Piezoelectric Composite Materials for Ultrasonic Transducer Applications. Part II: Evaluation of Ultrasonic Medical Applications

T. R. Gururaja, Walter A. Schulze, Leslie E. Cross, and Robert E. Newnham

Abstract—The electro-acoustic properties of Lead zirconate titanate (PZT) rod–polymer composites relevant for ultrasonic transducer applications are reported. Acoustic impedance of the composite materials was measured by three different techniques in the frequency range 0.3–3.5 MHz. Dependence of the acoustic impedance as a function of volume fraction of PZT and frequency was also modeled theoretically. Time-delay spectrometry was employed to calibrate the free-field transmitting and receiving voltage responses of the composite materials. The acoustic impedance of the composite materials was in the range of 3–10 M\(\text{rayl}\). The figure of merit in the receiving mode of composite materials was three times that of PZT. The figure of merit for a 20-percent PZT composite (\(Z = 7.3\ M\text{rayl}\)) was further enhanced by 50 percent using a single-layer impedance transformer of lucite (\(Z = 3.3\ M\text{rayl}\)). These composite materials were molded into curved shapes by simple thermal process to fabricate focused transducers. The axial and lateral beam profiles of focused composite transducers are presented.

I. INTRODUCTION

A DETAILED STUDY on the resonant modes of vibration of lead zirconate titanate (PZT) rod–polymer composites was already reported in Part I [1]. The results showed that although the polymer is piezoelectrically inactive, it plays a substantial role in the composite from the acoustic point of view. Moreover, it was shown that the mechanical properties of the Spurrs epoxy markedly influence the piezoelectric response of the composite. Larger ultrasonic displacement amplitude of the epoxy, as compared to that of the PZT at the thickness-mode resonance, was evidence of the efficient coupling of the acoustic energy from PZT to the epoxy. Since the acoustic impedance of the epoxy is relatively close to that of the human body, an effective coupling of acoustic energy from the transducer to the human body is ensured. The present paper deals with the evaluation of PZT rod–polymer composites with 1–3 connectivity as an ultrasonic transducer for medical diagnostic applications. Since the acoustic impedance of the human body is very close to that of water, the transducer evaluation was carried out with water as the loading medium.

Initially, the composite transducers were tested in the pulse–echo mode (Section II). In general, understanding the behavior of a transducer solely from the pulse–echo measurement is extremely difficult, because those measurements combine both transmitting and receiving characteristics of the transducer. The results are also modified by the characteristic impedance of the transducer as a function of frequency. Therefore, these parameters are measured individually. Section III describes the experimental results and theoretical modeling of the acoustic impedance of the composites as a function of frequency and volume percent PZT. The transmitting and receiving voltage response of the composite transducers are dealt with in Section IV and V, respectively. These results together with a knowledge of the piezoelectric response of the composite from Part I of this work will be used to account for the performance of the composite as an ultrasonic transducer. The effect of a single quarter-wavelength matching layer on the performance of the composite transducer is considered in Section VI. It will be shown that these composite materials can be molded into curved shapes by a simple thermal process to fabricate focused transducer. The axial and lateral beam profile of thus focused composite transducers are presented in Section VII, and a concluding discussion is given in Section VIII.

II. PULSE–ECHO MEASUREMENTS

The pulse–echo response of the airbacked composite transducers were determined by the tone-burst pulse–echo method described by Erikson [2]. A schematic diagram of the experimental set up is shown in Fig. 1. The composite transducer was mounted in a water tank at the end of a stainless steel tube using silicone rubber as a glue. The transducer mounting had independent angular adjustment in two orthogonal planes. The tone-burst signal of an appropriate frequency from a function generator (Interstate-74) was fed into a power amplifier (ENI-411A). The amplified tone-burst (10 V peak) of 15 to 20 cycles with a repetition rate of approximately 1 KHz was used to excite the transducer. A finely polished (±1 \(\mu\text{m}\)) steel block (\(10 \times 10 \times 2.5 \text{ cm}\)) was used as a reflector. The steel reflector was placed at the \(a^2/\lambda\) distance from the transducer, where \(a\) is the radius of the transducer, and \(\lambda\) is the...
Fig. 1. Block diagram of tone-burst pulse-echo method.

### TABLE I

<table>
<thead>
<tr>
<th>Volume Percent PZT</th>
<th>PZT Rod Diameter (mm)</th>
<th>Echo Signal (50 Ω Load) (V50 (volt))</th>
<th>6-dB Bandwidth (BW (MHz))</th>
<th>Figure of Merit (V50BW)</th>
<th>Echo Signal (diode isolation) (V50 (volt))</th>
<th>6-dB Bandwidth (BW (MHz))</th>
<th>Figure of Merit (V50BW)</th>
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<tbody>
<tr>
<td>10</td>
<td>0.45</td>
<td>0.8</td>
<td>0.4</td>
<td>5.6</td>
<td>0.32</td>
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<td>0.50</td>
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<td>0.45</td>
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<td>3.25</td>
<td>0.45</td>
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<tr>
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<tr>
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<td>5</td>
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<tr>
<td>Commercial Transducer (Rohé 5601)</td>
<td>—</td>
<td>1.2</td>
<td>1.8</td>
<td>2.25</td>
<td>1.2</td>
<td>3.0</td>
<td>1.3</td>
</tr>
</tbody>
</table>

*Center frequency f0 = 2.25-MHz.

wavelength of the center frequency of the transducer. The distance \(a^2/\lambda\) corresponds to the transition from near field to far field. At this distance the transducer beam is a collimated plane wave with a smoothly varying amplitude and phase profile [2].

The amplitude of the echo signal for a constant 10-V peak input was measured as a function of frequency around the peak response. The following parameters were determined.

1) Frequency of the maximum pulse-echo amplitude \(f_0\) (also referred to here as center frequency) together with the corresponding value of peak amplitude.

2) Frequencies \(f_1\) and \(f_2\) at which the pulse-echo amplitude is one half (-6 dB) of the maximum pulse-echo response. The product of the maximum pulse-echo amplitude and the 6-dB bandwidth \((f_2 - f_1)\) was used as the principal figure of merit for assessing the performance of the composite transducer. The quality factor \(Q\) defined as \(Q = f_0(f_2 - f_1)\) was used to characterize the broadband nature of the transducer.

The electric impedance of some composite transducer at resonance was relatively high (\(>100 \Omega\)) compared to the 50-Ω internal impedance of the amplifier which is in parallel with the transducer. Therefore, the received echo signal was loaded by the lower impedance of the amplifier. Since the electrical impedance of the composite depends on the volume percent PZT and thickness, the echo signals were loaded to different extents. Thus a comparison of the pulse-echo response of different composite transducers was difficult. The electrical loading effects were corrected by using back-to-back zener diodes, which were inserted between the amplifier and the transducer. The diodes allowed voltage to be applied to the transducer during excitation while acting as a high impedance during reception. The excitation and the reflected signals were detected using a 10× oscilloscope probe. The total capacitance of the probe, cables, and diodes was about 15 PF.

