{2}}{\pi l_0}\frac{D}{M}\left(\frac{Zec\omega_c}{M\omega_p^2}\right)^3\frac{1}{s^7}H_1(0)n_{t_1}H_2^2(0)n_{t_2}^2(1-\Gamma)\Gamma^{2n_{t_1}-t_2+n_t} \times\omega_0\cos[\omega_0(t-2\tau_2)+\psi]\exp\left\{-\frac{(t-2\tau_2)^2}{2t_i^2}\right\}, \tag{18}$$

$$\Gamma=\gamma\exp(-\pi s/\omega_0\lambda).$$

The expression (18) describes an RF field spike at the carrier frequency $\omega_0$, with an amplitude that has a maximum near $t=2\tau_2$ and a width $\sim t_i$. It is this spike which is detected as the echo signal that appears at a time $\tau_2$ after the second pulse.

5. We now compare the echo-signal properties that follow from (18) with the experimental data of [1].

a) The obtained theoretical dependence of the echo-signal amplitude on the RF field of the pulses $\sim H_1(0)H_2^2(0)$ agrees well with the measurement results of [1]. Deviations from the theoretical relation at $H_1(0)>H_2(0)$ ($H_2(0)=$ const) and at $H_2(0)>H_1(0)$ ($H_1(0)=$ const) can be eliminated by taking into account terms of higher order in $n_{t_i}(1-\Gamma)$ in the derivation of (17). The dependence of the echo signals on the pulse duration was not investigated experimentally.

b) With increasing interval $\tau_2$ between the pulses, the

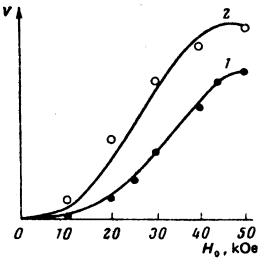


FIG. 2. Echo signal amplitude vs. the constant magnetic field: 1—Au, 2—Ag(0.05% Mn); $T=4.2$ K.

echo amplitude decreases, as follows from (18), in near-exponential fashion:

$$\gamma^{4\omega_0\tau_2/\pi}\exp\left(-\frac{4s}{\lambda}\tau_2\right)\approx\exp\left(-\frac{2\tau_2}{T_*}\right), \qquad T_*^{-1}=2\frac{s}{\lambda}+2\gamma_1\frac{\omega_0}{\pi}, \tag{19}$$

where is was assumed that the wave transmission coefficient $\gamma_1=(1-\gamma)$ is small. Expression (19) agrees fully with experiment.[1]

c) The theoretical dependence of the echo-signal amplitude $V$ and of the relaxation time $T_*$ on the constant magnetic field is described by the expressions

$$V=AH_0^3\exp(-\beta H_0^2), \qquad T_*^{-1}=\tau_{ph}^{-1}+\frac{\beta H_0^2}{2\tau_2}, \qquad \beta=\frac{2\tau_2}{\tau}\frac{Ze^2}{Mm}\frac{c^2\omega_0^2}{s^4\omega_p^4}, \tag{20}$$

where $A$ is a constant. In Fig. 2, curve 1 corresponds to values $A=0.001$ and $\beta=0.456\times10^{-9}\text{Oe}^{-2}$ in (20), and is in splendid agreement with measurements made in gold powder, while curve 2 ($A=0.0035$, $\beta=0.82\times10^{-9}$ $\text{Oe}^{-2}$) describes well the experimental data for silver powder. The experiment in[1] was carried out at $T=4.2$ K, which corresponds to the $\omega_c\tau>1$ assumed above.

The plots of the relaxation time $T_*$ on Fig. 3 fit well the experimental data at values $\tau_{ph}^{-1}=0.0095$ $\mu\text{sec}^{-1}$ and $\beta=0.62\times10^{-11}\text{Oe}^{-2}$ at $\omega_0=10^7$ Hz. With increasing frequency, the theoretical formula describes qualitatively the experimental results, but there is a quantitative difference, due apparently to violation of the "locality" limit $qv_F/\omega_c\ll1$. We note the importance of investigating relations of this type in order to determine the value of the non-electronic damping of the sound in metals.

d) A qualitative agreement of the experimental and theoretical results is obtained also for the temperature dependence of the echo amplitude on the temperature;

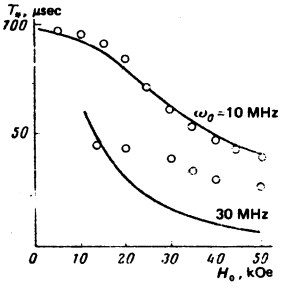


FIG. 3. Field dependence of the relaxation time.

this dependence, according to (18), is due to the temperature dependence of the electron free path time $\tau$ and the time $\tau_{ph}$ of non-electronic sound damping.

