OUR EXPERIENCE WITH SINGLE CRYSTAL PIEZOCOMPOSITE TRANSDUCER MATERIALS

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Abstract: Piezocomposite materials have significantly improved the performance of ultrasonic testing. When compared to monolithic piezoceramics, the coupling factor is higher and the acoustic impedance is lower. Both of these factors contribute to improved sensitivity and bandwidth. More recently, single-crystal piezoelectric materials are being developed. These new materials, when fabricated into piezocomposites, should produce and even more dramatic improvement in ultrasound testing.

This presentation reviews the sensitivity and bandwidth improvements that can be expected from single-crystal piezocomposites , and discusses our experience with the fabrication and evaluation of ultrasound transducers incorporating them. Performance and cost will be compared to current piezocomposite designs. The potential use of these materials in phased array probes will also be discussed.

Introduction: Ultrasonic inspection is used in many industries. Wall thickness measurement of pipes, flaw detection in welds, characterization of material properties, delamination detection in composite materials are some of the uses of ultrasonic inspection [1].

The ultrasound transducer is a critical component in the inspection system. All information gathered about the test piece is obtained from signals passing through a transducer twice – once during transmission and once during reception. In many, not all, situations increased system bandwidth and improved signal-to-noise ratios can yield better test results. Transducer design is an important factor in determining bandwidth and s/n ratios. Those features of the piezoelectric material itself that relate to bandwidth and s/n ratio are thickness coupling factor, acoustic impedance, and dielectric constant.

The thickness coupling factor is a measure of the piezoelectric material's conversion of stored electrical energy into acoustic energy and vice versa. All other factors being equal, increasing the thickness coupling factor increases the sensitivity of the transducer and the bandwidth of the transducer.

The acoustic impedance of the piezoelectric material determines the effectiveness of acoustic coupling to other materials. The closer the acoustic impedances, the greater the signal transfer. This also contributes to increased signal and bandwidth. The energy in the piezoelectric element causes it to resonate. As it resonates, some of the energy is transferred into the adjacent materials – the test piece on the front and the damping material on the back. If the match is poor, only a small portion of the energy is transferred on each cycle and the resulting signal in the test piece is relative long with low amplitude. If the acoustic impedance match is good, much more of the energy is transferred on each cycle resulting in fewer cycles, each of higher amplitude. Therefore, given a test piece material, it is desirable to use a piezoelectric material having a similar acoustic impedance, if possible.

The dielectric constant, although an important factor in transducer design, will not be considered in this discussion. Because of the limited availability of single-crystal materials, dielectric constant is not really a variable.

Transducer models enable researchers to estimate design performance without costly experimentation. Even when a model doesn't yield exact results, trends can be determined that guide the design of experimental models. We have used the KLM [2] model for several years and will use it in this presentation to review the motivation for considering single-crystal materials.

We have selected a 5 MHz, 6 mm immersion design as our test case. It is commonly used, so extensive data exists on the performance of monolithic and peizocomposite versions of this transducer. The predicted performance using monolithic PZT is shown in Figure 1.