The composite transducers fabricated to operate in thickness-mode resonance at a frequency of 2.25 MHz. This frequency, often used in ultrasonic imaging systems, was originally chosen for demonstrating the performance of the composite transducers.

The data presented in Table I refer to composites of thickness 0.6 mm with a center frequency around 2.25 MHz. With 50-Ω termination, the highest echo signal amplitude (2.4 V) was received from the composites with 20- and 30-volume-percent PZT rods of diameter 0.45 mm. These samples had comparable voltage-bandwidth product. The highest pulse-echo amplitude (3.25 V) with the back-to-back zener diode termination came from the composite sample with 20-percent PZT rods of diameter 0.45 mm.
Both types of ten-percent composites had higher electrical impedances and were severely loaded by the 50-Ω termination. The high-impedance termination using the zener diodes increased the pulse-echo voltage amplitude by a factor of two. However, this was significantly below the values recorded for 20- and 30-percent PZT as shown in Table I.

The pulse-echo responses of composites were compared with a commercial transducer (Rohe 5601 with the transducer diameter = 13 mm). This transducer was supposedly provided with backing and matching layers for the optimum performance. The composite transducers with 20- and 30-percent PZT compared favorably with that of the commercial transducer. However, the bandwidth of the composite transducer was narrower (Table I). It is interesting to note that the pulse-echo figure of merit of several composite transducer is comparable to that of an optimized commercial piezoelectric transducer.

As it emerges from the study of the thickness-mode resonance of the composites samples [1], thin composites resonating at approximately 2.25 MHz do not vibrate as collective unit. The PZT rods vibrate quite freely with only a light damping from the epoxy matrix. The composite transducer can be pictured as acting similar to a PZT disc with a light backing material. As the frequency of the thickness-mode resonance is decreased by increasing the thickness of the sample, the lateral interaction between the rods through the epoxy becomes stronger and the composite acts more like a homogeneous material. The strong lateral interaction in thick samples was found to be a result of the long wavelength of the transverse wave compared to the periodicity of the lattice. This was clearly seen from the observation of vibration pattern of the composite sample resonating in thickness mode at 270 kHz [1]. Since the stress transfer between the PZT and polymer is better when this requirement is satisfied, an improvement was expected in the pulse-echo figure of merit in composites operating at lower frequencies.

To experimentally verify the above proposition, composites with a range of thickness from 0.6 to 5.15 mm fabricated to study their performance as a function of frequency at peak response. The results indicated some improvement in the pulse-echo response compared to measurements at 2.25 MHz. For example, a relatively thick composite (thickness = 3.17 mm) with thickness mode resonance at 450 KHz displayed a loop gain of 1.0 (echo amplitude of 10 V for 10 V excitation) and Q of 3.5.

However, it should be noted here that the evaluation of thick composites resonating in the range of a few hundred KHz by the tone-burst pulse-echo method was complex due to the following reasons:

1) The electrical impedance at resonance frequency of the composite samples increased linearly with increase in thickness. A 20-percent PZT composite with a thickness of 4 mm resonating at 350 KHz had a minimum impedance of about 400 Ω. At this relatively high impedance level, even the diode isolation cannot provide the necessary decoupling from the 50-Ω termination. The transducer in the receiving mode appears more like a current source than a voltage source. The problem is even more serious for composites with five- and ten-percent PZT because the value of the impedance minimum at resonance frequency increases as the volume percent PZT is decreased.

2) As the testing frequency decreases, the sound wavelength increases; hence, the $a^2/\lambda$ axial distance at which the steel reflector is positioned becomes closer. For a transducer of diameter 1.9 cm resonating at 350 KHz, the $a^2/\lambda$ distance is approximately 2.1 cm (assuming $C = 1480$ cm/s in water at 20°C). The travelling time for sound in water from the transducer to the reflector and back for this distance is approximately 28 $\mu$s. To establish a steady-state condition, the transducer was excited for a minimum of 15 cycles. At 350 KHz, the transducer excitation corresponds to 43 $\mu$s, which is larger than the pulse-echo round-trip time. This means that the echoes begin returning before the electrical excitation has stopped, thus posing a serious problem.

A possible solution was to use the spectrum analyzer method [2]. The transducer was excited by an electrical impulse (250 V peak) of duration less than 100 ns supplied by an ultrasonic transducer analyzer (UTA-3, KB-Aerotech). A time-delayed gate is triggered with this excitation pulse, and it is adjusted in time delay and gate length to pass only the reflected echo. The processed signal from the analyzer was displayed on a high-frequency oscilloscope (Gould-O5300) to determine ringdown time of the transducer. The signal from the UTA-3 was displayed on a spectrum analyzer (HP 3585A) to obtain a plot of amplitude versus frequency of the reflected echo. Since the excitation pulse was very narrow, the problem of interference of the echo signal with the excitation pulse encountered in the tone-burst method was partly solved. However, the method was not free of other limitations. Since the transducer is not matched electrically to the pulse, not all the pulse energy is delivered to the transducer. The receiver has a terminating impedance of 50 Ω; thus, it has the serious loading effect on the received signal.

As explained earlier, it was very difficult to evaluate composite transducers and realize their advantages solely by pulse-echo measurements. Therefore, the composite materials were characterized separately for their acoustical impedance and transmitting and receiving voltage responses, which are reported in subsequent sections.

### III. Characteristic Acoustic Impedance

The characteristic acoustic impedance $Z$ (referred to as acoustic impedance from here on) of the transducer is an important property because it determines the effectiveness of the coupling of ultrasonic energy from the transducer to the load. The acoustic impedance is the product of density $\rho$ and velocity of sound $C$ in the material. In a single phase material, measurement of these properties is relatively easy and well described [3]. However, it is not so for composite materials. Composites usually exhibit anis-
ototropic behavior. The properties of the constituent phases must be averaged properly. In the PZT rod–polymer composites considered here, the interaction between polymer and PZT, and among neighboring PZT rods is a function of frequency. Therefore, dependence of acoustic impedance on frequency also needs to be considered. Three techniques, namely reflection, transmission, and resonance, were used to determine the acoustic impedance and its frequency dependence. The results are reported in the following subsections. The acoustic impedance of the composites were also theoretically modeled and compared with the experimental data.

A. Reflection Technique

In the reflection technique, the acoustic impedance of a composite was determined by comparing the amplitude of reflection of a plane acoustic wave from the sample with that from a standard material of known acoustic impedance, e.g., stainless steel. The experimental setup was the same as that used for the tone-burst pulse–echo technique (Fig. 1). The reflector was placed at the $a^2/\lambda$ distance. A commercial ultrasonic transducer was used to measure the pulse–echo signal from both the sample and the standard reflector. The transmitting voltage response and receiving voltage sensitivity of the transducer need not be taken into account as the same transducer is used for measuring reflections from both the standard material and the specimen.

