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We describe the preliminary results of a novel method for the noninvasive measurement of temperature distribution within a solid body using an acoustic beam. Applications of such a scheme could include the control and assessment of tumor treatment by hyperthermia in which small regions of tissue deep within the body are heated by either acoustic or microwave energy. A major practical difficulty in such a process is the accurate determination of the temperature distribution. The scheme we describe in this letter appears to be capable of detecting temperature differences with a sensitivity of a few tenths of a degree centigrade and with a spatial definition of the order of 1 cm^3. The basic technique in which the phase differences between two collinear acoustic beams, one broad and collimated and the other focused, are compared electronically, is described, and results obtained with a tissue phantom are used to illustrate the viability of the approach.

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The noninvasive measurement of temperature distributions with high sensitivity and spatial definition is of great interest in the field of tumor treatment known as hyperthermia.[1] In this procedure small regions of diseased tissue are heated by perhaps 5–10 °C by means of focused acoustic energy or by microwaves. A noninvasive technique to measure temperature over a region of the order of $10 \times 10 \times 10$ cm with a spatial definition of about 5 mm^3 and with a temperature sensitivity in the region of 0.1 °C is required. Such a technique would also be suitable for measuring the temperature of flames and in other situations where temperature cannot normally be measured with an invasive probe.

A scheme for this purpose, based on measurements with acoustic beams, was proposed by Sachs[2,3] some years ago. We propose here a differential measurement scheme which is relatively insensitive to the temperature of the region surrounding the volume to be measured and which can be adapted for use with acoustic beams, optical beams, or microwave beams where appropriate.

The approach we describe is based on a technique originally developed for the measurement of stress distributions within the bulk of metal components and is applicable to the measurement of any parameter which affects the phase velocity or attenuation of the probing beam. In this example, a pair of acoustic beams form a differential bridge in which relative phase differences can be determined with great accuracy. As illustrated in Fig. 1, one of these beams (beam 1) is broad and collimated, providing a reference path, while the other (beam 2) is focused and is used to probe the region of interest.

It may be shown that the phase shift from transducer to transducer of each beam, due to a small volume of material inside the beam, depends on the beam intensity and varies monotonically with temperature. Consider a small heated region which is far from the focus, but through which both beams pass (A in Fig. 1). The phase shifts experienced by the two beams will vary very little with changes in axial or transverse position of the point A; both beams are affected in approximately the same way. However, if there is a localized heated region close to the focus at, say, B in Fig. 1, then small movements of the beams, or equivalent of the heated region, will result in a large change in phase of the focused beam relative to the collimated beam. The phase of the collimated beam is affected in much the same way no matter where the heated region lies within it. Therefore, the differential phase shift of the two beams depends mainly on the contributions of regions near the focus.

The experimental arrangement is shown in Fig. 1. The medium in these initial trials was gelatin because its acoustic characteristics are similar to those of body tissue. A block of gelatin was cast in a plastic container, measuring

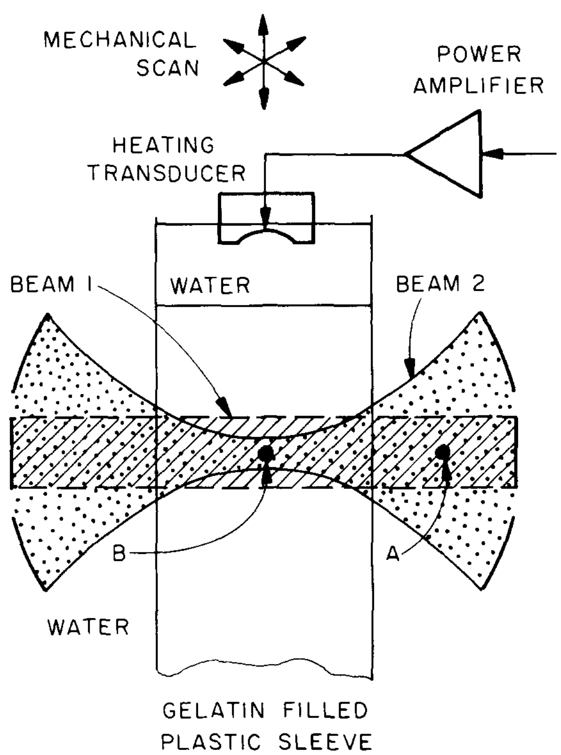

FIG. 1. Experimental system.

$10 \times 10 \times 10$ cm, and was immersed in a water bath.

A small heated region within the gelatin block was created by exciting an acoustic transducer with a focal length of 7.5 cm and 2 cm in diameter with a relatively high power level at 2.1 MHz. We were able to record the temperature profile of the heated region independently with two medical thermocouples. One of them was placed far from the heated zone, in the gelatin, to serve as a reference and the heating beam was moved above the second thermocouple. The power of the heating signal was set to give a maximum temperature difference of 1.2 °C between the heated zone and the unheated gelatin. With this heating power, the width of the heated region was found to be about 5 mm.

The phase measurement system originally constructed for stress measurements[4,5] was used to make the noninvasive temperature determination. The system consists of two flat transducers 2 cm in diameter and a pair of confocally aligned focused annuli of 5-cm diameter and 20-cm radius of curvature. Tone bursts at about 4 MHz are transmitted from each pair of transducers and propagate through the water bath and the sample. The phase difference between the two paths is determined very accurately using an electronic technique which has been described in detail elsewhere.[6] For these experiments, the system noise due to spurious vibrations, thermal convection currents in the water tank, etc., corresponded to a phase shift of less than 0.1°, whilst the maximum phase shift measured was of the order of 2°.

