THE JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA VOLUME 26, NUMBER 3 MAY, 1954

Determination of Absolute Sound Levels and Acoustic Absorption Coefficients by Thermocouple Probes—Experiment*

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(Received April 15, 1953)

A stable, readily constructable thermocouple probe has been developed for determining absolute sound levels in ultrasonic fields in liquid media. This paper includes criteria for design of such probes and a discussion of experimental measurements made with such a device.

It is a consequence of the method that if the sound intensity at an appropriate size thermocouple junction imbedded in an absorbing medium is known the acoustic absorption coefficient of the material can be determined. The method thus makes possible the determination of absorption coefficients of minute quantities of material.

The probe consists of a thermocouple imbedded in a sound absorbing medium which closely matches in density and sound velocity the medium in which the sound level is to be determined. In use the transducer which generates the acoustic field is exctied to generate sound pulses with a rectangular envelope. The initial time rate of change of the temperature at the thermocouple junction is determined. In addition to the measurement of the temperature change, the calculation of the absolute sound intensity requires only a knowledge of the absorption coefficient of the imbedding material and its heat capacity per unit volume at the temperature at which the measurements are made.

The experimental results include a comparison of the sound level determined by a thermocouple probe and a determination by radiation pressure methods. The values obtained by the two methods agree within the uncertainty of the experimental measurements.

I. INTRODUCTION

A HIGHLY stable, small, and readily constructable ultrasonic probe suitable for determining the absolute sound intensity in liquid media is described. It consists of a wire thermocouple imbedded in a sound absorbing medium which closely matches the liquid medium in density and sound velocity. To use the probe the transducer, which generates the acoustic field, is excited to generate sound at the desired frequency in the form of pulses with a rectangular envelope. The initial time rate of change of the temperature at the thermocouple junction is determined by measurements made with a suitable detector in electrical connection with the thermocouple. In addition to the measurement of the temperature change at the junction immediately after initiation of the acoustic disturbance the calculation of the absolute sound intensity requires only a knowledge of the acoustic absorption coefficient of the imbedding material and its heat capacity per unit volume at the temperature at which the measurements are made.

The temperature rise immediately after initiation of the acoustic disturbance can be separated into two components; one resulting from the action of the viscous forces between the wires of the thermocouple and the imbedding fluid medium and the other resulting from the absorption of sound in the interior of the absorbing medium. The component resulting from absorption is used in the calculation of the absolute sound intensity. Other investigators have used acoustic probes consisting of a temperature sensitive element imbedded in a sound absorbing medium[1] and have used the equilibrium temperature rise indicated by the temperature sensitive element as a measure of the sound level. Such probes are usually calibrated in a sound field of known level, if they are to be used for absolute level determination, since, the equilibrium temperature is critically dependent on the geometry and size of such a device. The principle of operation of the probe described in this paper eliminates the difficulties inherent in using the equilibrium temperature rise as an indication of the sound intensity.

It is a consequence of this method that, if the sound intensity at a thermocouple junction imbedded in a material is known, the absorption coefficient of the material can be obtained. Furthermore it makes possible the determination of acoustic absorption coefficients of minute quantities of material. The method, therefore, is especially useful in the study of biological systems.[2,3]

The determination of the absolute sound intensity by the method described herein has been compared with a radiation pressure evaluation. The results obtained by the two methods agree within the experimental uncertainty of the measurements.

We have used thermocouple probes of the type described both to determine absolute sound levels and for routine checking of the acoustic output of focusing irradiators operating at a frequency of one megacycle.

This type of probe is an extremely useful instrument for it (1) is small in size (2) is stable (3) is a primary

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* This research was supported by contract with the Aero Medical Laboratory, Wright-Patterson Air Force Base.

[1] See, for example, S. Morita, J. Phys. Soc. Japan 7, 214-219 (1952).

[2] W. J. Fry and R. B. Fry, J. Acoust. Soc. Am. 25, 6-11 (1953).