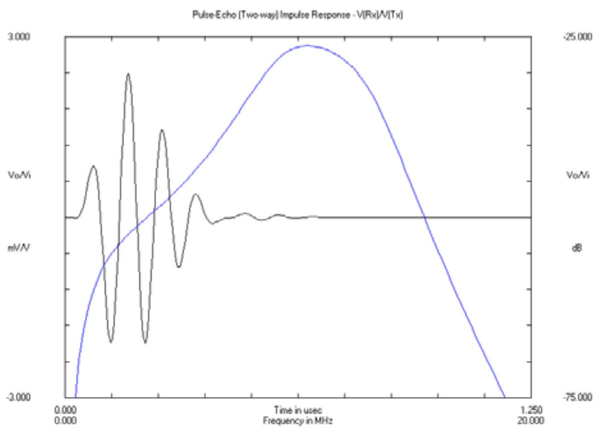

Figure 1 – Pulse-echo Impulse Response of a PZT Transducer

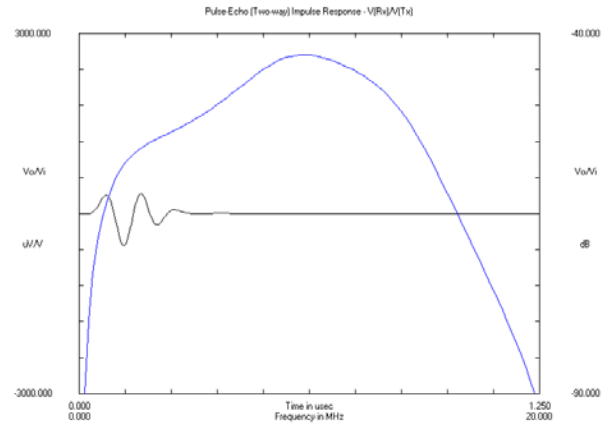

Figure 2 – Pulse-echo Impulse Response of a Lead Metaniobate Transducer

It is apparent from the figure that this design is not most appropriate for high resolution testing. The acoustic impedance of the PZT element is relatively high, 32 MRayles, and it is difficult to fabricate damping materials with a sufficiently high impedance to damp the piezoelectric element. An alternative, which has been used quite effectively, is the use of lead metaniobate as the piezoelectric element. This has a lower acoustic impedance (20 MRayles), which is more effectively damped by the same damping materially. Additionally, lead metaniobate itself has a lower mechanical Q, which contributes to improved pulse ringdown. Incorporation of lead metaniobate into this design yields the performance shown in Figure 2. Although the resolution (pulse ringdown) has improved, considerable signal amplitude has been lost because of the lower thickness coupling constant of lead metaniobate. Still, this has been one of the more commonly used methods of producing transducers for high resolution applications.

As piezocomposite materials gained acceptance, some of the deficiencies of lead metaniobate's performance were overcome. Piezocomposite materials are combinations of conventional piezoelectric materials and polymers that yield improved piezoelectric performance. These materials, with volume fractions around 30%, can have acoustic impedances of 10 MRayles, and lower, while still having coupling coefficients superior to monolithic PZTs [3]. The polymer provides internal damping coefficients approaching lead metaniobate. Because of the low acoustic impedance of the piezocomposite, the acoustic impedance of the damping material can be reduced. Incorporation of a PZT –based piezocomposite material into this transducer design yields the performance shown in Figure 3.

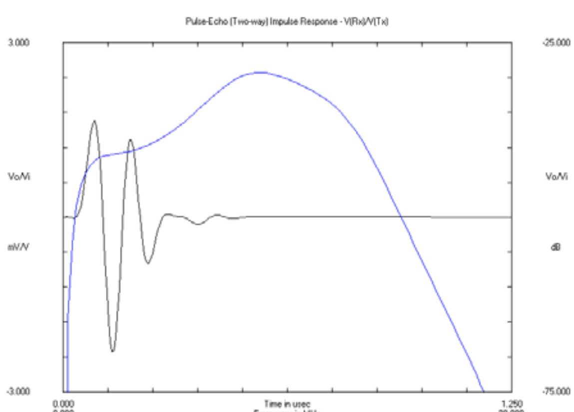

Figure 3 – Pulse-echo Impulse Response of a PZT Piezocomposite Transducer

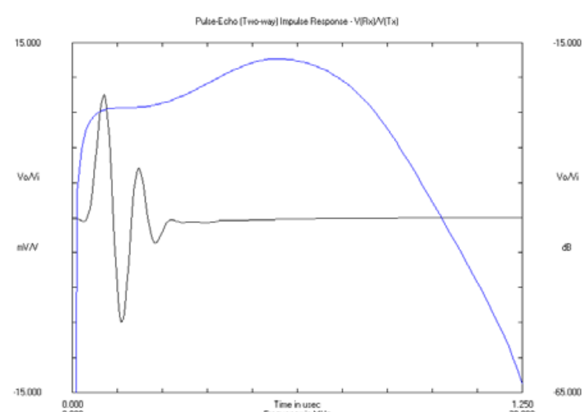

Figure 4 – Pulse-echo Impulse Response of a Single-crystal PMN-PT Piezocomposite Transducer

These designs have gained wide acceptance in many nondestructive testing applications.

Research has shown that single-crystal piezoelectric materials having compositions of lead magnesium niobate and lead titanate, or lead zinc niobate and lead titanate, have an interesting property – when used as a piezocomposite material, coupling factors as high as 0.9 should be achieved [4] [5]. Modeling such a material yields the impulse response shown in Figure 4. To appreciate the improvement, note that the vertical scale has been changed by a factor of 5. These results are not necessarily optimized, that is, further changes could be made in each of these models that may improve performance for particular applications. We believe it is clear, however, that single-crystal piezoelectric materials should provide significant improvements in ultrasonic transducer performance and are worthy of further investigation.

Results: It is not the intention of the authors to rank the performance of materials from various suppliers because much of the final performance will depend on material processing. Therefore, suppliers will not be identified by name. The cost of these materials is quite high compared to more conventional materials. Several years ago the material was cost $500 - $700 per square cm in small quantities. More recently, prices have decreased to approximately $ 200 per square cm. As available supplies increase, costs should decrease further.

