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Abstract

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PHYSICS

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DISPERSION OF THE SPEED OF SOUND AND THE PROPAGATION OF HYPERSOUND IN LIQUIDS

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I. Numerous investigations have been, and continue to be, devoted to the study of the dispersion of the speed of sound in liquids ([1]), which is explained by the great physical interest of the problem, and also by the fact that, with the exception of acetic and propionic acids ([2–4]) and, more recently, carbon disulfide ([5]), in low-viscosity liquids it has not been possible to detect dispersion of the speed of sound in the ultrasonic frequency range (10^6—10^8 Hz).

The quadratic dependence of the sound absorption coefficient α on the sound frequency f in such low-viscosity liquids as benzene, carbon tetrachloride, and many others, persisting up to the highest sound frequencies at which experiments have been performed ($f \sim 200$ MHz), suggests that dispersion of the speed should appear in these liquids at still higher sound frequencies (10^9—10^{10} Hz). Artificial generation and transmission into a liquid of such sound waves still encounter insurmountable difficulties. It is therefore expedient to determine, from a study of the fine structure of the Rayleigh line, the speed of hypersound (frequency 10^{10} Hz) and, comparing it with the values of the ultrasonic speed in the same liquids under the same conditions, to draw quantitative conclusions about the dispersion of the speed of sound. Attempts at such a study were undertaken long ago ([6–8]); however, only recently has this method yielded the first encouraging results ([9–11]).

II. The accuracy of determining the speed of hypersound from measurement of the distance between the components of the fine structure of the line of scattered light in liquids has so far not exceeded 2–5%, i.e., it is much lower than the accuracy of modern methods for determining the speed of sound. Therefore such experiments make it possible to detect only a very appreciable magnitude of dispersion of the speed of sound.

The following considerations may provide guidance in selecting substances in which one may hope to detect appreciable dispersion of the speed of sound.

From the formulas of the relaxation theory ([12]), taking into account one relaxation time and the definition of the second viscosity coefficient, it follows, as is not difficult to see, that the dispersion of the speed of sound is determined by the relation

$$\frac{\Delta v}{v} = \frac{\alpha_\eta v}{f^2(2\pi)^2\tau}\left[\frac{\alpha_{\text{meas}}}{\alpha_\eta} - 1\right], \tag{1}$$

where α_{meas} and $\alpha_\eta = \dfrac{(2\pi)^2 f^2}{2v^3\rho}\,\dfrac{4}{3}\eta$ are, respectively, the measured absorption coefficients and those calculated with allowance only for the first viscosity coefficient η, for sound of frequency f; τ is the relaxation time of the second viscosity coefficient η'. The absorption coefficient due to the second viscosity coefficient $\alpha_{\eta'}$ is determined from the condition $\alpha_{\eta'} = \alpha_{\text{meas}} - \alpha_\eta$. The speed of sound

$v = \frac{1}{2}(v_\infty + v_0)$, where v_∞ is the speed of sound beyond the relaxation region, and v_0 is the ultrasonic speed.

It follows from formula (1) that the dispersion is the greater, the larger $\alpha_{\text{meas}}/\alpha_n$, or, equivalently, the larger η' for a given τ. Thus, for example, for the previously studied ([9–11]) carbon disulfide, benzene, and carbon tetrachloride, $\alpha_{\text{meas}}/\alpha_n$ have, respectively, the values 280, 103, and 25, while $\tau < \frac{1}{2\pi f} \simeq 10^{-9}$ sec for benzene and $\tau = 26\cdot10^{-10}$ sec for carbon disulfide; therefore, in these substances one could expect a noticeable dispersion of the speed of sound, and it was in fact found ([9–11]). In the present work methyl bromide, methylene chloride, and chloroform were studied, since for them the values of the ratio $\alpha_{\text{meas}}/\alpha_n$ are, respectively, 354, 183, and 40.

Measurements of ultrasonic absorption in chloroform and methyl bromide were carried out for frequencies ~ 30 MHz. At this frequency the quadratic law for absorption is satisfied; therefore $\tau \ll \frac{1}{2\pi\cdot30\cdot10^6} = 5.2\cdot10^{-9}$ sec, but apparently, in these liquids, for which $\eta \sim 2\cdot10^{-3}$ poise, the quantity τ has the same order of magnitude as for benzene and carbon tetrachloride. Therefore, in these liquids as well one should expect a noticeable dispersion of the speed of sound.

In methylene chloride, André ([13]) recently found a strong dependence of α/f^2 on frequency in the interval 7.54–209 MHz. From these data André finds the relaxation frequency $f_c = \frac{1}{2\pi\tau} = 170$ MHz; consequently, $\tau = 9.3\cdot10^{-10}$ sec, whence, according to (1), one may expect a sound dispersion of more than 5%.

