Generation and Detection of Ultra-High-Frequency Sound in Liquids

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Two schemes using piezoelectric plates to produce acoustic waves in liquids in the kilomegacycle frequency region are described. The use of the thermoelectric method of detecting the acoustic energy in liquids is discussed briefly. Data obtained by these techniques are presented.

INTRODUCTION

THE problem of generating and propagating acoustic waves in liquids in the ultra-high frequency range has been considered by several investigators. Ringo[1] *et al.* succeeded in making acoustic measurements in mercury (24–28°C) in the frequency range from 150 to 1000 Mc and observed no significant change in the speed of sound or in the frequency-free absorption coefficient α, f^2 with frequency. More recently Stewart and Stewart[2] have reported observing the reaction on the Q of a resonant electromagnetic cavity, used to excite a quartz plate at 3.5 kMc, when a layer of water 0.001-in. thick is placed on the radiating surface, thereby succeeding in detecting the uhf acoustic radiation into the liquid.

Although a number of methods have been developed for measuring ultrasonic absorption coefficients in liquids, they all appear to suffer from major disadvantages as the attempt is made to employ them at higher frequencies. The interferometric, the optical, and the pulse methods suffer from alignment problems which become more critical as the wavelength of sound decreases. The assumptions of plane waves and uniform intensity distributions over the wavefronts are inherent in the optical method. The pulse transmission and reflection methods also suffer from limitations imposed by the transit time of a pulse of sound.

It is the purpose of this paper to describe briefly the transient thermoelectric method of detecting sound in liquids and to describe the use of two methods suitable for exciting X-cut quartz plates at resonance to propagate uhf acoustic waves in liquids. Data obtained by these methods are presented.

EXCITATION OF PIEZOELECTRIC PLATES

Two methods of exciting quartz plates to propagate uhf sound in liquids are described.

The first method can be described as standard as far as the transducer is concerned in that the piezoelectric radiator, a thin X-cut quartz plate electroded on both major faces, is supported by clamping on the periphery. The radiating face is in contact with the liquid medium under investigation and the opposite face is terminated by a material of low characteristic acoustic impedance. The radiating face is held at ground potential and the opposite face is electrically connected to the oscillator via one or more inserted short sections of coaxial transmission line and 50-ohm cable, as illustrated in Fig. 1. The inserted sections are designed to produce an impedance match between the 50-ohm line and the quartz plate assembly. For example, in the case of a single insert, the characteristic impedance of the coaxial section is designed, as is common practice, to be the root mean square of the input impedance of the transducer assembly and that of the 50-ohm line and its length is chosen as an odd multiple of a quarter wavelength of the wave in the section.

Quartz plates of such thickness as to have fundamental thickness modes of vibration of 4, 12, 15, 18, and 30 Mc, with diameters ranging from $\frac{1}{4}$ to $\frac{3}{4}$ in., have been employed. These have been operated at the odd harmonics to nearly 2 kMc. That is, for the 4 Mc plate operated at 1948 Mc, the highest operating frequency attempted thus far, the 487th harmonic is excited. The odd harmonic frequencies are excited in order to facilitate the electrical impedance match between the quartz plate assembly and the 50-ohm transmission line necessitated by the fact that the pulse lengths employed (0.1 sec) result in the establishment of steady-state conditions in the vibrating element.

The second method of exciting the quartz plate utilizes a resonant electromagnetic cavity. Here, the electroded quartz plate is placed in the reentrant structure of a cylindrical cavity, as shown in Fig. 2. The

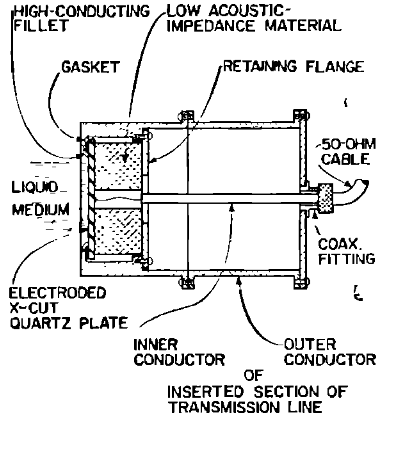

FIG. 1. Schematic diagram of transmission line coupling method of exciting X cut quartz plate.

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[1] G. R. Ringo, J. W. Fitzgerald, and B. G. Hurdle, Phys. Rev. 72, 87 (1947).

