LITERATURE CITED

1. O. M. Alishaeva and V. M. Entov, "Effect of an inaccessible pore volume on the displacement of oil by a polymer solution," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 6, 92-97 (1983).
2. V. M. Entov and A. M. Polishuk, "Role of sorption processes in the movement of polymer solutions in a porous medium," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 3, 68-76 (1975).
3. V. M. Entov, A. Ya. Fel'dman, and É. Chen-Sin, "Modeling the process of capillary displacement in a porous medium," Izv. Akad. Nauk SSSR, Programmirovanie, No. 3, 67-74 (1975).
4. I. Fatt, "The network model of porous media, I-III," Trans. AIME, 207, 144-181 (1956).

INFLUENCE OF AN EXTERNAL ELECTRIC FIELD ON THE PROPAGATION OF ULTRASOUND IN ELECTRORHEOLOGICAL SUSPENSIONS

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The influence of a constant external electric field on the velocity and attenuation of ultrasound in electrorheological suspensions is studied experimentally.

It is a well-known fact [1] that the elastic properties of liquids depend in different ways on the presence of polar or nonpolar solvents. An electric field, which orients the molecular dipoles, must affect the elastic properties of polar liquids. Such an influence can be detected by measuring the velocity of ultrasound [2]. Experimental and theoretical studies of the variation of the amplitude or phase of ultrasonic waves transmitted through a liquid in an electric field have been reported in a number of papers [1-6]. For example, Barone and Giacomini [3] have investigated the influence of an electric field on the orientation of constant molecular dipoles and also the variation of the viscosity and compressibility of "pure" polar liquids. Quartz oscillator crystals were immersed in nitrobenzene at a distance of 5 mm from a reflector. A slight variation of the oscillation frequency was observed when a potential of 4 kV was applied between the reflector and the forward electrode of the crystal. In this case the electric field vector was parallel to the direction of sound propagation. However, the observed frequency variation could not be unequivocally attributed to molecular orientation or heating of the medium. Nolle [4], proceeding from the premise of a variation of the sound velocity in liquids and the results of the experiments reported in [3], tested the hypothesis of phase modulation by an electric field in the case of perpendicular orientation. It was found that amplitude modulation is absent in all liquids, i.e., the acoustic attenuation is unaffected by an electric field. Phase modulation was observed in conducting liquids ($\nu = 5 \cdot 10^6$ S/cm). It was inferred from the form of the phase modulation (quadratic dependence on E) that thermal effects play the dominant role. However, Nolle observed appreciable amplitude and phase modulation when an adsorbing material, glass wool, was placed in the liquid; this result was attributed to the mechanical motion of the glass fibers. The measurements were carried out within error limits of $5 \cdot 10^{-4}$ dB/cm in a field of 1 kV/cm. Nolle's results were corroborated by Bonetti [5] in experiments with nitrobenzene, in which an electric field was not observed to have any influence on the velocity of ultrasound.

Thus, an analysis of the investigations reported to date shows that an electric field does not alter the amplitude and phase characteristics of sound propagating in "pure" liquids if the internal heating factor, which tends to diminish the field dependence of the ultrasound velocity in the majority of media, is eliminated. We have been unable to locate similar studies for disperse systems.

In our experiments we used electrorheological (ER) suspensions, for which it had been established previously in shear macroflows that the viscoplastic properties depend strongly

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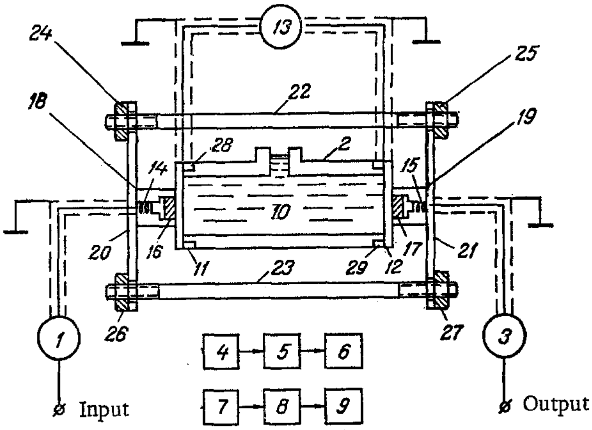

Fig. 1. Schematic view of apparatus for measuring the velocity and attenuation of ultrasound in electrorheological suspensions.

on the electric field [7]. The base of the suspension was transformer oil with additives of finely dispersed diatomite powder (2, 5, and 10% by weight). The average grain size of the diatomite powder, determined by a sedimentation procedure and also by means of a Coulter counter, ranged from 10 to 20 μm. Oleic acid dosed to 9-10% of the mass of the disperse phase was used as a surface-active agent. The activator was water (5-7%).

