PRECISION CALIBRATION OF ULTRASONIC FIELDS BY THERMOELECTRIC PROBES

William J. Fry and Floyd Dunn
Bioacoustics Laboratory
University of Illinois
Urbana, Illinois

Abstract

The highly stable, small and readily constructed ultrasonic probe, developed and in use at this laboratory for the past five years, is discussed from the point of view of construction, calibration and operation.

This transient type thermoelectric probe yields information concerning the pressure amplitude, particle velocity amplitude and intensity of the ultrasonic field in which it is placed. If the field characteristics are known, the principle of operation of the probe provides a method for determining the absorption coefficient of minute quantities of material.

Introduction

Knowledge of the following sound field variables is sufficient to completely specify the characteristics of an acoustic field at a single position by making observations at that position only: the particle velocity amplitude, the direction of the particle velocity, the pressure amplitude, and the phase relationship between the pressure and the particle velocity. In general, ultrasonic probes for use in liquids respond to only a single field characteristic. An example of this is the piezoelectric type probe which responds to the pressure. It would, of course, be highly desirable to have available a device which would respond to a sufficient number of field characteristics at a point to completely describe the field at the point. At the present time this does not appear feasible.

For some applications the thermoelectric probe described in this paper has some distinct advantages over the piezoelectric probe in that it yields directly values of the particle velocity amplitude and the pressure amplitude in acoustic fields of any configuration including both free and standing wave fields. For the traveling plane wave field, the probe yields the acoustic intensity. A most important aspect of this probe is the precision with which results can be obtained. It is possible, with this device to obtain values for the pressure amplitude and particle velocity amplitude with an uncertainty of not more than ±2%. Indeed, one can study the fine structure of an ultrasonic field in a liquid, with this instrument in the megacycle frequency range.

We will discuss further advantages and disadvantages of this thermoelectric probe after presenting design and constructional details, methods of operation, the type of data obtainable, and the precision with which this instrument can be used.

The detailed theoretical analysis of the thermoelectric probe behaviour in a sound field has been given by Fry and Fry.[1]

Probe Construction

The probe is constructed as follows:[2,3] A thermocouple junction is imbedded in a liquid sound absorbing medium. The absorbing medium is separated from the medium in which the sound field is to be examined by thin polyethylene sheets (0.003 in. thickness). The thermocouple wire (0.0005 in. diam. in the neighborhood of the junction) and the polyethylene windows are supported by a stainless steel cylindrical frame which has an inner diameter (or aperture) large enough to admit the passage of the sound beam through it without producing disturbance to the beam. See Fig. 1.

The acoustic absorbing material is chosen to have a density and acoustic velocity which closely match those of the liquid in which the sound field is to be examined. For investigations of ultrasonic fields in water and various salt solutions, castor oil is a suitable imbedding material since it has the proper combination of a relatively high acoustic absorption coefficient and a density and sound velocity which closely match those of dilute salt solutions. The percentage of incident sound energy reflected at the interfaces is, therefore, negligibly small. In the neighborhood of the thermocouple junction, the thermocouple wires are etched down to 0.0005 in. in diameter (or 0.013 mm). For a frequency of one mc/s in water, the wavelength is approximately 1.5 mm, i.e., the thermocouple junction is of the order of 1/100 of a wavelength.

The output of the probe, i.e., the thermoelectric emf produced by the temperature change at the thermocouple junction resulting from exposure to an acoustic disturbance, can be observed by a number of different methods. Two such methods are illustrated schematically in Fig. 2. Figure 2a shows the probe connected directly to a magnetic oscillograph. The deflection of the light beam is recorded photographically. Figure 2b shows the probe connected to a low noise amplifier which is in turn connected to an oscilloscope. The deflection of the oscilloscope beam is also recorded photographically.

