COMPOSITE PIEZOELECTRICS FOR ULTRASONIC TRANSDUCERS

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Abstract

The KLM transmission-line model is employed to analyze the performance of an ultrasonic transducer made from a composite piezoelectric material. The basic transducer parameters, including electrical and mechanical losses, are determined by analyzing the electrical impedance of the air-loaded composite disk in the vicinity of the thickness resonance. Using these parameters, the performance of a prototype 3 MHz composite transducer is calculated and found to be in good agreement with experimental data. On the basis of these results, the performance of the composite transducer with optimum acoustic and electrical matching is predicted. Our results reveal substantial promise for composite piezoelectric materials in making efficient broad-band ultrasonic transducers for medical imaging.

1. Introduction

Ultrasonic systems for medical imaging employ broad-band piezoelectric transducers to transmit short ultrasonic pulses through the body and detect the reflected echoes [1,2]. Optimal design of such transducers requires a piezoelectric material with high electromechanical coupling, k_t, and low acoustic impedance, Z, [3,4]. The conventional piezoelectric ceramics and polymers do not satisfy this requirement. Piezoelectric ceramics, such as lead zirconate-titanate (PZT), lead metaniobate and modified lead titanate [5,6], offer high electromechanical coupling ($k_t \sim 0.4 - 0.5$), and high acoustic impedance ($Z \sim 20$-35 Mrayls). On the other hand, piezoelectric polymers, such as PVDF and its copolymers [7], offer low acoustic impedance ($Z \sim 4$ Mrayls), and low electromechanical coupling ($k_t \leq 0.3$).

Recently, piezoelectric materials that combine the desired properties of high k_t and low Z have been developed by combining a piezoelectric ceramic and a passive polymer in a composite structure [8-11]. This composite structure, formally characterized by 1-3 connectivity, consists of a two dimensional array of parallel piezoceramic rods embedded in a polymer matrix. A wide range of properties can be realized with these composites by varying the piezoceramic and polymer components, and their volume fractions [12]. A crucial consideration in the design of such composites is the lateral spatial scale of the structure. This must be sufficiently small to avoid unwanted lateral stop-band resonances in the bandwidth of the transducer [13-15].

Broad-band ultrasonic transducers have been made from composite piezoelectric materials of various compositions [16-18]. In this paper we analyze the performance of such a transducer using the one-dimensional transmission-line model of Krimholtz, Leedom, and Matthaei (KLM) [19]. The composite material is treated as an effective homogeneous medium with mechanical and electrical losses. Experimental and simulated results are compared for a 3 MHz disk transducer provided with a single acoustic matching layer and a light backing. A computer program obtained from Stanford University allows us to optimize the electrical matching network, the acoustic impedance and the thickness of the acoustic matching layer [20]. Using this program we estimate the optimum performance obtainable from this particular composite sample.

2. Fabrication Technique

The transducer reported in this paper was made from a composite disk (diameter 19 mm, thickness 0.6 mm) fabricated from a PZT5A type ceramic and a rather stiff polymer. The spatial periodicity of this sample is less than 150 microns and the volume percentage of PZT is about 30%. The fabrication procedure of the composite is illustrated in Figure 1. A solid PZT disk is partially

Figure 1: Dice and fill fabrication of rod composites.

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diced in one direction and again in the orthogonal direction. A polymer epoxy is then poured into the grooves. After curing the epoxy, the base of the solid PZT is removed and the faces of the resulting composite disk are polished to the desired thickness.

In making the transducer, thin metal electrodes were deposited on the faces of the composite disk, and metal leads were attached to them with conducting epoxy. The composite disk was mounted on a light backing (Z = 1.4 Mrayls), and an acoustic matching layer of Mylar (Z = 3 Mrayls, thickness 170 microns) was attached to its front face using Araldite that has the same acoustic impedance as the Mylar. The assembled transducer was mounted in a Delrin Package and sealed with RTV silicone rubber.

3. Basic Transducer Parameters

The properties of the composite material relevant to its performance as a thickness-mode transducer are the following: the clamped dielectric constant, ε^S, longitudinal acoustic velocity, v^D, thickness electromechanical coupling coefficient, k_t, specific acoustic impedance, Z, mechanical quality factor, Q_m, and the dielectric loss, $\tan\delta$. Five of these parameters (ε^S, k_t, v^D, Q_m, and $\tan\delta$) are obtained by measuring the complex electrical impedance as a function of frequency in the vicinity of the thickness mode resonance, using the impedance circle technique [21]. Fine adjustments of these parameters are obtained by fitting the theoretically predicted impedance to the experimental data. An additional measurement of the density, ρ, is performed to determine the specific acoustic impedance, $Z = \rho v^D$.