[3] Fry, Wulff, Tucker, and Fry, J. Acoust. Soc. Am. 22, 867-876 (1950).

standard for absolute sound level (4) is insensitive to stray rf fields (5) has a low input electrical impedance. The principle is applicable to the determination of the acoustic absorption coefficients of minute amounts of materials. In the application of the method to the determination of the acoustic absorption coefficient of tissue in vivo the thermocouple can also be used to measure the temperature of the tissue at the specific location where the absorption coefficient is being determined.

This type of probe has some undesirable characteristics. The sensitivity is not high when the temperature sensitive element is a thermocouple constructed from metals most readily available in wire form. In addition it is not useful for measurements in sound fields in which a number of frequencies coexist.

II. PROBE DESIGN

A. Qualitative Description

A probe design which has been found satisfactory for use in determining absolute sound levels and beam shapes of acoustic fields set up in water or various salt solutions by focusing irradiators (operating in the one megacycle region of the frequency spectrum) in use in this laboratory is illustrated schematically in Fig. 1. The thermocouple junction is imbedded in a sound absorbing medium (a thin disk of Bakers DB brand castor oil) which acts as the acoustic absorbing material. The oil is separated from the medium in which the sound field is to be studied by thin polyethylene sheets (0.003 in. in thickness). In practice, the orientation of the probe has been such that the direction of propagation of the sound is at an angle of approximately 90° with respect to the direction of the wire. This direction of propagation is desirable since the metal wires have been observed for some configurations and wire sizes to conduct sound to the region of the junction. This effect has only been observed in narrow ranges of angles of incidence considerably different from normal incidence.† Since the characteristic impedance of the castor oil is close to that of water and the various salt solutions used, the percentage of incident sound energy reflected at the interfaces is very small. The thermocouple wire (0.0005 in. diameter in the neighborhood of the junction) and the polyethylene windows are supported by a cylindrical frame which is of an inner diameter large enough to admit the passage of the sound beam through it without interference. The temperature change at the thermocouple junction has been determined in our experiments either by observing visually or recording photographically the deflection of a galvanometer of a magnetic oscillograph connected across the thermocouple or by the use of a dc amplifier (Perkin Elmer Model 53) in conjunction with a pen recorder.

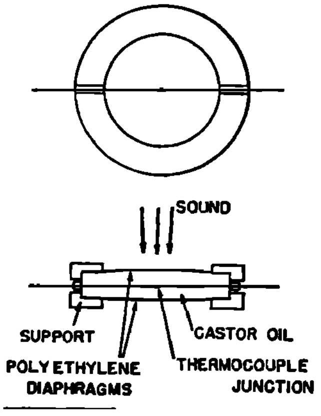

Fig. 1. Schematic diagram of a thermocouple probe.

The temperature change, as indicated by the deflection of a galvanometer, experienced by the thermocouple junction under an acoustic pulse of one second duration is shown in Fig. 2. A relatively rapid rise occurs just after initiation of the disturbance. This is followed by an almost linear rise for the remainder of the pulse. After cessation of the sound a rapid fall in temperature occurs followed by a slow return of the temperature to its value preceding the disturbance. The initial rapid increase in temperature results from the conversion of acoustic energy into heat by the viscous forces acting between the wire and the fluid medium. This phase of the temperature events approaches equilibrium rapidly, the rise time in Fig. 2 is close to that of the response of the galvanometer to a step function input. The second phase of the temperature sequence, the "linear" part, is caused by absorption of sound in the body of the fluid medium. The closeness of approach of this phase to linearity during irradiation is dependent upon the acoustic intensity, the form of the variation of the acoustic absorption coefficient with temperature, the heat conductivity coefficients of the fluid and the wires, the duration of the acoustic disturbance and the acoustic field distribution. With a suitably designed probe this second phase enables one to compute the absolute sound intensity if the absorption coefficient of the imbedding medium is known or if the absolute sound intensity is known the acoustic absorption coefficient can be calculated. The relatively rapid decrease in temperature immediately following termination of the period of radiation results from the removal of the viscous force mechanism which contributed a heat

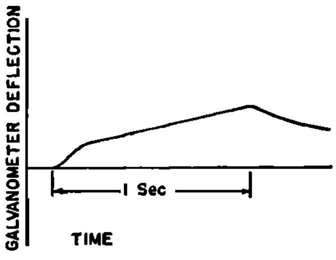

Fig. 2. Temperature change at a thermocouple probe in response to a pulse of ultrasound with a rectangular envelope.