The tone-burst pulse–echo experiment was carried out as a function of frequency with a stainless steel block ($10 \times 10 \times 2.54$ cm) reflector. The driving voltage of the transducer was kept constant at 10 V. It can be shown [4] that the pulse–echo amplitude $X$ is proportional to the reflection coefficient at the water–reflector interface. That is [4]

$$X \alpha \frac{Z_1 - Z_2}{Z_1 + Z_2}$$  (1)

where $Z_1$ and $Z_2$ are the acoustic impedance of the steel reflector and water, respectively.

The stainless-steel block was then replaced by a composite sample and the pulse–echo amplitude $Y$ was noted. If $Z'_1$ is the acoustic impedance of the composite sample

$$Y \alpha \frac{Z'_1 - Z_2}{Z'_1 + Z_2}.$$  (2)

From (1) and (2), the acoustic impedance of the composite sample ($Z'_1$) can be expressed in terms of $X$, $Y$, $Z_1$ and $Z_2$. Since it is known that $Z_1 = 45.4 \times 10^6$ rayl and $Z_2 = 1.5 \times 10^6$ rayl [5], the expression for the acoustic impedance of the composite sample is given by

$$Z'_1 = 1.5 \left( \frac{46.9X + 43.9Y}{46.9X - 43.9Y} \right) \times 10^6 \text{ rayl}.$$  (3)

By substituting the values of $X$ and $Y$ at a specified frequency, the acoustic impedance can be calculated from (3).

The validity of the technique was tested by determining the acoustic impedance of a few standard materials such as lucite, fused silica, and aluminum with known acoustic impedance of 3.1, 13, and 17 M rayl, respectively. The measured values of $Z$ for these materials were 3.2, 12.6, and 17.1 M rayl, which are in excellent agreement. The experiments were also conducted with transducers of different type (focused and nonfocused) and with the reflector placed at different distances (at $a^2/\lambda$ distance, at the focal length of the transducer, etc.). No substantial difference in the measured impedances was observed.

Composite samples of thickness 2–3 cm with 5, 10, 20, and 30 volume percent PZT rods of diameter 0.45 mm were fabricated. The samples were not poled because such thick samples require excessively large poling voltages (40–60 kV). Fig. 2(a) shows a plot of the acoustic impedance of several different composites in the frequency range from 0.3 to 1.3 MHz, and Fig. 2(b) extends the plot from 1 to 3.5 MHz. Low-frequency data were obtained using a lead metaniobate transducer (Ultran Lab, Inc., diameter = 2.5 cm) with a center frequency of 0.7 MHz and a very broad bandwidth ($Q = 1$). The distance between the transducer and the reflector was 7.5 cm corresponding to the $a^2/\lambda$ distance at 0.7 MHz. Measurements in the frequency range from 1 to 3.5 MHz were carried out using a
focused transducer (Rohe 5616, diameter = 1.9 cm, focal length = 9 cm) with a center frequency of 2.25 MHz. The separation between the transducer and reflector in this case was 9 cm, which is the focal length of the transducer.

The following observations were made by inspecting the acoustic impedance plots of Fig. 2. As expected, the acoustic impedance increased with increase in the volume percent PZT. Moreover, the acoustic impedance was strongly frequency dependent. The composite samples showed a series of minima in Z at low frequency. Above 2.5 MHz the variations are minimized and the value of Z reached a saturation. The position of the first minimum in Z occurred at a higher frequency for larger volume percent PZT. The acoustic impedance increased steadily at frequencies below the first minimum. The acoustic impedance of single phase epoxy, measured by the same procedure, is also shown in Fig. 2 for comparison. There was no variation of Z of epoxy in the frequency range considered in this work. The results were analyzed carefully to find an explanation for the observed dispersion in Z.

The minima for 5, 10, 20, and 30 percent PZT composites occur at 0.45, 0.625, 0.825 and 1.125 MHz, respectively. The frequencies have an inverse relationship with the lateral periodicity of the corresponding composite. The product of the frequency at the acoustic impedance minima and the lateral periodicity of the composite was found to be a constant of value 800 m/s. It is interesting to note that the frequency corresponding to the minima in Z in each composite matches with the resonance frequency $f_1$ [1]. The resonance frequency $f_1$ corresponds to the standing wave pattern of the transverse waves with the wavelength equal to the lateral periodicity of the lattice. It should be pointed out here that the value of the acoustic impedance at the minima was approximately the same for all volume percent PZT (1.6 M rayl), which is surprisingly lower than that of the epoxy (2.3 M rayl).

There is a small discrepancy in the values of acoustic impedance around 1 MHz measured using the two different transducers. This is possibly because the transducers were operating far away from their center frequencies, and hence were not very sensitive. Thus the measurements performed in the transition region from one transducer to the other are not very precise.

All of these phenomena may be explained as follows. The acoustic wave incident on the composite sets it into vibration. Due to the difference in compliance between the two component phases, namely PZT and Spurrs epoxy, a transverse wave originating at the interface and propagating in a direction perpendicular to the rod axis is launched into the epoxy matrix. At the frequency where the transverse wavelength is equal to the periodicity, resonant scattering of waves by the vertical planes of the PZT rods results in a two-dimensional standing wave pattern as described in Part I [1]. Measurements of the surface displacements of the composite at this frequency showed that the epoxy at the center of the unit cell of the periodic lattice vibrates 180° out of phase with PZT and with a much larger amplitude. This standing wave pattern is most likely established after a few cycles of the incident wave. The acoustic impedance minima at this frequency are caused by the cancellation effects between the incident wave and the large amplitude vibration of the epoxy with a phase difference of 180°.

Support for the above explanation is provided in Fig. 3, where tone-burst pulse-echo signals reflected from a composite sample are shown. Fig. 3(a) depicts a typical signal measured at frequencies far away from the minima in Z. (b) At a frequency corresponding to minima in Z. (c) At a frequency corresponding to minima in Z (expanded time scale).
in the last few cycles. The reflected signal from a composite at the acoustic impedance minima is shown in Fig. 3(b). The amplitude approaches a saturation value, but the signal declines after the first two cycles and reaches a minimum value. Interference of the signal with the reflected signal from the rear surface of the composite sample makes it difficult to analyze the wave pattern after a few cycles. Figure 3(c) presents similar data with an expanded abscissa. Thus, the acoustic impedance minima observed arises from the destructive interference between the incident signal and the reflections from the composite sample. Therefore, the minima in acoustic impedance are only apparent phenomena because of the complex resonance in the composites.

Resonance experiments [1] indicated another strong lateral resonance mode, referred to as $f_2$. This resonance was associated with standing waves along the unit cell diagonal. For a five-percent sample, $f_2$ was approximately 0.7 MHz and a corresponding minimum was seen in the acoustic impedance plot as expected (Fig. 2(a)). Acoustic impedance for the ten-percent sample is also seen to approach a minimum around 1.00 MHz (Fig. 2(a)), which corresponds to $f_2$ for the ten-percent composite. In addition to the acoustic impedance minima just described, additional minima were observed up to about 2 MHz, possibly due to more complex lateral modes.

### B. Modeling of Acoustic Impedance

The acoustic impedance of the composites was modeled to explain the observed frequency dependence discussed in the previous section.

