Comparing Generation III Relaxor-PT Single Crystal with Modified PZT-4 for Power Ultrasonics Devices

Abdul Hadi Chibli
University of Glasgow
Glasgow,Scotland,UK
2169169c@student.gla.ac.uk

Margaret Lucas
University of Glasgow
Glasgow,Scotland,UK
Margaret.Lucas@glasgow.ac.uk

Anthony Gachagan
University of Strathclyde
Glasgow, Scotland, UK
a.gachagan@strath.ac.uk

Sandy Cochran
University of Glasgow
Glasgow, Scotland, UK
sandy.cochran@glasgow.ac.uk

Abstract—Lead-based piezocrystals have been thoroughly investigated by various research teams for power ultrasonic transducers. The key objective of this work is to evaluate whether Gen. III single crystal could provide similar performance to the Navy type I (similar properties to PZT-4) and help in miniaturising the overall length of power ultrasonic instruments. This study started by incorporating four different material rings, Pz24, Pz26, and PIC181, as modified PZT-4, and Mn: PIN-PMN-PT (Gen. III single crystal) in cylindrical bolted Langevin transducers (BLTs) and comparing their key performance with respect to mechanical quality factor, electromechanical coupling coefficient, non-linearity, vibration response and nodal plane location. For the same operating frequency for all BLTs, the Gen. III single crystal transducer was found to be the shortest in length by 8 11 mm (7.6 10.4%). When testing the vibrational amplitude, the Gen. III single crystal has the highest tip normal-to-surface amplitude with lower current compared to other transducers. Gen. III was found to not follow the same non-linear behaviours as the piezoceramics transducer. Thus, the Gen. III transducer undergoes a change of material properties and depolarisation when excited with high voltage.

I. INTRODUCTION

In 1982, Kuwata's group at the Tokyo Institute of Technology in Japan introduced single crystals based on relaxor-lead titanate (relaxor-PT), which have subsequently revolutionised the field of piezoelectric materials due to their superior piezoelectric properties achievable through various domain-engineered configurations [1]. Since then, a first ultrasonic probe patent based on PZN-PT crystal was revealed [2], followed by remarkable findings of an extremely high strain that could be generated by PZN-PT and PMN-PT crystals [3] [4]. PMN-PT (Gen. I single crystal) has high dielectric and piezoelectric properties but suffers from low depolarisation temperature and quality factor. PIN-PMN-PT (Gen. II single crystal) improves on these properties, and doping with manganese (Gen. III single crystal) makes it more suitable for high-power ultrasonic devices. Applications, such as miniaturised power ultrasonic medical devices have attracted interest among researchers for their potential to improve robotic surgery [5] [6]. Therefore, this work aims to identify and characterise the most suitable piezoelectric material, including piezoceramics and piezocrystals, for use in miniaturised power ultrasonic devices.

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This work characterises and compares four piezoelectric rings, which are preliminary experimental Gen. III Mn: PIN-PMN-PT rings and commercial Pz24 and Pz26 (CTS Ferroperm, Kvistgaard, Denmark) and PIC181 (PI Ceramics, Lederhose, Germany). The rings are then incorporated in four cylindrical bolted Langevin transducers and the results are evaluated in terms of the difference between simulated and experimental transducer resonance frequencies, non-linearity using harmonic analysis, vibration amplitudes using a continuous drive excitation for the first longitudinal mode (L1) and nodal plane location for all transducers.

II. METHODOLOGY

As mentioned before. the Gen. III single crystal material was found to be more suitable for high-power ultrasonic devices than Gen. I and Gen. II. Therefore, this work will only focus on evaluating whether Gen. III would be an effective replacement for a modified version of PZT-4. Table I compares the suppliers' piezoceramic and piezocrystal rings' properties that are used in this work. The Gen. III Mn: PIN-PMN-PT ring with dimensions OD10 X ID5 X THK2 mm3 was compared with hard PZT rings such as Pz24 and Pz26 and PIC181intermofd,K,losses,densityandϵT33,QM3333. Thus, Gen. III Mn: PIN-PMN-PT has the highest d33, and K33, whereas, QM is the lowest and the losses tend to be the highest for this material. Pz26 has the highest Figure of Merit (FoM), defined as the product of QM and K33, followed by PIC181, which suggests that these two materials may provide the highest vibrational amplitude. However, including d33 in the FoM suggests that Gen. III single crystal may provide the highest vibrational amplitude.

