IMPROVED TRANSDUCER PERFOMANCE WITH NEW PIEZOELECTRIC MATERIALS FOR UNDERWATER IMAGING

M F Wallace	School of Engineering and Science, University of Paisley, Paisley, PA1 2BE
S Cochran	School of Engineering and Science, University of Paisley, Paisley, PA1 2BE
P Marin	PCT Ltd, Crombie Lodge, Balgownie Drive, Aberdeen, AB22 8GU
K Mayne	PCT Ltd, Crombie Lodge, Balgownie Drive, Aberdeen, AB22 8GU
M P Walsh	PCT Ltd, Crombie Lodge, Balgownie Drive, Aberdeen, AB22 8GU
R Wright	Tritech International Ltd, Peregrine Road, Westhill, Aberdeen, AB32 6JL
R Marsh	Tritech International Ltd, Peregrine Road, Westhill, Aberdeen, AB32 6JL

1 INTRODUCTION

In recent years, new single crystal piezoelectric (piezocrystal) materials have become available, offering significant improvements in range and spatial resolution for underwater ultrasonic imaging systems. These benefits are gained through increased transducer bandwidth and sensitivity, particularly when the materials are used in piezocrystal – polymer composite structures[1]. By enhancing overall system performance, the advantages of these materials are expected to feed through to commercial adoption of high performance imaging systems for demanding applications such as underwater target classification.

This paper presents conclusions from a three-year investigation into transducer design with $(x)Pb(Mg_{1/3}Nb_{2/3})O_3$-$(1-x)PbTiO_3$ (PMN-PT), one of the new materials. Practical considerations for its use are also discussed. A comparison of piezocrystal composite transducers with conventional ceramic composite transducers has demonstrated that the theoretical increases in performance with PMN-PT can indeed be realised in practice. However, at the present stage in piezocrystal commercialisation, assessment of material uniformity[2] and changes in behaviour with temperature[3] have indicated that adoption of these materials must include selection of a reliable material supply and consideration of possible material variation in the design process.

2 PERFORMANCE COMPARISON

2.1 Comparison of Material Properties

The piezoelectric parameters of recently developed PMN-PT single crystals have been extensively published elsewhere[4-7], providing a good indication of their potential to increase both the bandwidth and sensitivity of transducers for underwater sonar.

The electromechanical coupling coefficient, $k_t \geq 0.60$ and $k_{33} \geq 0.89$, are the clearest indicators of the performance benefits to be gained with PMN-PT. k_t is applicable to a thin plate and k_{33} to a rod or rods, for example in a 1-3 connectivity piezocrystal – polymer composite. In comparison, conventional commercial PZT-5H ceramic has lower coupling coefficients, $k_t = 0.50$ and $k_{33} = 0.68$. As transducer efficiency is approximately proportional to the square of the coupling coefficient, this indicates that the new piezocrystal materials should provide approximately a doubling of efficiency compared with piezoceramic.

The piezoelectric coefficients d_{33}, relating to transmission, and g_{33}, relating to reception, are also significantly higher for PMN-PT piezocrystals than ceramics. Together, these result in a much higher figure of merit, FOM = $d_{33}.g_{33}$, indicating the piezocrystal's ability to provide better sensitivity both in transmission and reception. Typical values are FOM ≈ 60 for PMN-PT and FOM ≈ 11 for PZT.

To evaluate the benefits of the improved material properties on the performance of basic acoustic transducers, the authors fabricated a series of prototype devices, with active layers consisting of PMN-PT and PZT composite. Figure 1 shows the conductance, G, of each type of composite element in a transducer immersed in water.

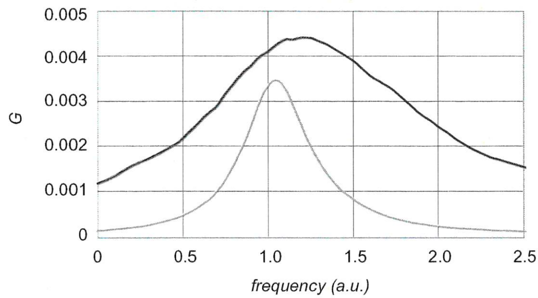


Figure 1. Conductance of PMN-PT composite (black) and PZT (grey) composite elements in a standard transducer configuration, immersed in water

Both transducers used in Figure 1 were 1-3 composite single element transducers with a light acoustic backing and a quarter-wavelength thick front matching layer. The results show that the PMN-PT piezocomposite transducer has both greater sensitivity, shown by the larger magnitude of conductance, and broader bandwidth, evident in the comparative widths of the transducers' conductance peaks.