Above 2 MHz the acoustic impedance was found to be relatively independent of frequency. At this frequency, experimental evidence showed that the PZT rods were vibrating without an appreciable lateral interaction. Therefore, this situation can be modeled using Reuss averaging [6] which assumes that the constituent phases experience the same stress. According to the Reuss averaging scheme, the modulus of elasticity parallel to the length of the rod $E_l$ is given by

$$\frac{1}{E_l} = \frac{v_1}{E_1} + \frac{v_2}{E_2}$$

where $v_1$ and $v_2$ are volume fractions and $E_1$ and $E_2$ are the appropriate elastic moduli of the constituent phases.

For unpoled PZT rods, the elastic modulus is $E = 1/s_{11} = 6.098 \times 10^{10} \text{ N/m}^2$ [7]. For the epoxy, the elastic modulus was found to be $E = 4.7 \times 10^9 \text{ N/m}^2$ [1]. From the calculated values of $E_l$ using (4) and the mean density $\rho$ listed in Table II of Part I [1], the acoustic impedance of the composites was evaluated from the expression

$$Z = (\rho E_l)^{1/2}$$

Both the measured and calculated values are compared in Table II. The frequency range above 2 MHz, where the wavelength of the transverse waves is much smaller than the periodicity of the lattice, is called region 1 for the purpose of discussion. There is a good agreement between the theory and the experiment supporting the explanation of the mode of vibration outlined above for frequencies about 2 MHz.

At frequencies below the minima in $Z$ corresponding to $f_1$, the lateral interaction increases gradually and the two phases vibrate in a cooperative mode. The displacements of PZT and epoxy were found not only to be in phase but also of almost equal amplitude [1]. Thus, the Voigt averaging scheme [6], which assumes constant strain on the constituent phases can be used to estimate the effective longitudinal modulus $E_l$ of the composite. The composite modulus according to the Voigt model is given by

$$E_l = v_1 E_1 + v_2 E_2.$$

Using the given values of the elastic moduli for the PZT and epoxy the effective modulus and acoustic impedance of the composites were calculated, and they are compared with the measured values of $Z$ at 0.3 MHz in Table II. This frequency range, where the wavelength of transverse waves is larger than the periodicity, is called region 3 in this paper. The theoretically predicted increase in the acoustic impedance at frequencies below the first acoustic impedance minima was seen in all the composites. However, the measured values were on the average 20 percent lower than the estimated value. The discrepancy between the experiment and theory is possibly due to the diffraction losses. Because of the relatively small size of the composite sample (diameter = 1.9 cm) compared to the size of the steel reflector (10 x 10 cm), it is conceivable that not all of the acoustic energy was reflected back from the composite sample to the transducer.

A correction to account for the diffraction losses in the measurements of acoustic impedance was applied experimentally by using the standard reflector of exactly the same

<table>
<thead>
<tr>
<th>Volume Percent PZT</th>
<th>Region 1 (Frequency &gt; 2 MHz)</th>
<th>Region 3 (Frequency &lt; 0.4 MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calculated Z</td>
<td>Measured Z at 3.5 MHz</td>
</tr>
<tr>
<td>5</td>
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</tr>
<tr>
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</table>
dimension as the composite sample. Then the experimental setup for the two reflections to be compared becomes identical, and hence the uncertainty in the measurement because of the diffraction losses is minimized. Fig. 4 compares the earlier data with the new data corrected for diffraction losses for a ten-percent composite sample. As can be seen, the corrected value of the acoustic impedance approaches 4.1 M rayl at 0.3 MHz, which is in excellent agreement with the predicted values based on the constant strain model (Table II). Based on the experimental and theoretical results, the acoustic impedance as a function of frequency can be classified into three regions.

In region 1, corresponding to frequencies above 2 MHz, the transverse wavelength is much smaller than the rod spacing $d$, and the two phases appear to be decoupled. There is not much influence of epoxy on the vibration of the PZT rods. A significant improvement in the pulse–echo response in terms of the figure of merit cannot be expected in this region, if the composite is used as a single element transducer. On the other hand, the situation is desirable for a linear- or phased-array transducer construction, where the acoustical cross-coupling between elements should be as low as possible.

In region 3, corresponding to the frequency far below the first minimum in the acoustic impedance, the composite acts as a homogeneous material. Maximum stress is transferred from PZT to polymer and vice versa. The composite is expected to perform better as a single element transducer with an improved pulse–echo figure of merit.

In region 2, the periodicity of the lattice and the wavelength of the transverse waves are comparable. This region is helpful in understanding the complex vibrational modes in two dimensionally periodic structures. In this region the composite can possibly be used as a resonant sound absorber.

C. Transmission Technique

The acoustic impedance of the composites was also determined by measuring the velocity of longitudinal waves along the PZT rod axis. The method chosen for measuring the longitudinal velocity was similar to the standing-wave method described by McSkimin [8]. An acoustic wave of a particular frequency is made to impinge on the sample. The wave transmitted to the specimen is reflected back and forth giving rise to a series of transmitted pulses. At discrete frequencies, the emerging wave trains will be in phase leading to a constructive interference. The constructive interference occurs at a frequency for which the path length (twice the specimen thickness) is equal to an integral number of wavelengths in the specimen at that frequency. The principle of the method is to determine the value of the integer at one of the discrete frequencies when the in-phase condition is satisfied. The experiment is described in detail elsewhere [9].

The longitudinal velocity was determined for 20- and 30-percent PZT composites around 0.5 MHz, which is below the frequency corresponding to the acoustic impedance minima (Fig. 2(a)). The velocity values were multiplied by the average density to obtain the acoustic impedance. The resulting data shown in Table III are in excellent agreement with the values estimated theoretically for region 3.

D. Resonance Technique

The velocity of longitudinal waves determined by the resonance technique described in Part I [1] was also used to determine the acoustic impedance of composite samples. The velocities for different composites are listed in the last column of Table V of Part I [1]. Values of the acoustic impedance evaluated from the measured velocity and density of composites are listed in Table IV. Theoretically calculated acoustic impedance are also tabulated for comparison. In the piezoelectric resonance experiments, PZT rods in the composite are electrically poled. Hence, for calculating the elastic modulus of the composite, the modulus of the PZT rods $E = 1/s_{11} = 10.5 \times 10^{10}$ N/m$^2$ [7] was used.

As it emerges from Table IV, in region 1 ($>2$ MHz), a poor agreement between the estimated and measured acoustic impedance was found. This was anticipated because the rods are vibrating relatively freely and the resonance technique measured the velocity of PZT phase only. Hence, the product of this velocity with the average density of the sample gives a much higher estimate of the acoustic impedance.

In region 3 ($<0.5$ MHz), the agreement between the
theory and the experiment is excellent (Table IV). It is interesting to note that the three completely independent techniques give extremely consistent data on the acoustic impedance in region 3.