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† Measurements made by D. Tucker at this laboratory.

source confined to the immediate neighborhood of the wire. The subsequent slow phase of the decline in temperature is a consequence of the cooling of the imbedding medium previously heated by absorption in the body of the medium.

The temperature rise of the thermocouple junction resulting from absorption of sound in the body of the imbedding medium is, of course, independent of the direction of propagation of the sound relative to the direction of the wire. However, the temperature rise resulting from the action of the viscous forces between wire and fluid medium is a function of the angle between the direction of propagation of the sound and the direction of the wire. Assuming that the densities and acoustic velocities of the absorbing medium and the liquid in which the sound field exists are closely matched; one can realize a nondirectional characteristic by, for example, subtracting currents or voltages (proportional to the temperature change at the junction) obtained at two different times during a single acoustic pulse. A detector could be constructed to indicate this difference directly.

Another feature of this type of probe which follows from the above description of the components of the response curve is that the recorded response curve on a single acoustic pulse in a single location might be used to determine the acoustic pressure amplitude and also the magnitude of the particle velocity if the direction of the velocity is known, and if the first phase of the response characteristic has been previously related quantitatively to particle velocity by experimental measurement in a pure traveling wave field.

In designing a probe of the type described herein we first note that it is, of course, desirable to choose an absorbing material for the imbedding medium which closely matches in velocity and density the corresponding quantities characterizing the medium in which the sound field is to be detected. For castor oil and water the densities differ by about three percent and the velocities differ by about 1½ percent. The intensity of a plane ultrasonic wave reflected at normal incidence from a water, castor oil boundary is thus of the order of 0.05 percent of the incident intensity if the frequency is low enough so that viscous forces are not of primary importance in determining the reflection coefficient.[4] Such is the case for a castor oil-water boundary at a frequency of one megacycle.

The following criteria determine the design of thermocouple probes to obtain a specified degree of accuracy for either (1) values of absolute sound intensity, if the absorption coefficient of the imbedding material is given or (2) the absorption coefficient if the absolute sound level is known. The relation basic to the evaluation of the quantities specified in (1) and (2) is the following:

$$\mu I = \rho C (dT/dt)_0, \tag{1}$$

where μ designates the acoustic intensity absorption coefficient of the imbedding medium, I represents the acoustic intensity, the product ρC designates the heat capacity of the imbedding fluid per unit volume and $(dT/dt)_0$ indicates the time rate of change of the temperature of the imbedding medium at the time of initiation of an acoustic disturbance (rectangular envelope). For a thermocouple wire diameter, in the neighborhood of the junction, of the order of 0.001 in. and a beam diameter (half intensity) of the order of a few millimeters it is permissible to identify the quantity $(dT/dt)_0$ of Eq. (1) with the initial time rate of change of the temperature indicated by the thermocouple. For a detailed analysis see the accompanying theoretical paper.‡

We now consider the effect of a temperature dependence of the quantity $\mu/\rho C$ on the time rate of change of the temperature.