The thermocouple probe functions in the following manner: The sound source is excited to produce a single square wave acoustic pulse of one second duration. Figure 3 is a photographic recording, indicated by the deflection of the oscilloscope beam (see Fig. 2a), resulting from the thermoelectric emf produced by the temperature change experienced by the thermocouple junction due to an acoustic pulse of one second duration. 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.[1] This phase of the temperature events approaches equilibrium rapidly. 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 amplitude, 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 for the plane traveling wave case 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 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.[1]

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 examined. For castor oil and water the densities differ by about 3% and the velocities differ by about 1½%. 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% of the incident intensity if the frequency is low enough so that viscous forces are not of primary importance in determining the reflection coefficient. Such is the case for a castor oil-water boundary at a frequency of one megacycle.

The relation basic to the design and operation of this probe for plane traveling wave fields is

$$\mu I = \rho C \left(\frac{dT}{dt}\right)_0 \tag{1}$$

where μ designates the acoustic intensity absorption coefficient of the imbedding medium per unit path length, I represents the acoustic intensity, the product ρC designates the heat capacity of the imbedding fluid per unit volume and $(dT/dt)_0$ indicates that fraction of the time rate of change of the temperature of the imbedding medium resulting from absorption in the body of the medium at the time of initiation of an acoustic disturbance of rectangular envelope. If the thermocouple wire diameter, in the neighborhood of the junction is of the order of 0.001 in. or less and if the beam diameter at half intensity is of the order of a few millimeters or more, then it is permissible to identify the quantity $(dT/dt)_0$ of Eq. (1) with the initial time rate of change of the temperature caused by absorption in the body of the medium.

From Eq. (1), it is readily seen that if the acoustic intensity absorption coefficient of the imbedding medium is known sufficiently accurately, the thermocouple probe system constitutes an absolute measurement method for the plane traveling wave case. Conversely, if the sound intensity is known at a thermocouple junction of sufficiently small size imbedded in an absorbing medium, then the acoustic intensity absorption coefficient of the material can be calculated. The method therefore makes possible the determination of absorption coefficients of minute quantities of material.

Calibration of Probe

The probe cannot be used as an absolute measuring device in accordance with Eq. (1) if sufficiently accurate data for the absorption coefficient of the imbedding material are not available. Under such conditions, the following radiation pressure method[4] is adopted for calibrating the probe. The calibration takes place in a free plane wave field. The radiation pressure detector comprises a small steel sphere suspended in the sound field. The unidirectional force due to radiation pressure deflects the steel sphere from its equilibrium position. The measured deflection is then used to compute the acoustic intensity at the position of the sphere, as well as, the pressure amplitude and particle velocity amplitude. This arrangement constitutes an absolute determination of the acoustic intensity. The thermocouple probe is then placed in the sound field and the thermoelectric response to a one second pulse is observed. Consider the probe display system of Fig. 2a. The deflection amplitudes of the initial response, the linear response and the total response, as observed by the oscillograph camera, can now be related to the previously determined values of the particle velocity amplitude, pressure amplitude and intensity, respectively. This is accomplished, for example, for the intensity by specifying the intensity in watts per square centimeter corresponding to a specified open circuit voltage at the probe terminals.

The second phase (or linear portion) of the thermocouple probe response, deviates from linearity as the acoustic amplitude increases. This is a consequence of thermal conduction,variation of the absorption coefficient of the imbedding medium with temperature and acoustic flow. Therefore, in practice, it is convenient to calibrate the overall electroacoustical system against the thermoelectric probe at relatively low sound levels and then extrapolate to higher sound levels. This requires that the electroacoustical system possess a component which indicates relative sound levels. This method will be illustrated by the following example. Consider that it is desired to determine the acoustic field characteristics of a free plane wave field at a particular point in the field. The sound source is an X-cut quartz plate and a fixed fraction of the voltage applied to the quartz plate is metered. The thermocouple probe has previously been calibrated against the radiation pressure detector discussed above. The probe display system is that of Fig. 2a. The probe sensitivity is expressed in terms of the magnetic oscillograph output for practical use, i.e., 12.30 watts/cm^2/cm. deflection of the oscillograph light beam. The voltage applied to the quartz crystal is successively set to increasing values and the deflection of the light beam of the magnetic oscillograph is observed simultaneously with the voltage indicated on the vacuum tube voltmeter which monitors a fraction of the crystal voltage. Figure 4 is a typical example of the resulting calibration curve. It is seen from this curve that thermocouple probe response is linear up to a galvanometer deflection of 0.8 cm. and a voltmeter deflection of 56 volts. It then follows that a voltmeter deflection of, for example, 200 volts corresponds to an acoustic intensity of 126 watts/cm^2, assuming that the intensity remains proportional to the square of the quartz crystal voltage.

