Mechanisms for formation of a radio-frequency echo in powders

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Two new, nonlinear mechanisms for formation of a radio-frequency echo in different powders, which readily explain the nature and the main properties of the "dynamic" echo and of the "holographic" recording, are proposed. A new effect—a phase modulation of the echo decay with time—is theoretically predicted for the first time.

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We present below two general mechanisms for formation of a radio-frequency (RF) echo in powders in different crystals (see Ref. 1), which explain well the nature and properties of this effect: 1) nonlinear damping Q_N^{-1} due to an amplitude-dependent internal friction; 2) nonlinear dispersion η_N due to an amplitude-dependent modulus defect (see also Ref. 2).

The nature of Q_N and η_N in metals, piezoelectric materials, and paramagnets is associated with a separation of dislocations from the fixing impurities[3] and with the nucleation of fresh dislocations, and in ferro-electric materials it is associated with the vibrations, shift, and reorientation of the domain walls[4,5] in the field of elastic vibrations excited by an RF field. (A mechanism for dislocation nonlinearity of the elastic properties of particles was used to explain the RF echo in piezo- and ferroelectric powders[6]; we show below that this mechanism is a special case of our second mechanism.) For an RF deformation amplitude $y_0 \sim 10^{-8}$–10^{-6} the separation of dislocations and domains is reversible: the dislocation loop (domain wall) breaks away during each vibration half-period and again attaches itself, etc.[3–5] the dependence of Q_N^{-1} and η_N on the elastic deformation amplitude during a free damping $y(t)$ in this case is quadratic:

$$Q_N^{-1}(y) = A_1 y^2, \qquad \eta_N(y) = C_1 y^2; \qquad A_1 \approx C_1 . \tag{1}$$

For $y_0 \sim 10^{-6}$ and higher the detachment from impurities has an irreversible, static nature. Therefore, Q_N^{-1} and η_N for a free damping after a pulsed excitation are amplitude independent and equal to their values at the end of the excitation $Q_N^{-1}(y_0)$ and $\eta_N(y_0)$, where y_0 is the deformation amplitude at the end of the pulse. The amplitude dependence $Q_N^{-1}(y_0)$ and $\eta_N(y_0)$ is quadratic and becomes linear with increasing y_0. For a free damping we have for Q_N^{-1} and η_N, respectively,

$$Q_N^{-1} \approx Q_N^{-1}(y_0) = A_2 y_0^2 = \text{const}, \qquad \eta_N \approx \eta_N(y_0) = C_2 y_0^2 = \text{const} ; \tag{2}$$

$$Q_N^{-1} \approx Q_N^{-1}(y_0) = A_3 y_0 = \text{const}, \qquad \eta_N \approx \eta_N(y_0) = C_3 y_0 = \text{const} . \tag{3}$$

The *emf* $\mathscr{E}(t)$ induced by a vibrating particle in the receiving circuit is proportional to the deformation amplitude $y(t)$. In the case of a reversible detachment (1) we have for $y(t)$ the following equation after the pulse:

$$\dot{y} + (\Gamma - i\omega)\, y - i\,\nu |\, y|^2 y = 0; \qquad \nu = \frac{\Omega}{2}(C_1 + i A_1), \tag{4}$$

where Γ is an amplitude-independent damping parameter, $\omega = \omega_0 - \Omega$, and ω_0 and Ω are the frequencies of the RF field and of the natural oscillations of a particle. Solving Eq. (4) for a two-pulse excitation and using Gould's formalism,[1,2] we find the response sequence in terms of the first-order Bessel functions $J_n(q_1)$, where $n = 1, 2, 3, \ldots,$

$$q_1 = \frac{\Omega}{2\Gamma}(C_1 + i A_1) y_1 y_2 e^{-\widetilde{\Gamma}_1 \tau}[1 - e^{-2\Gamma(t-\tau)}] . \tag{5}$$

Henceforth $\widetilde{\Gamma}_i = \widetilde{T}_{2i}^{-1}$ is the amplitude-dependent damping and τ is the pulse spacing. If $|q_1|^2 \ll 1$, then the expression for the first signal of a two-pulse echo will have the form

$$\mathscr{E}_1(t = 2\tau) \sim \int_0^\infty G(\omega)\, d\omega\, y_2 \frac{|q_1|}{2} e^{-\widetilde{\Gamma}_2 \tau} \cos\left[\text{arc tg}\,\frac{A_1}{C_1} + \psi_1(y_1, y_2, \tau)\right], \tag{6}$$

where $G(\omega)$ is the frequency distribution of particles and y_i is the amplitude of deformation produced by the ith pulse,

$$\psi_1(y_1, y_2, \tau) = \frac{\Omega}{2\Gamma} C_1 (1 - e^{-2\Gamma\tau})[y_2^2 - y_1^2(1 - e^{-2\widetilde{\Gamma}_1 \tau})] . \tag{7}$$

In the static case (2) in Eq. (6) instead of q_1 and ψ_1 we have

$$q_2 = \Omega(C_2 + iA_2)\gamma_1\gamma_2\tau e^{-\widetilde{\Gamma}_3\tau}, \quad \psi_2(\gamma_1, \gamma_2, \tau) = \frac{\Omega}{2} C_2\tau\left[\gamma_2^2 - \gamma_1^2(1 - e^{-2\widetilde{\Gamma}_3\tau})\right]. \tag{8}$$