IV. CALIBRATION OF COMPOSITE TRANSUDER AS A RECEIVER OF ULTRASONIC WAVES

This section deals with the evaluation of composite transducers as an ultrasonic receiver. The receiving sensitivity is considered to be of greater importance than the transmitting response, especially in biomedical–diagnostic applications, because only a limited acoustic energy level can be applied to the human body. This limit has to be sufficiently low so bioeffects of ultrasound, if any, are minimized. Hence if the receiving sensitivity is augmented, the body can be interrogated at lower ultrasonic levels. Therefore, initial attention was focused on the receiving properties of the composite transducers.

The receiving characteristics of a transducer were assessed by its free-field voltage sensitivity (Mo). The free field sensitivity is the ratio of the output open circuit voltage to the free-field sound pressure in the undisturbed plane progressive wave [11]. For an ultrasonic transducer, in addition to a highest possible voltage sensitivity, a fast pulse echo time and low ringing are required in order to achieve good axial resolution. In an air backed transducer, these parameters are mainly determined by the piezoelectric coupling coefficient k, and acoustic impedance Z of the transducer relative to that of the human body. In composite material since both k and Z are dependent on frequency, the reception characteristics are also expected to be a function of frequency.

The time-delay spectrometry (TDS) technique [12], which allows the determination of the free-field voltage sensitivity as a continuous function of frequency, was used for calibrating the composite transducers. The TDS concept is based on converting a propagation time from transmitter to receiver into a certain frequency shift by keeping a constant frequency sweep rate so the time and frequency are linked together. Consequently, selectivity in time is proportional to selectivity in frequency with the sweep rate as conversion factor (e.g., 0–20 MHz sweep in one second corresponds to 20 Hz per microsecond). Only one direct signal will be detected, if a band-pass filter receiving the electrical signal from the ultrasonic hydrophone is swept with a suitable delay in relation to the transmitter driving signal and has an appropriate (narrow) bandwidth. Hence, the TDS technique virtually eliminates the effects of multiple transmission paths, standing waves, and other interference caused by reflected signals.

The experimental arrangement employed for calibration (Fig. 5) utilized a spectrum analyzer (HP 3585 A) with a built-in frequency offset unit. The sine swept signal from the tracking generator drives a specially designed transducer (transmitter) via a power amplifier (ENI 411 A). The ultrasonic signal in the far field was detected with a needle-like (1 mm diameter) calibrated polyvinylidene fluoride (PVF₂) polymer probe [13] and fed into the spectrum analyzer input (1 Ω termination). The detected signal was compared with the calibration curve of the probe (Fig. 6) to determine the absolute pressure at the probe as a function of frequency. The unknown receiver (composite) was then positioned exactly in the probe location and its voltage response was recorded on the spectrum analyzer. Ratio of the voltage response of the composite transducer to the sound pressure as determined by the polymer probe gives the free-field voltage sensitivity of the receiver. The result is expressed in volts per micropascal or in decibels [dB = 20 log (Mo volt/μ Pa)].

In this experiment, the spectrum analyzer was interfaced with a computer (HP 9825 A) to record the data at each step and calculate the free-field voltage sensitivity as a function of frequency. The result was transferred back and displayed on the spectrum analyzer in decibels relative to 1 V/μPa.

The calibration uncertainty of the polymer probe (Fig. 6) in frequency range from 1 to 10 MHz is reportedly ± 1.5 dB and ± 2 dB from 0.1 to 1 MHz [14]. The probe exhibited good frequency characteristics up to 10 MHz with
relatively high sensitivity and gave highly reproducible calibration of the composite transducers.

A number of commercial and custom-made transducers were used as transmitters for calibrating the composites as receivers. The center frequency of the transducer varied from 0.3 to 3.5 MHz. The diameter of the transducers ranged from 0.5 to 2.5 cm. Such a wide variety of transmitters were used to make sure that the receiver was always in the far-field of the transmitter, the distance between the transmitter and receiver was maintained at 22 cm/s, the transmitter chosen in a particular case was such that this distance was greater than \( \pi (a_1^2 + a_2^2)/\lambda \), where \( a_1 \) and \( a_2 \) are the radii of the transmitter and receiver, respectively, and \( \lambda \) is the wavelength. Under such a condition, it was estimated from Sabin’s calculations [15] that the error introduced due to marginal test distance is less than 1 dB.

Using Mason’s model [16], Shaulov and Smith [17] have derived an expression for the maximum open-circuit voltage response (\( |V|_{\text{max}} \)) and the 3-dB bandwidth (\( \Delta f_{\text{3dB}} \)) of a homogeneous transducer without backing or matching layers.

The expressions are given by

\[
|V|_{\text{max}} = \frac{4g_{33}Pt}{\pi} \left( \frac{Z_2}{Z_1} \right)
\]

and

\[
\Delta f_{\text{3dB}} = \frac{C}{\pi t} \left( \frac{Z_1}{Z_2} \right)
\]

In these expressions, \( g_{33} \) is the piezoelectric voltage coefficient, \( P \) is the incident pressure, \( t \) is the thickness of the transducer, \( C \) is the velocity of sound in the piezoelectric medium, and \( Z_1 \) and \( Z_2 \) are the acoustic impedance of the loading medium and the transducer, respectively.

The gain bandwidth product \( G \), given by the product of the maximum voltage sensitivity and the 3-dB bandwidth is

\[
G = \left( \frac{|V|_{\text{max}}}{P} \right) \Delta f_{\text{3dB}} = \frac{4g_{33}C}{\pi \lambda}.
\]

For PZT 501A, \( g_{33} = 26 \times 10^{-3} \text{ Vm/N} \), \( C = 3800 \text{ m/s} \), and \( G = 40 \text{ V Hz/Pa} \).

The gain bandwidth product \( G \) was used in this work as the figure of merit in analyzing the receiving response of the composite transducer. The experimentally determined value of \( G \) for the composites was compared with the calculated value of \( G \) for PZT. Any improvement in the gain bandwidth product was consequently attributed to a more effective coupling of the ultrasonic energy due to the epoxy phase.

Composite samples with 10, 20, and 30 volume percent PZT and thickness ranging from 0.6 to 5.15 mm were calibrated for their receiving voltage response, and the results are summarized in Table V. The maximum voltage sensitivity and the 3-dB bandwidth were the two main parameters measured in each case. From these measurements, the gain bandwidth product \( G \) was calculated.

The measurements on each sample were carried out at least twice to check the reproducibility. Most of the composites were calibrated using more than one transmitter. The reproducibility in the voltage sensitivity was always within 0.5 dB. From the consistency in the measurements performed, a maximum error in the figure of merit was estimated to be ten percent.