The focus of the probing system was arranged to be coincident with one of the thermocouples so that the temperature at that point was always monitored. The temperature field was varied by scanning the heating tranducer above the block of gelatin and its position was recorded. The following experimental procedure was adopted: (1) The gelatin was heated, always using the same electrical power, to thermal equilibrium, giving a maximum temperature difference of 1.2 °C. (2) The heating signal was removed and cooling of the gelatin was recorded at 1-s intervals using both the thermocouple and the acoustic system.

We recorded the variation of the phase difference between the two beams during cooling for several positions of the heating transducer with respect to the focal point of the measuring system (Fig. 2). Curve 1 was obtained when

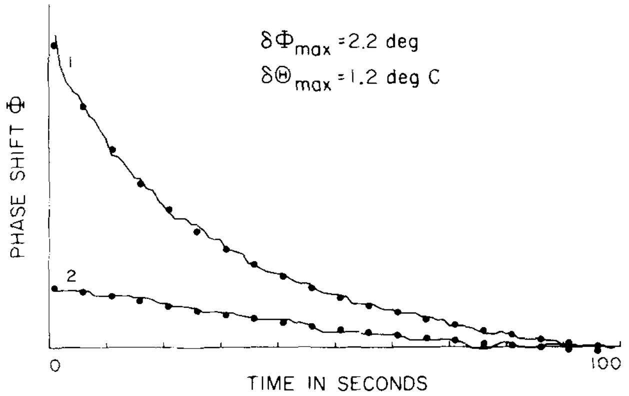

FIG. 2. Cooling curves for acoustic measurement and thermocouple measurement. Phase shift: Φ; temperature difference: θ.

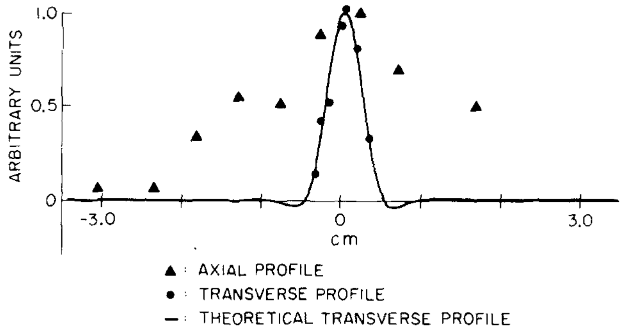

FIG. 3. Measured axial and transverse definition of system.

the focus of the heating transducer was coincident with the focal point of the transducers; curve 2 was obtained when the heated point was 3 mm away from the focal point of the probing beam in a direction perpendicular to the plane of propagation of the heating and measuring signals. The solid lines are experimental data while the points represent a least-square fitting of the data with a simple theoretical model. The model uses a Gaussian profile for the spatial response of the measurement system and a Gaussian solution of the heat equation for the variation with time of the temperature profile. This profile is assumed to be axially symmetric and invariant with the distance from the heating transducer, a reasonable assumption, provided the measured point is near the focus of the heating transducer and far from the edges of the block.

Cooling curves for several positions of the heating transducer were used to determine the axial and transverse definition of our measurement system (Fig. 3). The measured transverse definition of the system is of the order of 1 cm (with a heating beam 5 mm in diameter), and the axial definition of the order of 5 cm.

In conclusion, we have demonstrated that it is possible to map temperature distributions within a solid medium by measurements with acoustic beams. The sensitivity of the present system is of the order of a few tenths of a degree centigrade, close to the desired performance of a device for use in conjunction with hyperthermia treatment. The poor axial definition is due to the fact that the measuring system was originally designed for another pupose[4,5]; this could be improved by decreasing the focal length of the transducers.

Whilst the basic feasibility of the technique has been clearly established, several issues would require attention before a practical instrument could be evolved. It is desirable that the measurement time should be at most a few tenths of a second per point and that movements of the surrounding media have minimal effect on the measurement. Both of these requirements can, we belive, be readily met with a system such as the one described. The provision of a collinear reference path which suffers the same phase shifts as the signal path, *except* at the region of interest, is of great value in the suppression of body movements and this is one important aspect in which we believe our approach is superior to that of Sachs.[3] We also believe that in making precise measurements of velocity, it is preferable to determine the phase shift of the signals rather than their time of flight, since this avoids much of the uncertainty associated with trigger jitter in timing circuits.

It is important, of course, to make the measurement as insensitive as possible to disturbances in the surrounding medium. Therefore, ideally, both beams should be virtually coincident, except near the region of interest. A further development of this work has been carried out by Smith and Wickramasinghe.[7] Their work suggests that one may employ a single-focus beam, excited at the fundamental and some other frequency, typically the sound or third harmonic. Then there will be effectively two beams which will be essentially coincident except near the region of the focus, where the lower frequency beam will have a diameter larger than that of the higher frequency beam, and the relative phase difference between them may be measured.

In general, these techniques should be very powerful for examining an internal region in a material in which change in material properties due to temperature effects either the velocity or attenuation of a probing beam.

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