In Figure 2, the magnitude and phase of the electrical impedance of the air-loaded composite disk are plotted as functions of frequency. The measured magnitude and phase are plotted as circles and crosses, respectively. The solid lines describe a theoretical fit using the KLM model with front and back acoustic ports short circuited. The adjusted effective parameters determined in this experiment are listed in Table I.

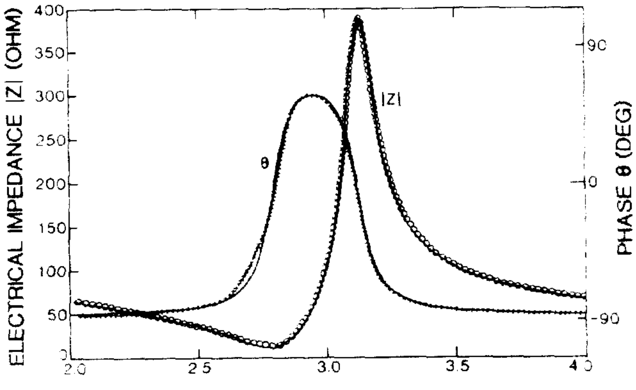

Figure 2: Theoretical curves fitted to the measured magnitude and phase of the electrical impedance of air-loaded composite disk. The parameters values used in this fit are given in Table I.

Table I: Effective parameters for a composite disk.

ε^S	180
v^D (m/s)	3750
k_t	0.49
Z (Mrayls)	13
Q_m	29
$\tan\delta$	0.05

To further confirm that these material parameters accurately describe the transduction properties of the composite material, the electrical impedance measurement was repeated with one face of the sample immersed in water.

The magnitude and phase of the electrical impedance of the water loaded composite disk are plotted as functions of frequency in Figure 3. The solid lines describe the prediction of the KLM model, based on the material parameters listed in Table I. The theoretical curves are in good agreement with the experimental data.

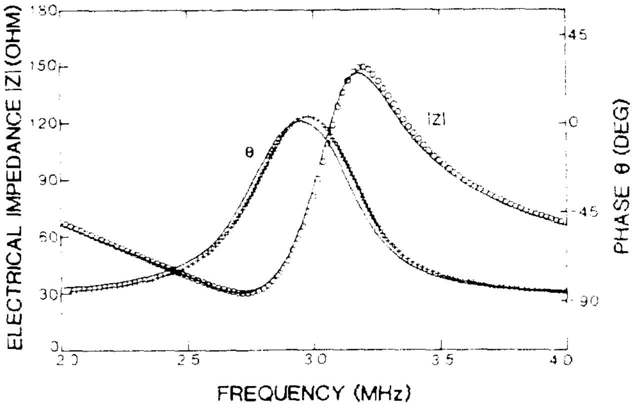

Figure 3: Measured electrical impedance of water-loaded composite disk compared with theory.

4. Transducer Performance

The composite disk characterized above was fabricated into a 3 MHz transducer by attaching a matching layer and a backing layer to its faces, as described in section 2. The pulse-echo performance of this transducer was examined by measuring the impulse response characteristics and the two way insertion loss.

In these measurements, the transducer was placed in a water tank at a distance of 5 mm from a steel block. The impulse response was measured using a Metrotek pulser-receiver system. When loaded with a 50 Ω resistor, the pulser (MP203) produced voltage spikes whose amplitude spectrum was flat to within ±1 dB up to 10 MHz. A Metrotek MR101 receiver amplifier in conjunction with a stepless gate passed the first reflected echo onto an HP3585 spectrum analyzer and a Tektronix 7904 oscilloscope.

Figure 4 shows the measured pulse-echo response of the composite transducer together with the simulated response. The measured and simulated pulse shapes are in good agreement. Specifically, there is a good agreement between the -20 dB and -40 dB ringdown times of the measured response (1.4 μs and 2.2 μs, respectively) and the simulated response (1.43 μs and 2.23 μs, respectively).

The sensitivity of the transducer and its frequency response were characterized by measuring the round trip insertion loss as a function of frequency. In this measurement the transducer was driven with an HP3314 sinewave generator. The generator was adjusted to transmit tone-bursts with an amplitude, V_t, of 5 volts and duration of about 15 cycles into a load equal to the source resistance (50 Ω). The insertion loss was determined from the amplitude, V_r, of the echo signal generated across the same load, as $20\log(V_t/V_r)-0.6$ dB, where the 0.6 dB accounts for the imperfect reflection of the steel block.