A special apparatus was developed to measure the velocity and attenuation of ultrasound in liquid media and suspensions under the action of an external electric field. Its operation was based on the technique of measuring the velocity of ultrasound by comparing the transit time τ_t of an ultrasonic signal in the investigated medium with the delay time τ_d of a reference signal in a standard delay line. The electrical signal in the standard delay line was delayed up to $\tau_d = \tau_t$, making it possible to perform a null comparison and to reduce the error of measurement of the ultrasonic transit time to 0.5 nsec [8].

Figure 1 shows a schematic diagram of the apparatus for measuring the velocity and attenuation of ultrasound. It contains, connected in series, a quartz oscillator–pulse shaper 1 for generation of the reference and delayed pulses, for which an industrial I2-17 time-interval meter is used, an acoustic chamber 2, an amplifier–pulse shaper 3, an amplitude detector 3, a repeater 5, and a digital voltmeter 6. In addition, the amplifier–shaper 3 and the oscillator–shaper 1 are separated by a mutual time-comparison network 7, which is connected through a monostable pulse generator 8 to an optical display 9, in this case a light-emitting diode (LED).

The acoustic chamber has a volume $\sim$6 cm^3 and is filled with the ER suspension 10. The outer casing of the chamber is detachable, and it is fitted with thin plane-parallel stainless steel metal electrodes 11, 12, which are connected electrically to an external high-voltage source 13. Piezoelectric transducers 16, 17, which have a resonance frequency of 1 MHz, are pressed against the casing by springs 14, 15. (Measurements were also carried out at f = 2.7 MHz.) To eliminate stray currents and to ensure a snug fit between the detachable parts of the acoustic chamber 2, metal shields 18, 19 are pressed against the chamber by rigid textolite plates 20, 21 and tension bolts 22, 23, and the whole assembly is tightened by means of nuts 24-27. The casing of the chamber is made of a Teflon-type (fluoroplastic) insulation material and is degreased to prevent any possible surface leakage of electrical charges. The wall thicknesses of the acoustic chamber 2 on the sides where ultrasound is transmitted and the thicknesses of the metal shields 18, 19 and flat electrodes 11, 12 have been chosen with a view toward maximum acoustic transmissivity and are multiples of half the ultrasonic wavelength, thus ensuring minimum losses of ultrasonic signal energy. For example, the wall thicknesses of the chamber 2 are equal to 1.3 mm, corresponding to the ultrasonic wavelength in the fluoroplastic material at a frequency of 1 MHz, and the thicknesses of the shields 18, 19 and the electrodes 11, 12 are equal to 0.5 mm, which is much smaller than the ultrasonic wavelength in steel and does not exert any appreciable influence on the attenuation of ultrasound. The electrodes 11, 12, like the piezoelectric transducers and shields, are identical; they are fitted onto the structural supports 28, 29 of the chamber 2 and are oriented plane-parallel relative to one another and to the transducers, so that in

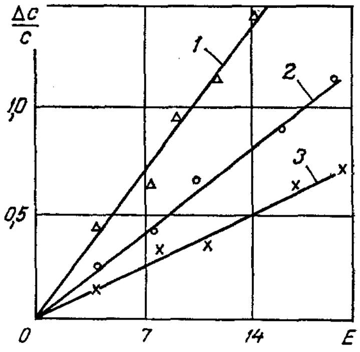

Fig. 2. Relative variation of the velocity of ultrasound $\Delta c/c$, %, vs electric field intensity E, kV/cm. 1) ψ = 10% (by weight); 2) 5%; 3) 2%.

conjunction with the high-voltage source 13 they generate in the acoustic chamber 2 an electric field, the intensity vector of which is in the direction of propagation of ultrasonic waves in the suspension 10. Inasmuch as the fluoroplastic material is an insulator and withstands an electric field up to 20 kV/mm, and as the plane-parallel electrodes 11, 12 are mounted on the supports 28, 29 of the chamber 2 to prevent their deformation (the chamber has an acoustic baseline of 4 mm), an electric field with a high degree of uniformity and a strength up to 2 kV/mm is created in the chamber by means of the source 13.