Single-crystal material was acquired from four suppliers. The physical appearance of the material differed greatly among the vendors. Some pieces were very transparent while others were only translucent. One vendor indicated that the differences in physical appearance were due to differences in manufacturing conditions but it seems that such differences might also affect piezoelectric performance.

The reader is referred to other presentations to review the fabrication of 1-3 piezocomposite materials [2] but it involves dicing a plate of the piezoelectric material into an array of square posts, and then surrounding those posts with a polymer. This process is reasonably reliable and has been used at our facility for many years.

The first attempt to dice the single-crystal material was unsuccessful. Even dicing in a single direction fractured the single-crystal material disqualifying it for further use. After reviewing the fabrication procedures presented by Michau [6], changes were made to slow the dicing process and increase the volume fraction from 30% to 60 % and success was finally achieved. Unfortunately, the resulting probes cannot be compares to PZT piezocomposite probes because they are not manufactured at this facility. Also, the material having a translucent, rather than transparent appearance was not diced successfully. It may be possible to do so with alternate dicing parameters, but this material seems much more fragile.

The diced ceramic was backfilled with an epoxy having an acoustic impedance of 3 Mrayles. After curing the epoxy, the monolithic portion of the original ceramic plate was removed by grinding. A photograph of the composite is shown in Figure 5.

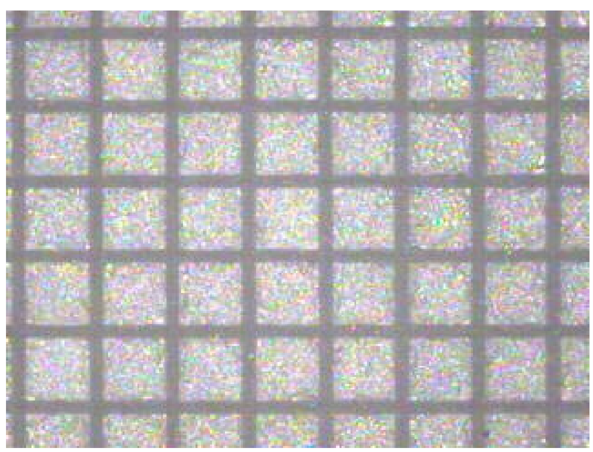

Figure 5 – 60% volume fraction PMN-PT piezocomposite using slower dicing speeds

Sputtered electrodes were applied to the samples and they were poled in a liquid bath at 25 degrees C with a poling field of 28 kvolts/cm.

The relative dielectric constant and the thickness coupling coefficient are given in Table 1. Although the coupling coefficient is superior to PZT/epoxy piezocomposites, it is not as good as expected.

TABLE 1. Properties of monolithic PZT, PZT piezocomposite, and PMN-PT single-crystal piezocomposite			
	PZT(5H type)	PZT Piezocomposite	PMN-PT Piezocomposite
Coupling coefficient (kt)	.55	.61	.77
Frequency constant (kHz-cm)	202	155	108
Dielectric constant	3800	1080	1300

Although the original intent was the construction and evaluation of 5 MHz transducers, some of the material was processed to a higher resonant frequency in which the anticipated improved resolution could be more beneficial. An attempt to fabricate 10 MHz samples yielded 9.3 MHz. The impedance spectrum of one sample, Figure 6, shows no extraneous resonances – even to 40 MHz.

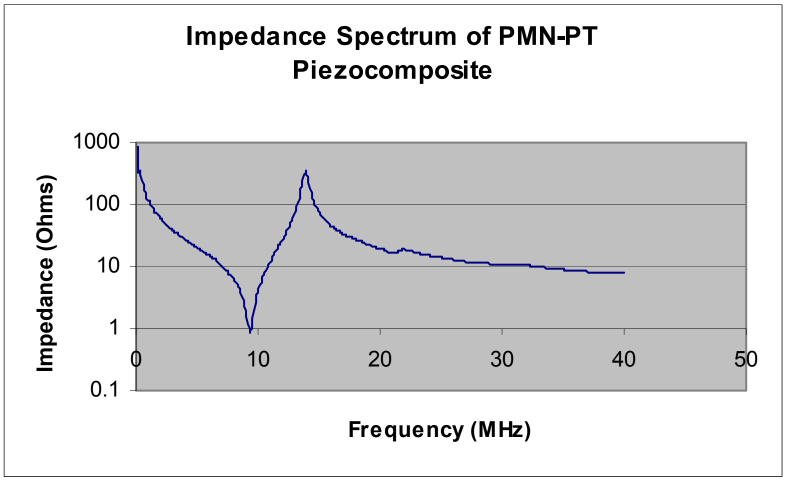

Fig. 6 – Impedance Spectrum of 9.3 MHz PMN-PT Piezocomposite

The 9.3 MHz ceramic was assembled into what is called a pencil probe configuration. The piezoelectric element is 2.25 mm (.090 in) diameter. Backing material and a suitable face were applied, very similar to current piezocomposite composite pencil probe designs. Performance was superior to our current design at 7.5 MHz. Bandwidth exceeds 100%, and gain exceeds normal designs by several db. Because of the different frequency, it was decided to compare waveshape to a modeled prediction shown in Figure 7. The actual single-crystal probe performance is shown in Figure 8 and compares favorably to the prediction.