2.2 Practical Device Comparison

Transducers based on piezocrystal and piezoceramic composite materials have also been tested with an imaging system.

A piezocrystal composite element was interfaced with a standard mechanically-scanned commercial sonar system operating in narrowband mode for image comparison with an equivalent piezoceramic composite element. Although the narrowband system used was not ideal to demonstrate the advantages of the piezocrystal material, which is more likely to be advantageous in a broadband system, the tests nevertheless showed that sharper images were produced with the piezocrystal composite element than with the standard piezoceramic composite element. For example, Figure 2 shows the interior of a canal lock and the slightly sharper image obtained from the PMN-PT composite element.

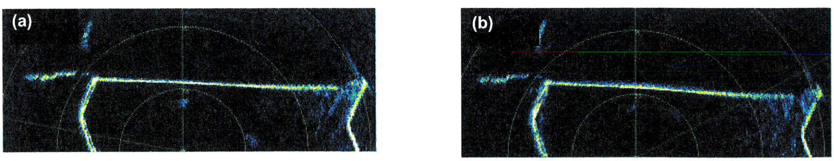


Figure 2. An image of the interior of a canal lock obtained with (a) PMN-PT composite transducer and (b) PZT composite transducer. The semicircular contours are 7.5 m apart.

The sonar system tests also showed that there were no immediate issues relating to material durability or the capability to sustain typical sonar system excitation levels over extended use. Therefore, if the theoretical performance benefits can be exploited within the acoustic design of an underwater sonar system, practical issues should not be a barrier to commercialisation. However, some considerations merited further detailed investigation, including material uniformity, temperature stability and material cost and these are discussed further in the next section of this paper.

3 PRACTICAL CONSIDERATIONS

3.1 Material Uniformity

The manufacturing process for PMN-PT piezocrystal differs from that of ceramics which are typically prepared as a paste followed by a process involving extrusion, drying and sintering[8]. In contrast, PMN-PT is manufactured in a batch process involving growth of a boule from a seed crystal along the length of a platinum crucible for a period of days or even weeks[9].

In early development, PMN-PT was grown with [111] orientation and then sliced diagonally to obtain the [001] orientation required for high performance thickness mode devices. The diagonal slicing could then result in material variation across a piezocrystal coupon as different parts were drawn effectively from different positions along the length of the crystal boule. Subsequently, advances in growth techniques have allowed the material to be grown with [001] orientation, reducing the potential for compositional variation within a coupon but not completely eliminating the problem of material property variation within the boule itself.

In the initial stages of the present investigation, the authors purchased and evaluated material from eight different suppliers[10] to evaluate the availability of reproducible PMN-PT piezocrystal. A selection of measured parameters for the eight piezocrystals are presented in Table 1, with PZT parameters included to show how each PMN-PT sample outperforms the commercially accepted piezoceramic.

	Supplier	1	2	3	4	5	6	7	8	PZT
Transmission coefficient (mV^{-1} x 10^{-12})	d_{33}	>2000	1800	>2000	1250	1825	1650	1440	>2000	590
Reception coefficient (Vm^{-1} x 10^{9})	g_{33}	30	34	24	43	32	32	26	31	19
Figure of Merit	FOM	>60	61.2	>48	53.8	58.4	52.8	37.4	>62.0	11.2
Thickness mode coupling coefficient	k_t	0.62	0.60	0.61	0.57	0.59	0.53	0.60	0.57	0.50
Bar mode coupling coefficient	k_{33}	0.94	0.86	0.88	0.88	0.94	0.91	0.93	0.94	0.68
Acoustic velocity (ms^{-1})	V_a	4660	4580	4550	4514	4580	4470	4460	4520	4350
Acoustic impedance (MRayl)	Z_a	38	36	36	35	39	37	36	37	34

Table 1. Material parameters for piezocrystal samples purchased from different suppliers. PZT-5H ceramic parameters are included for comparison.

The variation in parameters from supplier to supplier can be explained to some extent by variation in percentage of $PbTiO_3$ in the PMN-PT, i.e. variations in x in the chemical formulation

$(x)Pb(Mg_{1/3}Nb_{2/3})O_3$-$(1-x)PbTiO_3$. The authors therefore recommend that material is selected carefully for any specific application and this should be taken into account when choosing a preferred commercial supplier.