Let δT_c designate the difference between the temperature rise of the absorbing medium for $\mu/\rho C$ dependent on the temperature and the temperature rise, ΔT_c, of the absorbing medium for $\mu/\rho C$ independent of temperature. Then the ratio $\delta T_c/\Delta T_c$ is a measure of the deviation of the temperature time function from the relation which would be obtained if the value of the quantity $\mu/\rho C$ did not change from that obtaining at the time of initiation of the acoustic disturbance.

$$\frac{\delta T_c}{\Delta T_c} = \left(\frac{\mu}{\rho C}\right)_{T_0} \frac{It}{2} \left[\frac{\partial/\partial T(\mu/\rho C)}{\mu/\rho C}\right]_{T_0} = \frac{\Delta T_c}{2} \left[\frac{\partial/\partial T(\mu/\rho C)}{\mu/\rho C}\right]_{T_0}, \tag{2}$$

where T_0 designates the temperature of the absorbing medium before irradiation and t designates the duration of the acoustic pulse. This formula applies only if

$$\left[\frac{\partial}{\partial T}(\mu/\rho C) \Big/ (\mu/\rho C)\right]_{T_0} \Delta T_c \ll 1.$$

As a specific example,

$$\left[\frac{\partial}{\partial T}(\mu/\rho C) \Big/ (\mu/\rho C)\right]_{25°\mathrm{C}}$$

is equal to about -0.08 for castor oil. For a temperature rise of 1°C the ratio $\delta T_c/\Delta T_c$ is then equal numerically to about 0.04. Relation (2) is used in the processing of experimental data to determine absolute sound intensities by the method described in this paper.

As indicated above in addition to the temperature

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[4] H. L. Oestreicher, J. Acoust. Soc. Am. 23, 707–714 (1951). Using Oestreicher's formulas one computes that for a plane compression wave in castor oil at a frequency of one megacycle the normal pressures differ from one another and from the mean pressure by approximately one part in 10^6.

‡ W. J. Fry and R. B. Fry, J. Acoust. Soc. Am. 26, 294, (1954).

change which occurs as the result of absorption of acoustic energy in the body of the medium, the temperature also changes as the result of the action of viscous forces between the wire and the imbedding fluid. Since in practice the component of the temperature change caused by this mechanism is separated from that resulting from absorption in the body of the medium, the latter alone being used to determine either absolute sound level or acoustic absorption coefficient, it is unnecessary to develop a precise quantitative analysis of this effect for our present purpose. An approximate analysis is given in the theoretical section.

The time rate of conversion of acoustic energy into heat as the result of the action of the viscous forces is dependent on the relative orientation of the wire and the particle velocity of the acoustic disturbance in the neighborhood of the wire. We restrict our consideration of this problem to wire diameters which are much smaller than one wavelength of the acoustic disturbance since this is imposed as a requirement for the probes discussed in this paper.

For wire diameters of interest to us the temperature rise resulting from the action of the viscuous forces reaches an equilibrium distribution during the early part of the linear rise resulting from absorption. It is desirable to estimate the ratio, γ_0, defined as the equilibrium temperature rise at the thermocouple junction resulting from the action of the viscous forces divided by the temperature rise resulting from acoustic absorption in the body of the imbedding medium in the time t. One obtains the approximate relation

$$\gamma_0=\frac{Q_v\rho C}{2\pi K\mu It}[1+\log(r_2/r_0)], \tag{3}$$

where Q_v is the heat generated per second per unit length of wire by the viscous forces, r_0 is the radius of the wire and r_2 is a quantity which is dependent upon the particle velocity distribution within the sound beam. K designates the heat conductivity coefficient of the absorbing medium. For a focused beam with the junction positioned at the central maximum, r_2 can conveniently be taken equal to one-half the beam width at an intensity approximately 0.8 of the peak intensity.

If the wire is oriented transverse to the direction of the particle velocity the quantity Q_v is given by (52) and (57) in conjunction with Table I all of the theoretical paper. For a wire oriented along the direction of the particle velocity expressions (68) and (71) and Table II of the accompanying paper are appropriate.

As a specific example choose a wire diameter of 0.0005 in. (0.0013 cm) and imbed it in castor oil at 25°C ($\eta=6.5$ poises, $\rho C=2.0$ joules/cm^3/C°, $K=0.0018$ watt/cm/C° and $\mu=0.12$ cm^{-1}). Let the frequency of the acoustic disturbance be 1.0 mc and the duration 1.0 sec. For the beam distribution $I=I_0f(r)$, where $f(r)=1-1.48r^2$, r_2/r_0 is of the order of 200 if the junction is placed at the intensity maximum. The computed value of γ_0 is 0.9.