From the velocity of the transverse waves in the Spurrs epoxy (1150 m/s), the transverse wavelength was calculated at the frequency of the maximum reception sensitivity. As discussed earlier, the interaction between the PZT and the epoxy increases when the wavelength of the trans-

\[\text{Fig. 6. Calibration chart of PVDF ultrasonic probe.}\]
Table V

Receiving Voltage Response (M_r) of Composite Transducers

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Volume Percent PZT</th>
<th>Rod Diameter (mm)</th>
<th>Thickness t (mm)</th>
<th>Periodicity (d) (mm)</th>
<th>Frequency at Maximum Response (MHz)</th>
<th>Transverse Wavelength at Maximum Sensitivity λ (mm)</th>
<th>Maximum Sensitivity M_r (µV/Pa)</th>
<th>3-dB Bandwidth Δf_{3dB} (KHz)</th>
<th>Figure of Merit G (VHz/Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>10</td>
<td>0.45</td>
<td>0.66</td>
<td>1.27</td>
<td>2.25</td>
<td>0.50</td>
<td>0.39</td>
<td>130</td>
<td>288</td>
</tr>
<tr>
<td>101</td>
<td>10</td>
<td>0.45</td>
<td>1.93</td>
<td>1.27</td>
<td>0.88</td>
<td>1.29</td>
<td>1.01</td>
<td>200</td>
<td>105</td>
</tr>
<tr>
<td>102</td>
<td>10</td>
<td>0.45</td>
<td>3.64</td>
<td>1.27</td>
<td>0.44</td>
<td>2.60</td>
<td>2.04</td>
<td>496</td>
<td>168</td>
</tr>
<tr>
<td>103</td>
<td>10</td>
<td>0.45</td>
<td>5.15</td>
<td>1.27</td>
<td>0.30</td>
<td>3.83</td>
<td>3.01</td>
<td>955</td>
<td>120</td>
</tr>
<tr>
<td>200</td>
<td>20</td>
<td>0.45</td>
<td>0.66</td>
<td>0.9</td>
<td>2.25</td>
<td>0.50</td>
<td>0.55</td>
<td>144</td>
<td>252</td>
</tr>
<tr>
<td>201</td>
<td>20</td>
<td>0.45</td>
<td>2.54</td>
<td>0.9</td>
<td>0.625</td>
<td>1.84</td>
<td>2.04</td>
<td>531</td>
<td>154</td>
</tr>
<tr>
<td>202</td>
<td>20</td>
<td>0.45</td>
<td>3.05</td>
<td>0.9</td>
<td>0.525</td>
<td>2.21</td>
<td>2.45</td>
<td>750</td>
<td>133</td>
</tr>
<tr>
<td>203</td>
<td>20</td>
<td>0.45</td>
<td>3.95</td>
<td>0.9</td>
<td>0.400</td>
<td>2.86</td>
<td>3.17</td>
<td>933</td>
<td>115</td>
</tr>
<tr>
<td>204</td>
<td>20</td>
<td>0.45</td>
<td>4.60</td>
<td>0.9</td>
<td>0.352</td>
<td>3.26</td>
<td>3.62</td>
<td>1047</td>
<td>109</td>
</tr>
<tr>
<td>205</td>
<td>20</td>
<td>0.45</td>
<td>5.15</td>
<td>0.9</td>
<td>0.300</td>
<td>3.83</td>
<td>4.25</td>
<td>1128</td>
<td>110</td>
</tr>
<tr>
<td>251</td>
<td>20</td>
<td>0.28</td>
<td>2.60</td>
<td>0.6</td>
<td>0.625</td>
<td>1.84</td>
<td>3.06</td>
<td>684</td>
<td>133</td>
</tr>
<tr>
<td>301</td>
<td>30</td>
<td>0.45</td>
<td>2.44</td>
<td>0.73</td>
<td>0.7</td>
<td>1.64</td>
<td>2.24</td>
<td>575</td>
<td>140</td>
</tr>
</tbody>
</table>

Fig. 7. Receiving voltage sensitivity of a composite transducer (f_0 = 2.25 MHz).

The transmitting characteristics of a transducer for medical imaging can be characterized by its voltage response (S_v) and Q. The transmitting voltage response is the ratio of the sound pressure apparent at a distance of one meter in a specified direction from the effective acoustic center of the transducer to the voltage applied across the electrical input terminals [11]. In this study the transmitting voltage response of the composite transducers was determined at the near-field far-field transition region (a^2/λ distance) along the axis of the circular transducer. The Q of the transducer is the ratio of frequency at peak response to 3-dB bandwidth.

As shown in Table V, the figure of merit G for both ten- and 20-percent PZT composite with f_0 ≈ 2.25 MHz appears to be independent of the volume fraction of PZT and is very close to that of the calculated value of 40 (VHz/Pa) for single-phase PZT. The resonance data and the acoustic impedance results both indicated that the PZT rods in the composite at f_0 = 2.25 MHz vibrate relatively freely. The figure of merit G of the composite, being close to that of free PZT rods, is a further confirmation of the inferred vibration pattern in the composite when the periodicity is larger than the transverse wavelength. As the wavelength approaches the periodicity, laterally resonant modes are set up, and the interference between the two modes results in a reduced figure of merit (sample 101). The figure of merit G gradually increases for larger ratio γ = λ/d as expected. The figure of merit for γ ≈ 4 is increased three folds over that of PZT. Samples 102, 201, and 301 are made of 10, 20, and 30 volume percent PZT and have approximately the same value of the ratio γ (~2). It is interesting to note that the figure of merit of these samples is close to 80 (VHz/Pa). Similar agreement can be found between samples 103 and 203 with γ = 3.

The observed behavior indicated that the performance of a composite is directly related to the ratio between the wavelength of transverse waves and the periodicity of the lattice regardless of volume percent of PZT. This experimental observation suggested that one of the ways of increasing the efficiency of the composite for operation at high frequency (2 to 5 MHz) is to scale down the composite structure.

V. CALIBRATION OF COMPOSITE TRANSDUCERS AS A TRANSMITTER OF ULTRASONIC WAVES

The transmitting characteristics of a transducer for medical imaging can be characterized by its voltage response (S_v) and Q. The transmitting voltage response is the ratio of the sound pressure apparent at a distance of one meter in a specified direction from the effective acoustic center of the transducer to the voltage applied across the electrical input terminals [11]. In this study the transmitting voltage response of the composite transducers was determined at the near-field far-field transition region (a^2/λ distance) along the axis of the circular transducer. The Q of the transducer is the ratio of frequency at peak response to 3-dB bandwidth.
The same experimental setup shown in Fig. 5 was used for the calibration of the composites as a transmitter. The composite transducer to be calibrated is excited by the tracking generator of the spectrum analyzer via the power amplifier. The ultrasonic signal at the $a^2/\lambda$ distance detected by the calibrated needle-like polymer probe [13] was fed into the spectrum analyzer input (1 MΩ). The detected signal was adjusted for the calibration of the probe to calculate the pressure at $a^2/\lambda$ distance. The excitation voltage as a function of frequency was also measured by feeding the output of the power amplifier to the input (1 MΩ) of the spectrum analyzer. Quotient of the detected pressure to the excitation voltage gives the transmitting voltage response. In this experiment also the spectrum analyzer was interfaced with a computer (HP 9285A) to record the data at each step to calculate $S_0$ in dB (relative to 1 μPa/V). The test distance between the two transducers being only $a^2/\lambda$, an error is introduced in the measurements [15]. Since the radii of the composite transducer and the probe were kept constant, and all the measurements were performed at $a^2/\lambda$ distance from the projector, the correction factor is a constant. The correction factor was estimated to be approximately equal to 3.5 dB, which should be added to the measured $S_0$ in all the experiments.