[2] J. L. Stewart and E. S. Stewart, J. Acoust. Soc. Am. 33, 538 (1961).

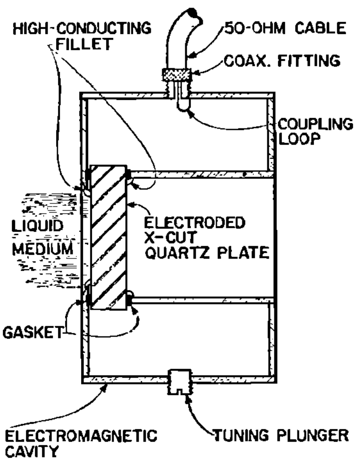

FIG. 2. Schematic diagram of resonant electromagnetic cavity transducer.

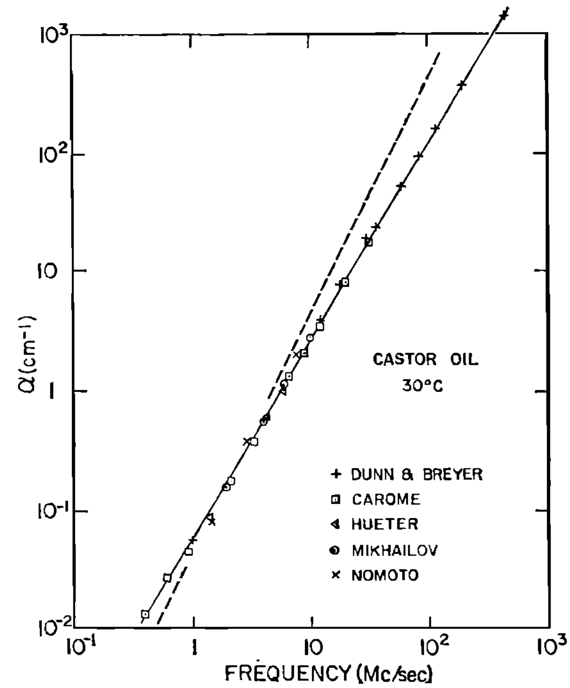

FIG. 4. Acoustic amplitude absorption coefficient of castor oil vs frequency at 30°C.

design of the cavity follows from established engineering principles,[3] taking due account of the fact that the relative dielectric constant of the piezoelectric material is considerably greater than unity. Accordingly, a cavity transducer was designed and fabricated to resonate at 820 Mc, the 205th harmonic of the 4-Mc quartz plate. Excitation was accomplished by coupling the 50-ohm rf transmission line to the fundamental mode of the magnetic field of the cavity via a small wire loop from the center conductor of the transmission line to ground. A threaded plug was provided to enable altering the volume of the cavity for final tuning adjustment. The Q of the cavity, when the quartz plate radiates acoustic waves into a liquid having a $\rho c \simeq 1.5\times 10^5$ g cm sec, is approximately 40, implying a half-power frequency width of approximately 20 Mc. Thus only a few odd harmonic frequencies of the 4-Mc quartz plate can be excited to generate appreciable acoustic intensity in the liquid by the fixed-dimension cavity employed here.

Note added in proof: Since submitting the manuscript for publication, it has been found possible to solder the quartz plate, having vacuum-deposited gold or silver electrodes on the major faces, directly to the metallic members of either transducer, thereby eliminating the gaskets and electrically conducting fillets illustrated in Figs. 1 and 2.

Both methods are capable of producing sound amplitudes of sufficient intensity, in liquids, to be detected with ease. The fixed-dimension cavity method, however, has the inherent disadvantage of being restricted to a narrow frequency range of operation by the electromagnetic Q of the unit. Extension of these methods by an order of magnitude in frequency for investigations in the temperature range of interest for many liquids may be encumbered by the increased attenuation of compressional waves in quartz.[4,5]

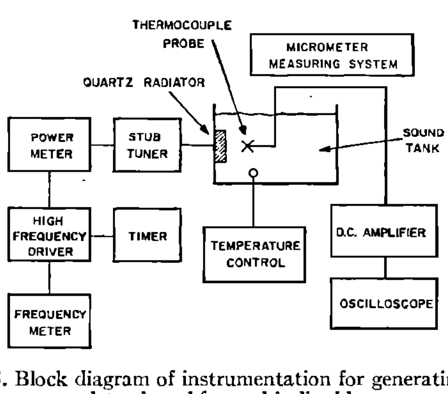

FIG. 3. Block diagram of instrumentation for generating and detecting uhf sound in liquids.