Thus, the good qualitative agreement between the theory developed here and the experimental data offers evidence in favor of the physical model assumed by us for echo formation in metallic powders. A quantitative comparison and determination of the physical characteristics of the investigated metal is meaningful if the totality of the experimental relations considered above is obtained for a single sample. This, in our opinion, would be a natural continuation of the experiments on echo phenomena in metallic powders.

## APPENDIX

We consider the value of the function (13) on the surface $z = 0$:

$$Y_{t_1}(0,t) = Ae^{i(\omega t+\varphi)}\left(1-\frac{\varkappa}{\gamma}\right)\frac{(-\varkappa)^{n_{t-t_1}}}{1+\varkappa}[1-(-\varkappa)^{n_{t_1}}]+\text{c.c.} \qquad (A.1)$$

In the absence of damping ($\Gamma = \gamma e^{-l/\lambda} = 1$) and under constant action of the alternating field ($n_{t-t_1} = 0, n_{t_1} \to \infty$) we have

$$Y_\infty(0,t) = 4Ae^{i(\omega t+\varphi)}\delta(\omega t_i - \pi(2n+1)), \quad n = 0, 1, 2, \ldots, \qquad (A.2)$$

which reflects the fact that in the stationary regime in the sample there are excited only natural oscillations.

In the case of weak damping [$(1-\Gamma) \ll 1$] over times on the order of the pulse duration [$n_{t_1} \gg 1$, but $(1-\Gamma)n_{t_1} \ll 1$] the amplitude of the function (A.1) is equal to

$$2A[f_1(x)f_2(x)f_3(x)]^{1/2}\Gamma^{n_{t-t_1}+1}, \quad x = \omega t_{i_1} \qquad (A.3)$$

where

$$f_1(x) = 1+\Gamma^2-2\Gamma\cos x, \quad f_2(x) = 1+\Gamma^{2n_{t_1}}-2(-\Gamma)^{n_{t_1}}\cos n_{t_1}x,$$
$$f_3(x) = (1+\Gamma^2+2\Gamma\cos x)^{-1}.$$

The function $f_3$ has a sharp maximum on the order of $(1-\Gamma)^{-2}$ with a width $\sim 2(1-\Gamma)$ at $x = \omega_{t_i} = (2n+1)\pi$. The functions $f_1$ and $f_2$ vary slowly over intervals $\Delta x \sim (1-\Gamma)$, and therefore

$$\begin{aligned}[f_1(x)f_2(x)f_3(x)]^{1/2} &\approx [f_1((2n+1)\pi)f_2((2n+1)\pi)f_3(x)]^{1/2}\\ &\approx n_{t_1}[\theta(x-(2n+1)\pi-1+\Gamma)-\theta(x-(2n+1)\pi+1-\Gamma)]\\ &\approx n_{t_1}2(1-\Gamma)\delta(x-(2n+1)\pi).\end{aligned} \qquad (A.4)$$

Thus, in the case of weak damping of the waves, a good approximation is the assumption that the pulse produces only natural harmonics in the sample, just as in the stationary case.

Recognizing that the quantity $\mathscr{H}$ in (14) is proportional to $\xi^3$, we can easily obtain the following approximation:

$$\mathscr{H} \approx n_{t_1}n_{t_2}^2\sqrt{2}(1-\Gamma)\Gamma^{2n_{t_1}-\tau_2+n_{t_1}}\delta(\omega t_i - \pi(2n+1)), \qquad (A.5)$$

which leads to (17).

[1)] A similar model of a powder provided a good qualitative description of electroacoustic echo in piezo- and ferroelectrics.[7, 8]

[2)] We note that the problem of sound generation by stationary electromagnetic radiation in bounded metal samples was solved by Kravchenko.[9]


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