Further research into the variation of material properties within a single batch of material confirmed the possibility of variation even with material purchased from a single supplier[2].

		Average Value	Standard Deviation	Maximum Value	Minimum Value
Transmission coefficient ($mV^{-1} \times 10^{-12}$)	d_{33}	1534 ± 24%	145	1920	1190
Stiffness at constant electric displacement (Nm^{-2})	c_{33}^D	1.580 ± 2.4%	1.968	1.618	1.543
Relative permittivity at constant stress	ε^T_{33R}	7098 ± 27%	829	8841	5302
Relative permittivity at constant strain	ε^S_{33R}	1030 ± 33%	128.7	1367	813.2
Density	ρ	8078 ± 1.4%	29	8122	8012
Acoustic velocity (ms^{-1})	v_s	4432 ± 1.9%	26	4488	4378
Acoustic impedance (MRayl)	Z_a	35.80± 2.0%	0.25	36.18	35.25

Table 2. Material parameters for piezocrystal samples purchased from a single supplier.

As can be seen from Table 2, changes in density, ρ, velocity, v_s, and acoustic impedance, Z_a, are less than 2%, and therefore likely to be acceptable in translating a transducer design from development to manufacturing. However, the change in the piezoelectric transmission coefficient, d_{33}, and relative permittivities, ε^T_{33R} and ε^S_{33R}, are considerably larger.

To determine the impact of these varying parameters on the material's performance within an acoustic transducer, a one-dimensional modelling program, based on direct solutions of the one-dimensional wave equation, was used to simulate the pressure output from three simulated transducers. Each transducer was assumed to be manufactured from a sample of PMN-PT with different material properties, one sample with the average material properties, and the other two with the extreme cases of the largest and smallest parameters measured.

The average value piezocrystal was assumed to be the standard transducer, normalised to an area of 6241 mm^2, to provide an electrical impedance magnitude of 50 Ω at the fundamental resonance frequency. This same area was then used in the analysis of the transducers with the maximum and minimum values so that all effects apart from varying material properties could be assumed to be consistent.

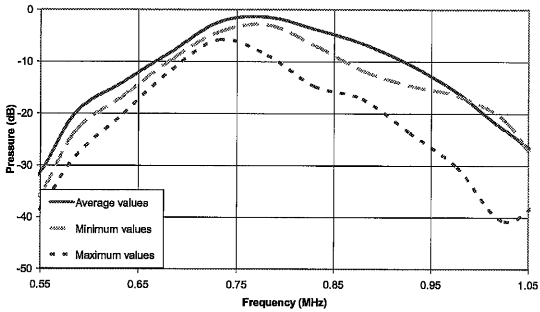


Figure 3. Pressure output response of three simulated PMN-PT transducers with average parameters (solid line), minimum parameters (long dashed line) and maximum parameters (short dashed line).

The results in Figure 3 show a dramatic drop in sensitivity in the transducer with maximum value parameters compared to the standard transducer. Additionally, variations in bandwidth of 7.41% and in centre frequency of 49 kHz indicate the potential effect of material variation on production transducer performance. Therefore, it may be necessary for the transducer designer to incorporate additional stages to consider this variation in the design process or to request material with tight tolerances from the supplier.

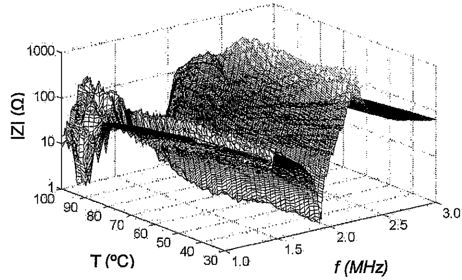
3.2 Temperature Stability

Another issue in relation to the recently developed piezocrystals is the existence of a lower temperature phase transition, $T_{R\text{-}T}$, than the Curie temperature and its effect on the material's piezoelectric performance.

Early research[11] has demonstrated the effect of temperature on a material's dielectric permittivity but the impact of increased environmental temperature on piezoelectric parameters such as k_t, v_s and Z_a remain relatively unknown. Here, the temperature stability of PMN-PT piezocrystal is presented briefly in comparison with conventional piezoceramic, with a particular focus on the changes observed in the material's electrical impedance magnitude spectrum, |Z(f)|.