An analysis of the procedure used to determine the sensitivity of the thermocouple probe based on the method of least squares yields an uncertainty of ±2.5%. A similar analysis of the calibration of an unknown free plane wave sound field (e.g., the data shown in Fig. 4) yields an uncertainty of ±1%. Thus, the overall uncertainty in determining the acoustic intensity for this field is ±3.5%. The above uncertainties are the calculated standard deviations (determined by the method of least squares) of the observed points from the straight line of best fit.

Conclusions

To conclude, it may be apropos to list advantages and disadvantages of the thermoelectric probe. The advantages are (1) the probe yields directly values of the particle velocity amplitude and the pressure amplitude, (2) it is small in size, (3) it is highly stable, (4) it is a primary standard for determining absolute sound levels, (5) it is insensitive to stray rf fields and (6) it has a low input electrical impedance. The disadvantages are (1) the sensitivity is low when the temperature sensitive element is a thermocouple constructed from metals commercially available in wire form and (2) it cannot be used for determining wave shapes.

References

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4. Fox, F. E. and V. Griffing, J. Acoust. Soc. Am., 21, 352 (1949).

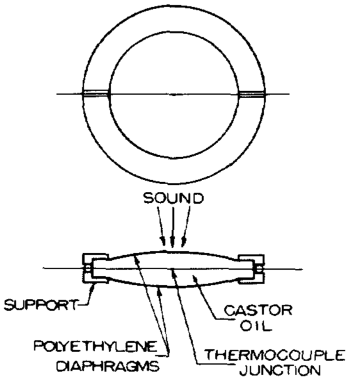

Fig. 1
Schematic diagram of a thermoelectric probe.

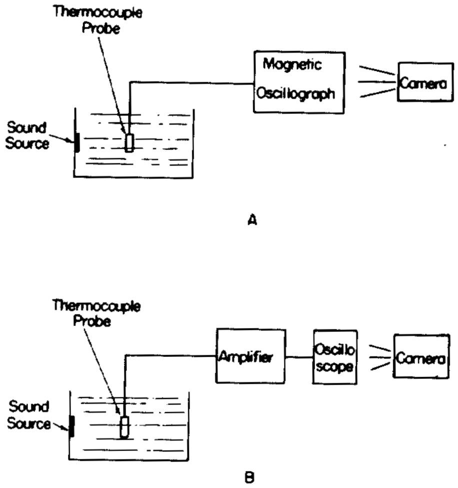

Fig. 2
Block diagram illustrating two methods of observing the thermoelectric emf produced by the thermocouple junction.

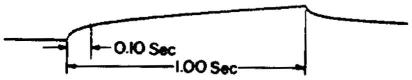

Fig. 3
A photographic recording of the deflection of the oscilloscope beam resulting from the thermoelectric emf produced by the temperature change experienced by the thermocouple junction due to an acoustic pulse.

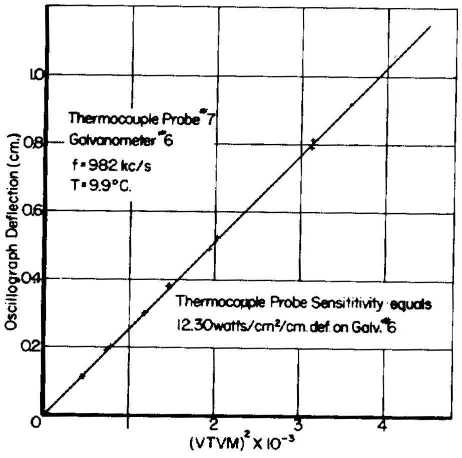

Fig. 4
A typical acoustic field calibration curve.