III. EXPERIMENTAL MEASUREMENTS

In this section we present quantitative measurements of absolute sound level (or acoustic absorption coefficient) obtained by using a thermocouple probe in the manner outlined above, i.e., by determining the initial time rate of change of temperature of the medium in which the thermocouple is imbedded when the medium is subjected to a pulse of acoustic radiation with a rectangular envelope. Comparison of the results with radiation pressure measurements is also included herein.

Measurements were made with probes consisting of either a copper constantan or iron constantan thermocouple (wire diameter approximately 0.0005 in. soldered with a lapped junction) imbedded in castor oil. The source of sound, frequency 980 kc, was a focusing irradiator of the type used routinely in this laboratory for accurately controlled irradiation of regions of central nervous systems. The beam width at half intensity is about 4.0 mm. The irradiator is supported in a holder which enables the device to be moved about in the directions of three mutually perpendicular rectangular axes. The probe is held in a fixed position. The direction of propagation of the sound is at right angles to the direction of the thermocouple wires. The acoustic absorption coefficient for castor oil is markedly dependent on the temperature. In practice, therefore, when this material is used, it is necessary to determine the temperature of the probe at the time that measurements in the sound field are made. Accurate values of the absorption coefficient of the absorbing material as a function of temperature must be available in order to use this method. Of course, if an accurate value is available at only one temperature one might adjust the temperature of the bath in which the probe is immersed for the purpose of making measurements. Dr. T. F. Hueter has been kind enough to have ultrasonic absorption coefficient measurements made using the pulse technique at several frequencies and at two temperatures on the particular shipment of castor oil (Baker's DB Brand) that we have used in our thermocouple probes. These data[5] indicate that, in general, the ratio of absorption coefficients at two different temperatures is not equal to the ratio of the shear viscosity coefficients at the two temperatures.

We consider now a typical determination of the absolute sound level at a frequency of 980 kc using a copper-constantan thermocouple (wire diameter given above) probe operating at a base temperature of 25°C. The probe is placed in the center of the focal region of a transducer whose intensity beam pattern in this

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[5] T. F. Hueter and A. Kuckes (private communication). See Quarterly Progress Report, July-September (1952) of the Acoustics Laboratory, M.I.T.

region is plotted in Fig. 3. An analytical expression for the distribution near the maximum is $f(x)=1-1.48x^2$. The records shown in Fig. 4 were obtained with the probe in a fixed position in the sound field of the focusing transducer and in series connection with a galvanometer of a magnetic oscillograph. The three records correspond to three different driving levels at the transducer. The deflection of a second galvanometer of the oscillograph indicated the driving level. The deflections of this second galvanometer are given numerically in the figure. The records of Fig. 4 were obtained with pulses of sound with a rectangular envelope in duration 0.98 second. Although the following quantities are not required in the subsequent calculations we note that the resistance of the thermocouple of the probe is 5.2 ohms, the characteristics of the galvanometer, as mounted in the oscillograph are; sensitivity 4600 mm/ma, resistance 36.0 ohms, and resonant frequency 35 cps.

The initial rapid phase of the deflection records is the result of the action of viscous forces between the fluid medium and the wire. It should be noted that the recorded rise time of this component of the temperature change is limited by the response time of the galvanometer. The galvanometer deflection in response to square wave excitation, differs from its equilibrium value by $1/e$ of that value in approximately 0.017 second.

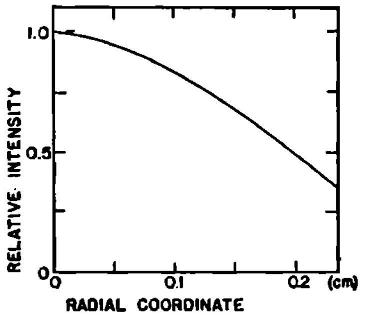

FIG. 3. Beam pattern in the focal region, radial coordinate perpendicular to the direction of propagation.