The measurements were carried out as follows. Reference pulses with a low repetition rate were sent from the output of the I2-17 instrument to the radiating transducer 16, which transformed them into ultrasonic pulse signals. The latter were transmitted through the thin wall of the electrostatic shield 18, the insulating wall of the acoustic chamber, 2, and the electrode 11, entering the suspension 10, in which they propagated in the direction from the radiating transducer 16 to the receiving transducer 17 in a time τ_t. The reference pulses from the I2-17 instrument were thus converted into ultrasonic probe signals, and their repetition period was selected according to the condition $T_{rep} \gg \tau_t$, which is necessary in order to protect the measurement circuit effectively against reverberation noise effects. After the transit time τ_t the ultrasonic waves reached the second electrode 12, then passed through the insulating wall of the acoustic chamber 2 and the thin wall of the shield 19, and excited the receiving transducer 17, which, in turn, converted the ultrasonic waves into electrical signals. The latter were amplified to a definite level in the amplifier—shaper 3 and were then sent to the amplitude detector 4 and the mutual time-comparison network 7. Besides generating reference probe pulses, the I2-17 instrument also functions as a pulse delay device, where the delay time can be adjusted relative to the reference pulse train within 0.5 nsec error limits, which is ensured within the coarse delay range by the high frequency stability of the quartz oscillator and in the fine delay range by the performance parameters of the tunable signal delay line. The value of the delay time τ_d is set in the I2-17 instrument equal to the transit time of ultrasound in the medium, i.e., $\tau_d = \tau_t$; this equality is monitored by means of the mutual time-comparison network 7 with the monostable pulse generator 8 and the LED display 9 connected to it. The operation of the mutual time-comparison network 7 is such that for $\tau_d = \tau_t$ it generates a short trigger pulse to drive the monostable pulse generator 8, which produces an extended pulse to fire the LED 9.

Experiments have shown that the above-described apparatus guarantees an error of comparison of the temporal positions of pulses not exceeding a few tenths of a nanosecond and can therefore be used to obtain a like resolution with respect to the transit time of ultrasound. For $\tau_d = \tau_t$ the readings of the ultrasonic transit time are read from the scale of the I2-17 instrument. The measured value of τ_t represents the sum total of two principal parts: $\tau_t = \tau' + \tau''$, where τ' is the transit time of ultrasound in the suspension and τ'' is the delay time of ultrasound in the structural elements of the chamber. The acoustic chamber was calibrated to improve the accuracy of the measurements. For this purpose the source 13 was turned off, and the empty chamber (without the suspension 10) was disassembled at the locations of the structural supports 28, 29 and was reassembled with the electrodes 11 and 12 right up against one another. The measurement part of the apparatus was turned on, and the delay time

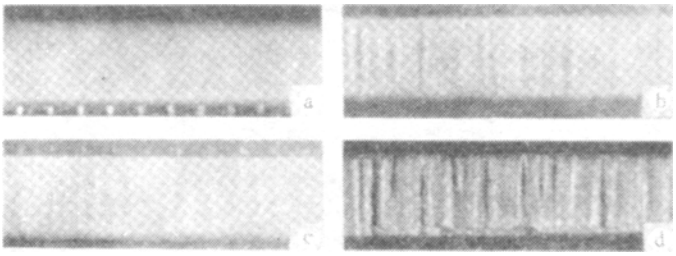

Fig. 3. Photographs of structural formations in a 1% suspension of diatomite in transformer oil for various electric field intensities. a) E = 0 kV/mm; b) 1; c) 2; d) 2.5 kV/mm.

τ'' of ultrasound propagating in the chamber structural elements, which is a constant, was determined. Then the original construction of the chamber was restored. The following quantities were obtained in the investigations: $\tau_t = 7.9$ μsec; $\tau' = 5$ μsec; $\tau'' = 2.9$ μsec. Accordingly, the relative resolution of the apparatus with respect to the ultrasound velocity c is

$$\frac{\Delta c}{c} \simeq \frac{\Delta\tau}{\tau'} \simeq \frac{0.5\cdot 10^{-9}}{5} = 10^{-4} = 0.01\%,$$

which is sufficiently high. The absolute value of the velocity was calculated according to the formula $c = L/\tau'$, where L is the acoustic baseline.

The attenuation of ultrasound in the rheological suspension was determined by measuring the level of an ultrasonic signal transmitted through the circuit comprising the amplitude detector 4, the repeater 5, and the digital voltmeter 6, in which case the frequency and amplitude of the probe pulses were fixed.