Composites of different thickness and volume fraction were calibrated for their transmitting voltage response at their thickness mode resonance frequency. The results are summarized in Table VI. Fig. 8 shows a typical plot of transmitting voltage sensitivity of a composite transducer with $f_0 = 2.25$ MHz.

It was observed that for transducers operating around 2.25 MHz, the transmitting voltage response ($S_0$) depends on the volume percent PZT. There was a 6-dB reduction in $S_0$ observed going from the 20-percent PZT composite to the ten-percent PZT composite. A further reduction of 8–10 dB was observed for the five-percent composite. The observation suggests that the transmitting response of a composite transducer is proportional to the volume fraction of the piezoelectrically active material present in the composite. If this hypothesis is correct, it plausibly explains why the 20-percent composites gave about twice the pulse-echo signal of the ten-percent composite (Table 1).

The composite transducers resonating below 1 MHz were calibrated to examine the effect of the cooperative interaction between PZT and epoxy on the transmitting voltage response. However, a frequency independent figure of merit could not be defined to ascertain the frequency dependence of the transmitting voltage response because of the following reasons.

1) At low frequencies, where the dimensions of the projector are small in comparison with the wavelength in water, the transmitting characteristics are well described [11]. The piezoelectric material being stiffness controlled, a constant voltage applied to the transducer results in a constant displacement. Furthermore, since acoustic pressure generated by the transmitter is proportional to the acceleration, the transmitting voltage response increases at a rate of 12 dB/octave [$S_0 \propto (\text{frequency})^2$]. At high frequencies, where the transducer dimensions are comparable to the wavelength, the simple source concept cannot be applied because of resonance effect. 2) The transmitting voltage response also depends on the directivity pattern of the transducer [18]. When the circumference of the circular transducer is less than one half wavelength, that is
Fig. 9. Plot of maximum transmitting voltage response \( S_T \) as a function of frequency at maximum \( S_N \).

\[ ka = 2\pi a/\lambda < 0.5, \] the piston behaves like a point source and when \( ka \) exceeds three, the piston is more directional.

In this study, the following assumptions were made to evaluate the frequency dependence of the transmitting voltage response of the composite. Since all the composites are operated at half-wavelength thickness resonance, the thickness \( t \) of the sample bears a constant relation with wavelength at the operating frequency. Furthermore, since the amplitude of excitation signal is kept constant, a constant displacement can still be assumed in comparing the transmitting voltage response at different frequencies.

Under this assumption, the transmitting voltage response is expected to increase at a rate of 12 dB/octave as the frequency is increased [11]. Because the radius of the transducer is kept constant, an increase in the operating frequency makes the ultrasonic beam from the transducer less divergent, resulting in an increased pressure along the axis [18]. From the above argument it appears that the frequency dependence of the transmitting voltage response should be greater than 12 dB/octave.

Fig. 9 shows the plot of maximum transmitting voltage response as a function of frequency. The transmitting voltage response for 10 and 20 percent PZT composites were 195.8 and 201.9 dB (1 \( \mu P a/V \)) respectively. With the previously stated assumptions, a reduction of 24 dB in the transmitting voltage response was expected for the measurements performed at 0.5 MHz. However, a reduction of only 10 dB was actually measured. Also it is observed from Fig. 9 that at low frequencies (around 0.5 MHz), the rate of increase of \( S_T \) with frequency fits a straight line of slope 8–10 dB/octave.

These results confirm that the transmitting voltage response of composite transducers is, as anticipated, a function of frequency. At frequencies where the transverse wavelength is large compared to the periodicity, there appears to be an increase (\( \approx 14 \) dB) in the transmitting voltage response. The enhancement can be attributed to the improved interaction between PZT and epoxy at lower frequencies (<0.5 MHz). The improved performance should, however, be extended to a higher frequency range (2–5 MHz), which is typical for ultrasonic diagnostic applications. This will require having a large ratio of the transverse wavelength to the periodicity at the operating frequency.

The \( Q \) of the composite transducers operating at different frequencies are compared in the last column of Table VI. For composites resonant around 2.25 MHz, \( Q \) is approximately six and is comparable to the values of \( Q \) measured by the resonance technique in air [1]. Coupling the transducer to a water load has not altered the bandwidth characteristics, which is an indication of poor coupling of ultrasonic energy into water. Composites resonant around 0.5 MHz had relatively large \( Q \) in air (20–30), but by water loading the \( Q \) was reduced to about four. This is most likely due to a better matching of ultrasonic energy between the composite and water.

The acoustic impedance at 2.25 MHz for a given volume percent PZT composite is much lower than the value at about 0.5 MHz. The data on acoustic impedance suggest that the transfer of acoustic energy from water to the composite or vice versa should be better at high frequencies. The results on the transmitting and receiving voltage responses indicate that at higher frequency, the energy is not being properly coupled to the piezoelectric phase although the transfer of energy between the two media may be more effective. The observed behavior is again an indication of poor acoustic coupling between PZT and polymer at frequencies (2.25 MHz) where the transverse wavelength is much smaller than the periodicity. Thus, if the composites prepared in the study are operated around 0.5 MHz, there appears to be efficient transfer of acoustic energy from PZT to water via the epoxy phase. As a result, substantial improvement in the receiving and transmitting voltage responses was observed.

VI. EFFECT OF THE MATCHING LAYER ON THE PERFORMANCE OF COMPOSITE TRANSDUCERS

The composite transducers showed a substantial improvement in receiving and transmitting voltage responses, when operated at resonance in the low frequency range where the transverse wavelength is large compared to the periodicity. The \( Q \) of the composite transducer was reduced from about 25 to about four when coupled with water load. The measured value of \( Q \) is relatively large for medical diagnostic applications where a \( Q \) of 2–2.5 is usually recommended [19] for a good axial resolution. Larger \( Q \) in the composite transducers was also apparent from the slow pulse-rise time and prolonged ringing in the pulse-echo response.

Relatively large \( Q \) values observed in the composite transducers was attributed to the acoustic impedance mismatch between the transducer and the load. The acoustic impedance of a 20 percent PZT composite in the low-frequency range is 7.3 M rayl (Table IV) which results in a pressure reflectivity of 65 percent with water load. To improve the impedance matching, a matching layer between the transducer and the load was considered. For optimum transmission, the matching layer has to be a quarter wavelength in thickness and of characteristic impedance equal.
to the geometric mean of those of the transducer and of the loading medium [20]. In the present situation, \( Z \) of the matching layer was calculated to be 3.3 M rayl. Several polymer systems have acoustic impedance in this range.

A 20-percent PZT composite 3.07 mm in thickness was chosen to study the effect of a quarter-wave matching layer. Since lucite \( (Z = 3.2 \text{ M rayl}) \) was readily available and had an acoustic impedance very close to the required value, a quarter-wave matching layer of lucite material was pressure-bonded to the transducer using an epoxy (Tracon 2115). The thickness of the bonding layer was less than 25 \( \mu \text{m} \). The frequency \( (f_0) \) at maximum pulse-echo response was 0.54 MHz. This composite with the matching layer was characterized for its receiving and transmitting voltage response.