TRANSIENT THERMOELECTRIC METHOD OF DETECTING uhf SOUND

The method used to detect the uhf acoustic waves employs a small copper–Constantan thermocouple probe imbedded in the liquid under study.[6,7] The probe is made by etching commercially available 0.0005-in.-diameter wire in acid in the vicinity of the junction (to reduce the original diameter), and fabricating the thermocouple by a welding technique in which a condenser is discharged through a circuit containing the thermocouple elements. The probes used for making the

[3] See for example, T. Moreno Microwave Transmission Design Data (McGraw-Hill Book Company, Inc., New York, 1948), Chap. 13, p. 210.

[4] H. E. Bömmel and K. Dransfield, Phys. Rev. 117, 1245 (1960).

[5] E. H. Jacobson, in *Quantum Electronics*, edited by C. H. Townes (Columbia University Press, New York, 1960), p. 468.

[6] F. Dunn, J. Acoust. Soc. Am. 32, 1503 (1960).

[7] W. J. Fry and F. Dunn, in *Physical Techniques in Biological Research*, edited by W. L. Nastuck (Academic Press Inc., New York, 1962), Vol. IV, Chap. 6.

measurement described in this paper had a maximum dimension in the neighborhood of the junction of 5μ. This does not represent the minimum size for such probes (for example, 1-μ Wollaston wire is commercially available).

The quartz plate, in contact with the liquid, is excited electrically, at an odd harmonic, to produce a single acoustic pulse with rectangular envelope of 0.1 sec duration. As a result of this relatively short acoustic pulse, the action of the viscous forces brought into play by the relative motion between the thermocouple wires and the imbedding liquid, produces a transient temperature rise in the immediate neighborhood of the thermocouple junction. The transient thermal emf produced in the thermocouple circuit is a measure of the acoustic intensity in a plane wave field in the neighborhood of the junction. The transient thermal emf is fed into a dc amplifier which in turn is fed to the vertical deflection plates of an oscilloscope (see Fig. 3). The thermocouple response, which is directly proportional to the acoustic intensity in the neighborhood of the junction, is observed as the deflection of the electron beam spot from its initial equilibrium position. The deflection of the oscilloscope beam spot is observed for varying distances between the source and probe (this measurement being made with a micrometer having a least count of 0.00001 in.). The points are plotted on semilog paper and a straight line of best fit is drawn through the set of points. The acoustic intensity absorption coefficient per unit path length is then readily computed from a knowledge of the slope of this line, assuming that the

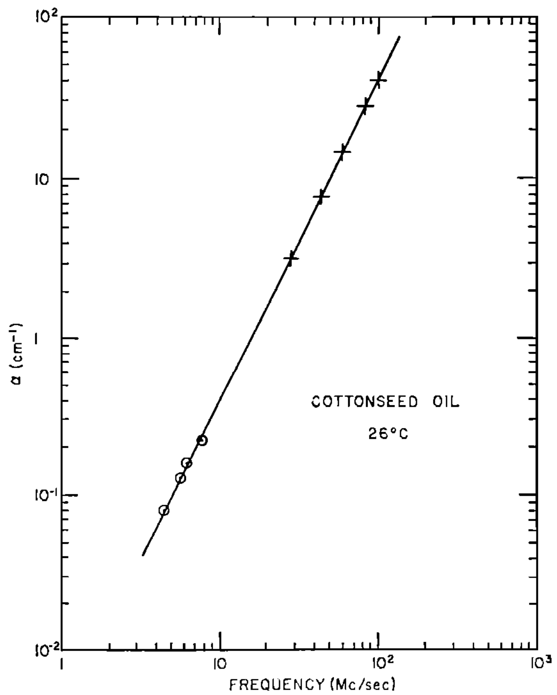

FIG. 5. Acoustic amplitude absorption coefficient of cottonseed oil vs frequency at 26°C; + Dunn and Breyer; ⊙ Mikhailov.[9]