Preliminary tests were carried out with transformer oil (in the as-delivered state c = 1420 m/sec), in which variations of the velocity and attenuation of ultrasound in an electric field were not observed. Possible effects at the solid—liquid interface were also excluded. In particular, the probable attraction of surface acoustic waves (SAW's) to the walls of the cell and the formation of chains and clusters can alter the wave impedance and thereby produce an additional phase shift. The velocity and attenuation of ultrasound were measured in a 10% suspension of diatomite without SAW's for fields E = 0, 0.5, 8 kV/cm. The results did not differ from the values of $\Delta c/c$ and α in four-component suspensions. Ultrasonic measurements can also be performed in the absence of SAW's in low-concentration suspensions, reducing the time of all the tests to 1-3 min. The experimental results for ER suspensions are shown in Fig. 2 for a transducer resonance frequency of 1 MHz. With an increase in the electric potential, an increase in the velocity of ultrasound was observed for all the solid-phase concentrations, indicating an increase in the effective elastic properties of the medium [9]. The influence of the solid-phase concentration on the function $\Delta c/c \sim \varphi(E)$ is single-valued. The observed net effect is intensified with an increase in ψ. However, a variation of the amplitude of the ultrasonic pulse in transmission through the ER medium was not detected within the measurement error limits. To assess the influence of the orientation factor a cylindrical fluoroplastic cell of diameter 20 mm and length L = 100 mm was constructed. Piezoelectric transducers were placed at its ends, and metal plate electrodes were mounted along the path of propagation of ultrasound, generating an electric field with an intensity vector $\vec{E}\perp\vec{C}$. Measurements of the delay time of an ultrasonic pulse in the ER suspension did not exhibit any variations in the velocity of ultrasound, but large attenuation of the ultrasonic wave amplitude was observed. For example, the maximum variation of the attenuation coefficient α for a 10% diatomite suspension in transformer oil at U = 8 kV on a 10 cm baseline was 30%.

The results can be interpreted as follows. Under the action of an external electric field the solid-phase particles surrounded by the activator sheathes produce strong aggregates, dendritic formations, and cross-linking structures, which are oriented along the field vector. The electric potential between the solid-phase particles and between the plates and the ends of the bridges increases with an increase in E. Additional particles are pulled into the structural matrix, and the cross-links become stronger. Whereas the medium was previously quasihomogeneous, it now exhibits a distinct stratification (Fig. 3). Auxiliary rigid ducts are ostensibly formed for the ultrasonic signal, where the velocity of propagation is higher than in the fluid suspension. For a perpendicular orientation of the electric field and ultrasonic velocity vectors in the ER suspension, the linear dimensions of the inhomogeneities situated across the ultrasonic wave increase, and, as a result, the losses due to electric interaction of the wave with the structural matrix increase. The impedance of the matrix, whose elements dampen the ultrasonic wave, depends on the value of E. In the final analysis, this means that the mechanical energy losses and the attenuation coefficient α will increase.

The results obtained here offer convincing evidence that ER suspensions acquire effective elastic properties, which require further study in order to determine the dynamical operating regimes of various devices based on the electrorheological effect.

NOTATION

ν, electrical conductivity, S/cm; E, electric field intensity, kV/cm; τ_t, transit time of an ultrasonic pulse between electrodes, nsec; c, velocity of ultrasound, m/sec; ψ, concentration of the solid phase, %; U, electrical voltage, kV; α, attenuation coefficient, m^{-1}.

LITERATURE CITED

1. A. W. Smith and L. M. Ewing, J. Chem. Phys., 7, 632-638 (1939).
2. R. M. Bolt and A. Giacomini, J. Acoust. Soc. Am., 20, 341-343 (1948).
3. A. Barone and A. Giacomini, Ric. Sci., 15, 263-273 (1945).
4. A. W. Nolle, "Electric-field modulation of ultrasonic signals in liquids," J. Appl. Phys., 20, 589-592 (1949).
5. A. Bonetti, "Velocita degli ultrasuoni in campo elettrico e influenza della temperatura," Ric. Sci., 18, No. 7, 777-780 (1948).
6. S. Backer, "Son et l'ultra-son dans un gas visqueux," Science, 17, 1-43 (1938).
7. A. V. Lykov (ed.), The Electrorheological Effect [in Russian], Nauka i Tekhnika, Minsk (1972).
8. I. A. Chernobai and A. S. Shilyaev, Inventor's Certificate No. 832446: "Technique for the continuous determination of the velocity of ultrasound," Byull. Izobret., No. 19 (1981).
9. I. P. Golyamin (ed.), Ultrasonics, A Short Encyclopedia [in Russian], Sovetskaya Éntsiklopediya, Moscow (1979).