The gain bandwidth product \( G \) in the receiving mode of the matched transducer was 180 (VHz/Pa), which is 4.5 times higher than that of a corresponding PZT rod. The transducer has a very broad band response with \( Q \) of 1.8. The transmitting voltage sensitivity was 186.5 dB relative to 1 \( \mu \text{Pa/V} \), and \( Q \) in the transmission mode was also about 1.8. Comparing the results of the matched transducer with those of unmatched 20-percent PZT composites such as 201, 202, 251 (Tables V and VI) operating around 0.5 MHz, it can be seen that major contributions for the enhanced response came from the broadening of the bandwidth. This is quite evident from the pulse-echo response of the matched transducer shown in Fig. 10. The pulse-rise time is very fast and the ringing is low (Fig. 10(a)), as exemplified in the broad nature of the frequency spectrum (Fig. 10(b)). These experiments demonstrate that composite transducers with a single matching layer can have excellent performance in medical diagnostic applications.

As mentioned previously, the improved performance should, however, be extended to the higher frequency range (2–5 MHz) typical for ultrasonic diagnostic applications. From the experimental results, the substantial improvement can clearly be attributed to the strong interaction between the PZT and epoxy where the transverse wavelength was large compared to the periodicity. This observation suggests that one of the ways of increasing the efficiency of the composite for operation at high frequency is to scale down the composite structure. This means that the rod diameter and the periodicity of the lattice in the composite structure should be scaled down by at least a factor of five to operate at approximately 2 MHz.

**VII. FOCUSED COMPOSITE TRANSDUCER**

This section deals with shaping a composite transducer to focus a sonic beam to a narrow beamwidth. Composite materials can be molded into curved shapes by a simple thermal process as explained in the following.

Thin composites \( (\approx 0.6 \text{ mm}) \) of 10 and 20-percent PZT were prepared in a flat shape by the usual procedure. A spherical mold with a curvature of 9.5 cm was heated in a small oven to 80°C which is just above the glass transition temperature of the Spurrs epoxy \( (T_g \approx 70°C \text{ at } 100 \text{ Hz}) \). At this temperature epoxy was quite soft and flexible. The composite sample was placed on the mold and allowed to reach thermal equilibrium. A slight deformation under gravity was noticed. The backing mold was placed on top to force the composite to conform to the spherical curvature of the mold. The mold set was kept at 80°C for about an hour and cooled slowly \((\approx 1°C \text{ per minute})\) to room temperature.

To measure the axial beam profile, the focused composite transducer was driven by continuous wave excitation at the frequency of maximum response. The calibrated miniature hydrophone probe (Section IV) [13] was used to measure the transmitting voltage response along the axis of the transducer. Fig. 11 shows the axial beam profile of a 20-percent PZT composite transducer \( (f_0 = 2.25 \text{ MHz}) \) before and after focusing. The peak response for nonfocused transducer was 200 dB relative to 1 \( \mu \text{Pa/V} \) at 12.1 cm, which corresponds to the expected \( a^2/\lambda \) distance. After focusing, the response peaked at an axial distance of 7.6
cm with a gain of 8.5 dB in the voltage response. Table VII summarizes the results of the focusing studies on both ten- and 20-percent PZT composite transducers. The maximum response in all the cases occurred at a distance slightly farther than the expected 6 cm, which was based on the theoretical calculations by C'Neil [21]. This discrepancy is probably due to the fact that the theory was developed for a single-phase material and may not be fully valid for the composite transducer.

The lateral beam profile at the distance of maximum response was measured using the polymer probe. An x-y-z micromanipulator was used to move the hydrophone probe away from the axis of the transducer in steps of 0.63 mm. The lateral beamwidth was calculated from the points where the effective relative pressure was $\frac{1}{e} = 0.368$ of the peak [22]. The lateral beamwidths at the peak response are given in Table VII. There was nominally a 30- to 40-percent reduction in the beam width after focusing. The beamwidths are slightly larger than the theoretically calculated value of 4.6 mm [22].

The tone-burst pulse-echo response with the stainless steel reflector at the distance corresponding to the peak response was measured for both the nonfocused and focused transducers (Table VII). Since the transmitting voltage response was increased by a factor of two (6 dB) on focusing, a considerable improvement in the pulse-echo amplitude was also expected. Surprisingly, it was noticed that in most cases there was actually a small decrease in the pulse-echo signal. It was suggested that the spherical curvature on the transducer affects the receiving voltage sensitivity and is the cause for the decreased pulse-echo signal. A further support for this is presented in the following.

The degree of the concavity $h$ of the transducer is comparable to the wavelength $\lambda$ in water at 2.25 MHz ($h/\lambda = 0.7$), and hence modifies substantially the phase profile of the reflected beam at the transducer face. Since the receiving voltage sensitivity is dependent on the phase profile of the pressure at the transducer face [15], focusing was expected to affect the receiving sensitivity. As anticipated, the average gain in bandwidth product of a focused transducer operating at 2.25 MHz was 26 MHz $V/Pa$ compared to the measured value of 36 Hz$V/Pa$ for a flat transducer (Table V).
VIII. CONCLUSION

The composite transducers were initially characterized by the pulse-echo method. To evaluate the composites thoroughly, the acoustic impedance and the transmitting and receiving voltage responses were measured separately as a function of frequency. Frequency dependence of the acoustic impedance was modeled by calculating the average elastic modulus at two extreme conditions. The acoustic impedance modeled using the Voigt constant strain model showed excellent agreement with the measured values at 0.3 MHz. Measured values of acoustic impedance at 3.5 MHz were in excellent agreement with the values modeled by the constant stress model.

The figure of merit in the receiving mode for a composite with \( f_0 = 2.25 \text{ MHz} \) was close to the calculated value for a single-phase PZT. This result indicated virtually no contribution from the epoxy phase because of the weak interaction between PZT and epoxy. As the operating frequency was reduced below 0.5 MHz, the figure of merit \( G \) increased by a factor of three. The substantial improvement in \( G \) provided additional evidence for the strong interaction between PZT and epoxy at low frequencies. A similar improvement was observed in the transmitting voltage response for composites operated around 0.5 MHz.

The performance of the composite transducer was further improved by the use of a quarter wavelength matching layer of lucite material between the transducer and load. The figure of merit \( G \) in the receiving mode of the composite transducer was increased by about 50 percent when the matching layer was used. The \( Q \) of the matched transducer was less than two, which is advantageous in achieving good axial resolution.

The results show that the 1-3 composite materials are excellent candidates for medical diagnostic transducer applications. However, it should be noted that the improved performance of the composite transducer should be extended to higher frequencies (2–5 MHz) typical for the ultrasonic diagnostic applications. It was demonstrated that the composite transducers can be focused by a relatively simple technique. As a result of focusing, it was possible to generate a concentrated sonic beam with narrower beamwidth.

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