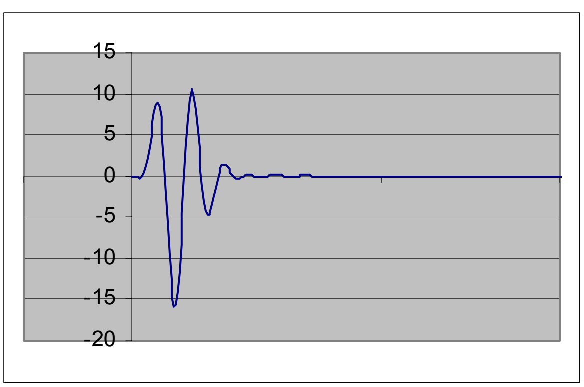

Fig.7 – Predicted performance of the 60% volume fraction PMN-PT immersion probe

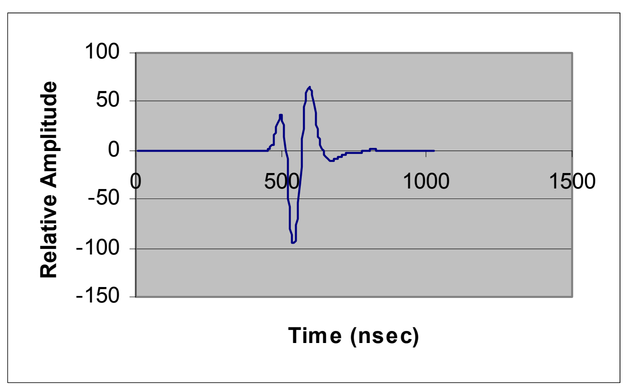

Fig. 8- Single-crystal piezocomposite probe performance

Discussion: The cost of single-crystal PMN-PT is many times greater that of PZT. The expected performance improvement can justify this increase in some high resolution applications that are currently difficult using PZT piezocomposites. Also, in small area probes, such as the 2.25 mm diameter "pencil probe", the cost increase is not large and compares with other single crystal materials such as lithium niobate. As PMN-PT production procedures are perfected, one would expect declining costs to permit introduction into a wider variety of transducer designs.

The variation in appearance of the material from various vendors is a concern to the authors. The "clarity" of the samples seemed to correlate to dicing success. Perhaps this is only coincidental and further work is warranted.

Dicing the single crystal material was difficult, but ultimately successful. Piezoelectric elements up to 9.3 MHz, and 60% volume fraction were constructed. The methods used are still in development and the authors believe dicing times will decrease with higher yield rates. They also believe that lower volume fractions will be achieved in the near future. These achievements should improve the market application of PMN-PT piezocomposites.

The thickness coupling factor of a piezocomposite normally approaches the value of k_{33} for the base material. The published k_{33} value for the PMN-PT material used in this work is approximately 0.9 yet the experimentally measured kt for the single-crystal piezocomposites is only 0.77. There are several possible reasons for this reduction. As indicated earlier, it was difficult to dice the material without fracturing. It is possible that even those pieces that were successfully diced, actually contained damage that reduced the piezoelectric performance. It can be seen deduced from the low frequency constant that poled single crystal material is less stiff than PZT. Therefore, it is possible that a more compliant epoxy filler is required to achieve higher coupling factors.

It seems reasonable that NDT phased array transducers would benefit from the higher coupling factor of the PMN-PT piezocomposites. The higher dielectric constant and planned increased bandwidth should improve both linear and 2-D array designs. It is planned to construct 1-D and 2-D array transducers using the single-crystal materials for performance comparison to current PZT designs, and these results will be reported at a later time.

Conclusions: Our work indicates significant improvements in transducer performance are achievable using piezocomposites fabricated from single-crystal PMN-PT. The cost of the raw material and the fabrication difficulty currently restrict the application of these materials to those applications demanding high performance devices, but these issues will probably subside as use increases. Additional work is necessary to determine whether fabrication damage was a factor in the slightly lower that expected performance. New transducer designs, including 1-D and 2-D arrays, optimized for these piezoelectric materials should further improve transducer performance.

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