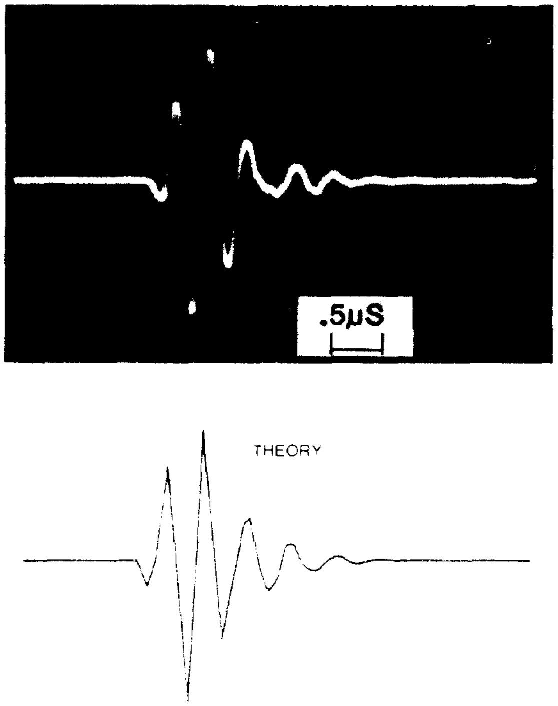

Figure 4: Measured impulse response compared with theory.

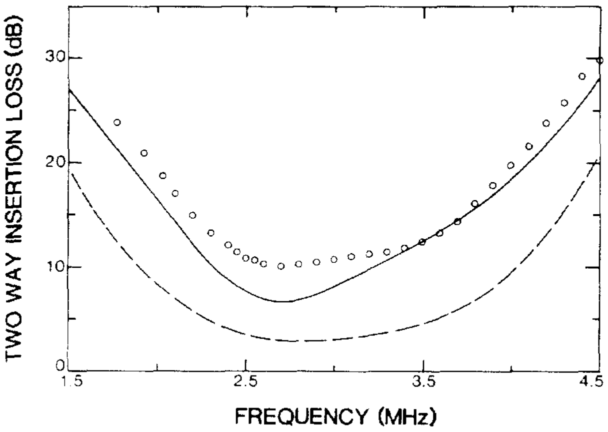

Figure 5: Measured (circles) and calculated (solid line) insertion loss for the composite transducer with acoustic but no electrical matching. The dashed line represents theoretical prediction for transducer made from the same composite material but with optimum acoustic and electrical matching.

Figure 5 shows the measured insertion loss as a function of frequency (circles) together with the theoretical expectation (solid line). The measured insertion loss exhibits the expected variation with frequency, but attains values slightly higher than the calculated ones. The maximum deviation is about 3.5 dB. Corrected loss calculations would require consideration of the frequency dependent losses in each layer of the transducer.

The experimental results shown in Figure 5 were obtained without electrical matching of the transducer to the source. Nevertheless, good sensitivity (minimum insertion loss 10 dB) is observed over a broad bandwidth (6 dB fractional bandwidth 54%). With a series tuning coil of 3.8 μH, the minimum insertion loss decreased to 6.5 dB, and the 6 dB fractional bandwidth increased to 62%.

The computer program obtained from Stanford University allows us to optimize the electrical tuning network and the acoustic impedance and thickness of the acoustic matching layer [20]. The optimization is designed to minimize both the ringdown times as well as the insertion loss. Optimum design of a transducer with a single matching layer from a composite disk with the parameters listed in Table I, is expected to yield -20 dB and -40 dB ringdown times of 1 μs and 1.7 μs, respectively. The frequency dependence of the insertion loss of such a transducer is described by the dashed line in Figure 5. This simulated curve indicates a minimum insertion loss of 3 dB, and 6 dB fractional bandwidth of 68%. The design and performance of optimized composite transducers will be described elsewhere.

5. Conclusions

Rod composites with sufficiently small spatial periodicity behave as homogeneous piezoelectric materials with high electromechanical coupling and low acoustic impedance. The combination of these properties makes the composite materials suitable for the design of efficient broad-band transducers for medical ultrasonic imaging. The design of such transducers can be based on the KLM transmission line model for acoustic transducers. Simulated results reveal substantial promise for composite transducers with both optimum acoustic matching layer and electrical matching network.

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