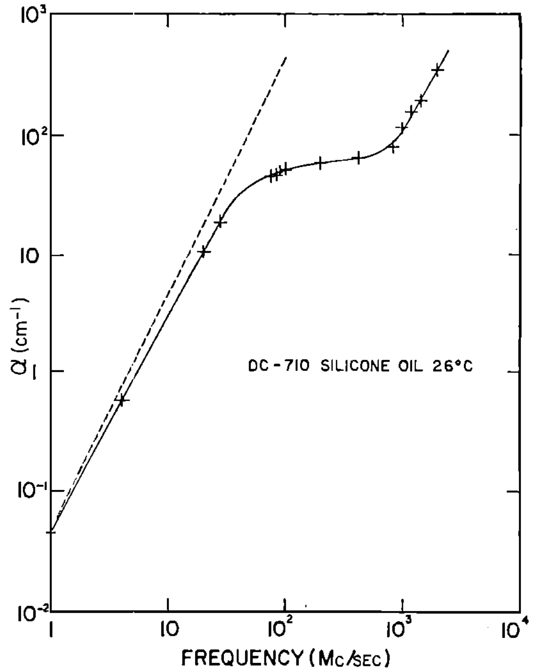

FIG. 6. Acoustic amplitude absorption coefficient of Dow-Corning silicone fluid vs frequency at 26°C.

intensity decreases exponentially with increasing distance from the source.

The transient thermoelectric method of detecting uhf sound in liquids possesses the following advantages over other methods. It is possible to make the detecting element sufficiently small such that variations in the sound field over the detector are negligible. Alignment difficulties are reduced in importance, since accurate travel of the detector in one dimension only is required. The method does not require extended plane wave fronts. The detector is a low-impedance device so that electrical pickup is minimized. Extremely short pulse durations and time resolution of pulses are not required. A disadvantage of the method is that it cannot be used for determining wave shapes.

EXPERIMENTAL RESULTS

For all of the measurements reported below, the acoustic intensity ranges from 10^{-3} to 10^{-2} w/cm^2 and the temperature rise in the liquid varies from 10^{-2} to 10^{-1}°C.

Figure 4 shows the absorption data obtained by the method described above for castor oil at 30°C together with data obtained by other methods.[8–11] It is seen that the agreement between the five independent investigations is generally good. The curve drawn through the

[8] B. J. Wuensch, T. F. Hueter, and M. S. Cohen, J. Acoust. Soc. Am. 28, 311 (1956).
[9] I. G. Mikhailov, Soviet Phys.—Acoustics 3, 187 (1958).
[10] O. Nomoto, T. Kishimoto, and T. Ikeda, Bull. Kobayasi Inst. Phys. Research 2, 72 (1953).
[11] E. F. Carome, John Carroll University, Cleveland, Ohio (private communication).

plotted points has a slope of 1.66. The dashed line is the Stokes low-frequency absorption. The measured values lie below the Stokes values throughout the frequency range above 1 Mc. Figure 5 shows the absorption data for cottonseed oil at 26°C obtained by the method discussed in this paper and by the pulse method.[9] It is seen that cottonseed oil behaves as a true Stokes liquid in the frequency range of measurement from 3–100 Mc. Figure 6 shows absorption data for Dow–Corning silicone fluid 710 at 26°C to nearly 2 kMc determined by the transient thermoelectric method. The point at 1 Mc was also determined by another method.[12] The dashed curve is the Stokes low-frequency absorption. On the assumption of negligible velocity dispersion, the data fits, very closely, a single relaxation process centered at approximately 40 Mc.

SUMMARY

The transient thermoelectric method of detecting uhf sound in liquids is shown to be capable of determining amplitude absorption coefficients at least as high as 1500 cm^{-1} (castor oil at 420 Mc, 30°) and to be operable over the frequency range to at least 2 kMc (Dow–Corning silicone fluid 710, 26°C). Cottonseed oil is shown to be a true Stokes liquid in the frequency range from approximately 3–100 Mc.

Two methods of exciting X-cut quartz plates, at high, odd harmonic frequencies, to radiate sound waves in liquids in the ultra-high-frequency region are shown to be suitable for use with the transient thermoelectric detection method. One method utilizes one or more short sections of coaxial transmission line to obtain an impedance match between the quartz plate assembly and the 50-ohm line to the generator. In the second method, the quartz plate is placed in the reentrant structure of a resonant electromagnetic cavity.

ACKNOWLEDGMENT

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[12] V. A. Del Grosso, U. S. Naval Research Laboratory, Washington, D. C. (private communication).