10 mm x 10 mm samples of PMN-PT and PZT, with thicknesses of 0.8 mm and 1.0 mm respectively, were used for the investigation. |Z(f)| was measured at intervals of 2° C using a 4294A impedance analyzer (Agilent Technologies, South Queensferry, UK), over the frequency range at which the material's fundamental resonance occurred. Figure 4 shows the data acquired for each material from 30 – 100 ° C.

(a)



(b)

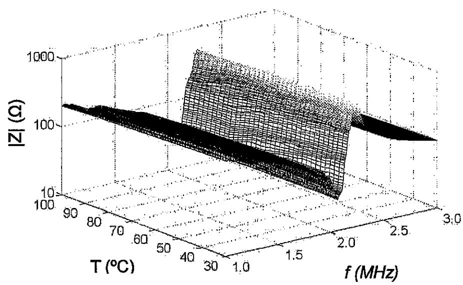


Figure 4. |Z(f)| analysis of (a) PMN-PT and (b) PZT ceramic over a range of environmental temperatures.

As expected from its relatively high Curie temperature and lack of a T_{R-T} phase transition, the behaviour of the PZT ceramic remains consistent through the measured temperature range. The values of the material's piezoelectric parameters, for example k_t shown in Figure 5, are essentially constant throughout the temperature range of 30 – 100°C. In contrast the piezoelectric properties of PMN-PT single crystal degrade significantly with temperature above approximately 50°C, as illustrated in Figure 5. Nevertheless, the material still provides better piezoelectric properties at the required limit of 60 °C for underwater sonar than that of PZT.

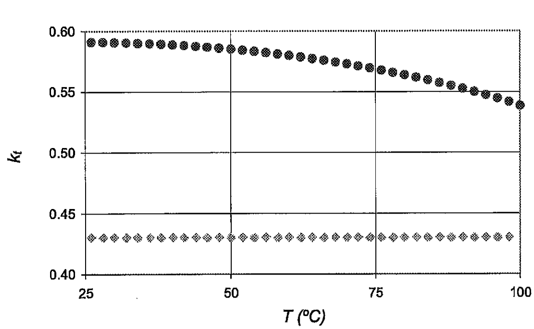


Figure 5. Variation in k_t of (a) PMN-PT (black) and (b) PZT (grey) with increased environmental temperature.

3.3 Material Cost

In its early development, difficulty was experienced in growing PMN-PT piezocrystals of usable size for acoustic devices and the yield in terms of usable material within a single boule was low, reflected in the very high price of the material in the late 1990s. Since this era, the price of the material has dropped by more than an order of magnitude from $15/mm^3 to as low as less than $0.3/mm^3 principally because of advances in growth techniques and higher volume manufacturing.

At present, there are around ten commercial suppliers of PMN-PT piezocrystals of whom most can produce crystal boules of about 25 – 75 mm in diameter, with a current view to increase this to 100 mm in due course. The additional benefits from reduction in defects and compositional variation and increased market demand have recently led to further significant reductions in cost and it is expected that on-going increases in market demand will continue to allow costs to be reduced.

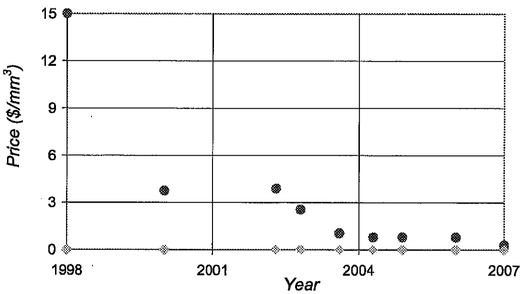


Figure 6. Guideline price of PMN-PT single crystal (black) and PZT ceramic (grey)

4 CONCLUSIONS

PMN-PT single crystals have been the subject of intensive research since their discovery in the early 1990s and have been well-established as a promising replacement for commercially used piezoceramics for some time now. However, the commercial adoption of the material has been limited by lack of understanding of its capabilities and constraints for underwater sonar and because of cost.

In this paper, basic transducer conductance measurements and underwater sonar images from a PMN-PT composite element have demonstrated that the new material can provide higher performance than PZT ceramic. The question of material uniformity, based on the difference in the manufacturing process compared with ceramic, has been considered and it has been shown to be amenable to analysis through additional design steps prior to transducer manufacture and careful material specification.

The existence of a relatively low temperature phase transition, $T_{R\text{-}T}$, was a further potential cause for concern but measurements presented here have shown that PMN-PT can operate effectively up to at least 60 °C, therefore allowing straightforward access to most sonar systems.

5 ACKNOWLEDGEMENTS

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