The second phase of the deflection records, which is the result of temperature changes caused by absorption in the body of the medium, can readily yield the absolute sound level. One procedure is to attempt to obtain the time rate of change of deflection of the galvanometer at the time of initiation of the acoustic disturbance. The linear portion of the curve just following the initial rapid rise furnishes us with an estimate for this quantity. However, it is difficult to decide when the contribution of the first phase to the deflection can be neglected just after the initial rapid rise. In practice, a better procedure is to determine the slope of the second phase at a later time. For the records given in Fig. 4 the slopes were determined at 0.5 second. The value of the acoustic absorption coefficient used in the calculation of absolute level in this case is that corresponding to the temperature obtained by adding to the base temperature the increase corresponding to the deflection (resulting from absorption in the body of the medium alone) at the position at which the slope is being determined. The deflection corresponding to the viscous force action is not included since the resulting temperature change is confined to the immediate neighborhood of the wire. In Fig. 5 the deflection resulting from absorption in the body of the medium is plotted as a function of the square of the deflection of the galvanometer which measures the transducer driving voltage. The points of the curve were obtained from the three records of Fig. 4. The values obtained from Fig. 4, which constitute time rates of change at different temperatures were first corrected to a common temperature (25.0°C) before plotting in Fig. 5. The temperature dependence of the acoustic absorption coefficient and the heat capacity per unit mass are, of course, necessary to this evaluation. The graph of Fig. 5 can be used in conjunction with the relation between temperature rise at the thermocouple junction and the deflection of the gal-

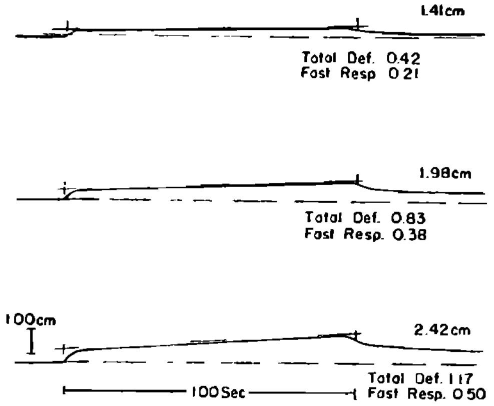

FIG. 4. Galvanometer deflection as a function of time for a copper constantan thermocouple probe subjected to a pulse of radiation at three different sound levels. The number on the upper right of each record is proportional to the acoustic pressure amplitude. The base temperature of the probe was 25.0°C for these records.

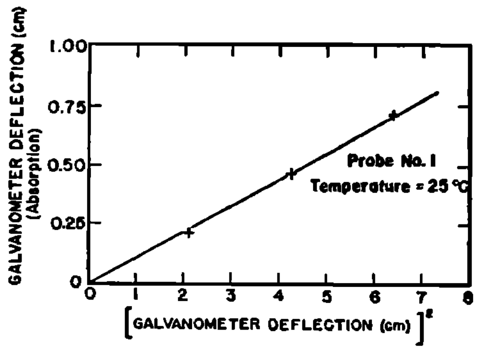

FIG. 5. The ordinate of the graph is proportional to the time rate of change of the temperature of the thermocouple junction resulting only from acoustic absorption in the body of the medium in which the thermocouple is imbedded. The envelope of the ultrasonic pulse is rectangular. The abscissa is proportional to the square of the transducer driving voltage.

vanometer of the oscillograph, which is determined by direct measurement (2.50°C/cm def.) to yield a relation between time rate of change of temperature and transducer driving voltage. The sound intensity corresponding to any time rate of change of temperature then follows from Eq. (1).