III. The investigation was carried out on an apparatus described earlier ([14]). A Fabry–Perot etalon was used, with a 5 mm spacing between the interferometer mirrors, coupled with an ISP-51 spectrograph. The focal length

of the camera objective was 60 cm. The 4358 Å line of the mercury spectrum in a low-pressure arc was used as the exciting light; the liquids were obtained in sealed ampoules with the qualification "pure."

The hypersonic speed was calculated by the formula

$$v' = c\Lambda\Delta\nu, \tag{2}$$

where c is the speed of light, $\Delta\nu$ is the frequency shift of the components (the Mandelstam–Brillouin components), and the hypersonic wavelength $\Lambda = \frac{\lambda}{2n\sin\vartheta/2}$ (here λ is the wavelength of light, n is the refractive index, and ϑ is the scattering angle).

The results of measuring the hypersonic speed are given in Tables 1 and 2. Each photograph was processed several times, and the values given are averages of several measurements*.

Table 1

Hypersonic speed in methylene chloride at 20°
(ultrasonic speed $v_0 = 1092$ m/sec)

Photograph Nos.	1	2	3	6	7	Average
Hypersonic speed in m/sec	1257	1255	1235	1220	1259	1245 ± 36

$$\Delta v/v = 12.3\%$$

Table 2

Hypersonic speed in methyl bromide at 24°
(ultrasonic speed $v_0 = 971$ m/sec)

Photograph Nos.	2	3	4	6	7	Average
Hypersonic speed in m/sec	1106	1106	1121	1087	1074	1099 ± 30

$$\Delta v/v = 11.6\%$$

* In the present work, as in works ([9–11]), some difference was observed in the magnitude of $\Delta\nu$ for the Stokes and anti-Stokes Mandelstam–Brillouin components. The cause of this phenomenon remains unclear.

The Mandelstam–Brillouin components in chloroform are not as sharp as in the other two liquids studied; therefore, for chloroform one can speak only of an estimate of the magnitude of the sound velocity and dispersion.* According to this estimate, $v \sim 1200$ m/sec, $\Delta v/v \sim 17\%$, $\tau \sim 0.6 \cdot 10^{-10}$ sec and $a \sim 5 \cdot 10^4$ cm^{-1}.

The experimental values of $\Delta v/v$ make it possible to determine all the parameters of hypersound propagation ([12]). The results of such a determination are given in Table 3.

Table 3

Substance	n	$\frac{\Delta v}{v} \cdot 10^3$	$\eta \cdot 10^{-3}$, poise	η', poise	$\tau \cdot 10^{10}$, sec	$f_c = \frac{1 \cdot 10^8}{2\pi\tau}$, Hz	$\alpha_\eta \cdot 10^{-3}$, cm^{-1}	$\alpha_{\eta'} \cdot 10^{-3}$, cm^{-1}	$\alpha \cdot 10^{-3}$, cm^{-1}	$\alpha\Lambda$
Methylene chloride	1.4237	12.3	4.03	1.1	3.3	4.8	6.1	4.3	10.4	0.26
Methylene bromide	1.5446	11.6	1.4	0.65	1.2	13.3	1.6	12.6	14.2	0.28

Such determinations are valid if the relaxation process responsible for sound absorption can be described by a single relaxation time. If, however, the phenomenon is characterized by two or more relaxation times, then the determination of τ on the basis of formula (1) and the measured $\Delta v/v$ is not legitimate and must be carried out using more complicated formulas.

In work ([13]) it is indicated that absorption in methylene chloride is characterized by two relaxation times.** If one assumes that this is indeed so and that, for methylene chloride, $\tau_1 \simeq 10^{-9}$ sec, then the value of τ_2 must differ from that found by us from formula (1) and placed in Table 3. The results obtained in the present work, as well as the results ([9–11]), are not only of independent interest but are also regarded by us as a strong argument in favor of the correctness of the relaxation theory.

In all cases of liquids in which an appreciable dispersion of the sound velocity was detected, ultrasonic absorption is apparently completely due to a relaxation mechanism.

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* In the future it is planned to study the fine structure of the scattering line in chloroform using a narrower exciting line.

** If, from Andreae' s data, one constructs the absorption curve per wavelength $\alpha\Lambda$ as a function of frequency f, then the last experimental point lies before the maximum of the curve. A rough extrapolation shows that the relaxation frequency

$$f_c = \frac{1}{2\pi\tau} \simeq 300\text{–}320 \text{ MHz}$$

and $\tau \simeq 5 \cdot 10^{-10}$ sec; however, these parameters do not describe the observed

([13]) frequency measurements of α/f^2, which apparently also indicates the impossibility of describing the phenomenon with a single relaxation time.

Note: Figure translations are in progress. See original paper for figures.

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