We shall limit ourselves to the two limiting cases in the linear region (3): (a) $y_1 \gg y_2$ and (b) $y_2 \gg y_1$. We find for them in Eq. (6):

$$\text{a) } q_3 = \frac{\Omega}{2}(C_3 + iA_3)\gamma_2\tau, \qquad \psi_3(\gamma_1, \tau) = -\frac{\Omega}{2} C_2\gamma_1\tau\,(1 - e^{-\widetilde{\Gamma}_4\tau}); \tag{9}$$

$$\text{b) } q_4 = \frac{\Omega}{2}(C_3 + iA_3)\gamma_1\tau e^{-\widetilde{\Gamma}_4\tau}, \qquad \psi_4(\gamma_1, \gamma_2, \tau) = \frac{\Omega}{2} C_3\tau(\gamma_2 - \gamma_1). \tag{10}$$

The first signal of a stimulated echo in a three-pulse echo, which is governed by the mechanisms (1), is characterized by the constant $T_1 = T_2/2$. In the case of the mechanisms (2) or (3) T_1 is determined by the recovery time of $Q_N^{-1}(y_0)$ and $\eta_N(y_0)$, which is of the order of several hours and even many days. For cases (a) and (b), the first stimulated echo has the form

$$\text{a) } \mathscr{E}_1(t = \tau_1 + \tau) \sim \gamma_3 q_3 \sim \gamma_2\gamma_3; \qquad \text{b) } \mathscr{E}_1(t = \tau_1 + \tau) \sim \gamma_3 q_4 \sim \gamma_1\gamma_3, \tag{11}$$

where τ_1 is the third pulsing.

The main result of the investigation is $\mathscr{E}_n \sim J_n(q_i)$ in all cases, and for $|q_i|^2 \ll 1$ and $\mathscr{E}_1 \sim |q_i| \sim |\eta_N + \tau Q_N^{-1}|$ for the primary echo; i.e., the signal is proportional to η_N and Q_N^{-1}. It seems that the dynamic echo[1] is caused by a reversible separation of dislocations (domains), and a "holographic" recording is a consequence of an irreversible motion or nucleation of fresh dislocations and domains. The pulse fields used in the experiments produce $y_0 \sim 10^{-7}$–10^{-4}. Using the experimental data for $Q_N^{-1}(y_0)$ and $\eta_N(y_0)$,[3,5] we can easily see from Eqs. (8), (9), or (10) that at $y_0 \sim 10^{-5} |q_i| \sim 1$ in piezoelectric materials, metals, and paramagnetic materials and it has the same value even at $y_0 \sim 10^{-6}$ in ferroelectric powders. This means that the proposed mechanisms are highly effective and that equations such as (6), which were obtained by expanding $J_n(q_i)$ in powers of q_i, are constrained by small excitation pulses. This conclusion correlates with the experiments[1] which showed that at small fields the weak-signal approximation breaks down.

It follows from Eq. (6) with allowance for Eqs. (9) and (10) that at $y_1 \gg y_2$ the amplitude of the signal is independent of y_1, and at $y_2 \gg y_1$ it increases linearly with y_2, which has been confirmed experimentally.[1,7] Under these conditions the signal from the stimulated echo is independent of y_1 and y_2, respectively (see Ref. 11), which also coincides with the experiment.[7]

An important consequence of equations such as (6) is that if

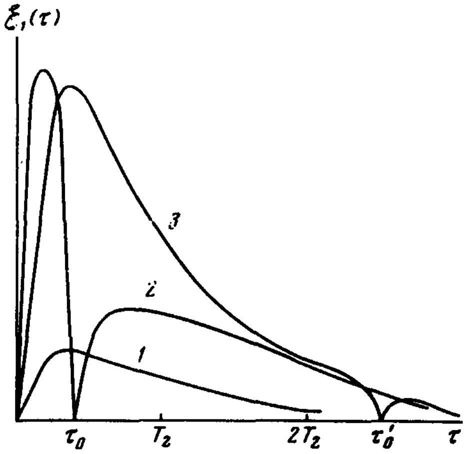

FIG. 1. Dependence of a two-pulse echo $\mathscr{E}_1(\tau)$ on the pulse spacing τ: (1) for a reversible separation; (2) and (3) for an irreversible separation: (2) $y_1 > y_2$ and (3) $y_2 > y_1$.

$$\operatorname{arctg}\frac{A_i}{C_i} + \psi_i = \pm(2n+1)\frac{\pi}{2}; \qquad n = 0, 1, 2, \ldots \tag{12}$$

the amplitude of the signal vanishes. Since ψ_1 is finite and small for any value of τ, we can see that condition (12) is not satisfied for a dynamic echo and the signal, after increasing from zero at $\tau = 0$ to a certain maximum, monotonically decreases with increasing τ (see curve 1 in Fig. 1). The condition (12) is satisfied for ψ_2 at $y_1 > y_2$ and for ψ_2 when the sign on the right-hand side is negative, and it is satisfied for ψ_2 at $y_2 > y_1$ and for ψ_4 when the sign is positive. The estimates show that for $y_1 > y_2$ the first minimum occurs when $\tau_0 \lesssim T_2$ (curve 2), and for $y_2 > y_1$ it occurs when $\tau_0' > T_2$ curve (3). The analyzed effect, a consequence of a nonlinear dispersion, generally characterizes all Gould-type echo effects.[2] In the special case: $n = 0$, $y_1 > y_2$ this effect was observed by Fossheim *et al.*,[1] but they did not explain it. The importance of Eq. (12) is that is makes it possible to determine the values of Q_N^{-1} and η_N experimentally.

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