As a specific example, we compute the acoustic intensity from the graph of Fig. 5 for a value of the square of the galvanometer deflection of 5.25. The deflection caused by absorption in the oil is, at this driving level, 0.58 cm. Corresponding to this deflection, we compute a value of 1.45°C per second for the time rate of change of temperature. The heat capacity of castor oil per cm^3 at 25°C is 2.02 joules. The intensity absorption coefficient per unit path length extrapolated from values given in reference 5 is, at 25.0°C and 980 kc, equal to 0.140 cm^{-1}. From these values one obtains a value for the intensity from relation (1) of 20.9 watts/cm^2. This is the value of the sound intensity at the thermocouple junction. Since the sound must pass through 2.5 mm of castor oil before reaching the junction one can compute the intensity of the sound incident on the probe by dividing the value just calculated by 0.965. One then obtains for the intensity of the sound incident on the probe a value of 21.7 watts/cm^2.

In Fig. 6 the deflections obtained for one second pulses of radiation are plotted as a function of the square of the deflection of the galvanometer which measures the driving voltage across the transducer. The relation between the galvanometer deflection and the square of the driving voltage is linear at low driving voltages. As the driving voltage increases the relation deviates from linearity, and for this particular probe at a deflection of one centimeter the deviation amounts to about 4 percent. A sensitivity for the probe-galvanometer system can be defined as watts/cm^2 per cm deflection of the galvanometer for a one second pulse of radiation as the deflection approaches zero.

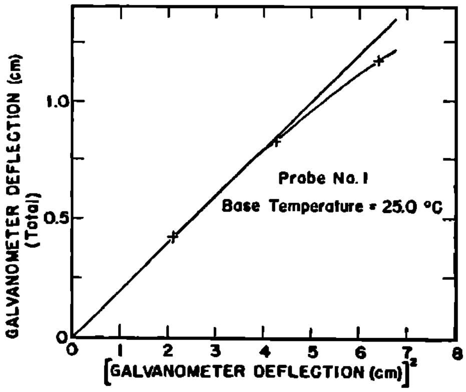

FIG. 6. The ordinate of the graph is proportional to the total temperature change obtained at the thermocouple junction as a result of subjecting the junction to a 1.00-second acoustic pulse with a rectangular envelope. The abscissa is proportional to the square of the transducer driving voltage.

With a detector of increased sensitivity such as a Perkin Elmer dc breaker amplifier, one has available a working range for the purpose of beam pattern measurements which is suitably linear for the probe described. The sensitivity of the probe under discussion is 20.8 watts/cm^2/cm def. over the linear range which is limited to sound intensities less than about 15 watts/cm^2.

It is convenient in practice, when using a probe-galvanometer system of the type used in this laboratory, to define also a sensitivity for the probe-galvanometer system as: watts/cm^2 to obtain a one centimeter deflection of the galvanometer for a one second pulse of radiation. Frequency and base temperature are also specified. From the graph, Fig. 6, and the specific value of intensity calculated above using the graph of Fig. 5, we note that the probe has a sensitivity as just defined of 21.7 watts/cm^2 to obtain a one centimeter deflection with a one second pulse of radiation, at a base temperature of the probe of 25.0°C and a frequency of 980 kc. It would, of course, be highly desirable to have a probe of this type whose sensitivity is relatively independent of the base temperature. Other materials may be more suitable than castor oil in this respect.

The numerical value just quoted for the sensitivity of the probe, which was obtained by calculation based on the absorption coefficient, will be compared with a value for the same quantity obtained by inserting the probe into a position in a sound field where the sound intensity has been determined by radiation pressure measurements. The radiation pressure measurements were made following the method described by other investigators.[6]

To obtain a value for the sensitivity based on radiation pressure measurements one reads the rf voltage across the transducer for a one centimeter deflection of the galvanometer across the probe. Then, from the measured values of radiation pressure as a function of transducer driving voltage, one can compute the acoustic intensity as a function of the voltage. The intensity corresponding to a driving voltage which yields a one centimeter deflection of the thermocouple probe-galvanometer system is then immediately available. Several determinations of the sensitivity of probe No. 1 by the radiation pressure method were made over a period of months. The average of these determinations ($T=25.0$°C) is 22.5 watts/cm^2 to obtain a one centimeter deflection with a pulse length of 1.00 sec. This is to be compared with the value 21.7 watts/cm^2 computed above on the basis of the acoustic absorption coefficient. The two values differ by less than 4 percent, the value obtained from radiation pressure measurements being higher.

If the absolute sound intensity is known at the position of a thermocouple junction imbedded in a

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[6] F. E. Fox and V. Griffing, J. Acoust. Soc. Am. **21**, 352 (1949).

medium subjected to an acoustic disturbance, the absorption coefficient can be computed from measurements of the type just described. It is, of course, necessary to take into account the probe design criteria discussed in detail in the theoretical paper in order to estimate the degree of accuracy of values of the absorption coefficient μ computed on the basis of relation (1). This method of determining absorption coefficients has the great advantage of requiring only a small amount of the material. This is extremely useful in studying biological systems.

A thermocouple probe similar to the one used to obtain results presented above and operated within the linear range was compared with a small $BaTiO_3$ probe and with a radiation pressure detector utilizing a small ball (0.062 in. in diameter) from the viewpoint of determining field distributions. For this purpose, the focusing transducer referred to previously in this paper was used to generate sound pulses of one second duration. The thermocouple probe was placed in the focal region of the field with the thermocouple direction at right angles to the direction of propagation. In order to determine the accuracy of field distributions determined by the total deflection of the galvanometer across the thermocouple probe two types of tests were performed.

First, the beam distribution in a radial direction perpendicular to the direction of propagation was determined by moving the probe from one point to the next parallel to the direction of the thermocouple wires (in the neighborhood of the junction) and then by moving it in a direction at right angles to the wire direction. The two patterns obtained in this manner match within the accuracy of the experimental measurements. If we assume that the field is cylindrically symmetrical this shows that the orientation of the wire leads to the thermocouple junction does not affect the measured distribution pattern for fields varying with space coordinates as rapidly as the field of Fig. 7. In order to check the symmetry of the field the thermocouple probe was rotated 90° about an axis in the direction of propagation. The radial distribution patterns determined for this orientation of the probe were identical with the patterns obtained before rotation of the probe. One concludes then that the field distribution as measured by total temperature rise at the junction is independent of the direction of the thermocouple wires in the plane perpendicular to the direction of propagation for a field changing with the space coordinates as rapidly as that used in this test.

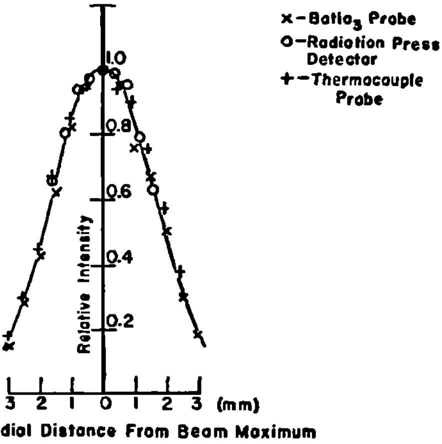

FIG. 7. Comparison of beam patterns taken with (1) thermocouple probe, (2) $BaTiO_3$ probe, and (3) radiation pressure detector.

Second, a comparison was made of the distributions determined by (1) thermocouple probe (2) $BaTiO_3$ probe (approximately one millimeter in maximum diameter) (3) radiation pressure detector utilizing the deflection of a steel ball 0.062 inch in diameter. The results of Fig. 7 were obtained. The sound intensity relative to the maximum value is plotted in the direction of the vertical axis and the radial distance from the beam center is plotted along the horizontal. A single curve is superimposed on the graph of the data points. The three detectors yield results in good agreement with one another. However, it appears from Fig. 7 that the beam width as determined by the radiation pressure detector (0.062 inch diameter ball) and by the thermocouple probe is slightly broader than that determined by the $BaTiO_3$ probe.

ACKNOWLEDGMENT

F. J. Fry also contributed to this research.