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Table I
SUMMARYOFTHEHARDPIEZOCERAMICAND ⟨001⟩ POLED RELAXOR-PT CRYSTAL PIEZOELECTRIC AND DIELECTRIC PROPERTIES, USED TO FABRICATE THE BLT TRANSDUCERS.

Performance metrics	Pz24 (CTS Ferroperm)	Pz26 (CTS Ferroperm)	PIC181 (PI Ceramics)	Mn: PIN-PMN-PT
d33(pC/N)	149	328	238	1300
QM	1700	2700	2000	800
k33	0.66	0.68	0.65	0.89
Loss (%)	0.2	0.2	0.3	0.5
Density (kg/m3)	7700	7700	7890	7800
FoM (MQ.k33)	1122	1836	1300	712

A. Transducer Construction and Impedance Analysis

Comparing the material properties and characteristics of the rings without incorporating them in a transducer would be insufficient as ring characteristics and vibration at resonance, are expected to change when the rings are incorporated in a transducer structure. For this reason, four BLTs with Pz24, Pz26, PIC181 and Mn: PIN-PMN-PT rings were simulated (OnScale an Ansys company, Pennsylvania, USA) to have an L1 mode around 20.5 kHz. All cylindrical transducers' front and back masses were designed from titanium with length changes for each ring material to achieve the required resonance frequency and a nodal plane centred at the middle of the stack. The diameter of all the BLTs was set to 10 mm, similar to the outer diameters of the rings. Thus, from the material properties of the rings, the Gen. III single crystal transducer is expected to be shorter than the piezoceramic transducers as the compliance of the Mn: PIN-PMN-PT rings is higher than the other rings (softer material with lower speed of sound).

The electrical impedance magnitude and frequency characteristic at resonance for the four cylindrical transducers were measured using an impedance analyzer (Agilent 4294A, Precision Impedance Analyzer, Keysight Technologies, CA, USA), with 1.0 V peak-to-peak applied. The frequency range of interest was around 20.5 kHz to cover only the resonance and anti-resonance frequency characteristics of the L1 mode.

B. Harmonic Analysis

Finite Element Analysis (FEA) uses a linear mathematical approximation to predict the modal shape and vibrational amplitude at the tip of a transducer. Thus, the expected vibration at the tip is directly proportional to the increase in the applied input voltage and current. However, practical transducers often have non-linear characteristics that cannot be ignored during prolonged use. These non-linearities could cause an increase in temperature, stress between components, and possible damage to the piezoelectric rings. Nonetheless, non-linearities are normally anticipated as shifting of the operating frequency in the L1 mode or other required mode of operation, or other responses such as the 'jump' phenomenon and softening and hardening effects.

All transducers were swept from 600 Hz below to 600 Hz above the L1 mode resonance frequency, at increasing excitation levels 1, 10, 20, ..., 100 VRMS with 4000 cycles of a burst sinewave and frequency incremented by 5 Hz and a wait time between consecutive measurement of around 2.5 s using a power amplifier (HFVA-62, Nanjing Foneng Technology Industry Co., Ltd, Nanjing, China) and a signal generator (Keysight 33220A 20 MHz Function/Arbitrary Waveform Generator, Keysight Technologies, CA, USA). Then, the normal-to-surface responses for all cylindrical transducer tips were recorded using a 1D laser Doppler vibrometer (LDV).

C. Vibrational Amplitude

For measuring the normal-to-surface responses for all cylindrical transducer tips, a continuous periodic signal is required. For the four cylindrical transducers, vibration was measured using a 1D laser scan head (CFV-055, Polytec GmbH, Waldbronn, Germany), with each transducer connected to an ultrasonic driver (PiezoDrive, PDUS210 - 210W Ultrasonic Driver and Analyzer, Shortland, Australia). The PiezoDrive software allows a phase tracking controller to track the L1 resonance frequency of each transducer, ensuring the maximum vibration amplitude is generated by the transducer. The normal-to-surface response of the cutting blade tip associated with the L1 response for each transducer was captured at current levels incremented by 50, 100, ... 250 mARMS.

D. Experimental Modal Analysis

Experimental modal analysis (EMA) is a powerful experimental technique that is widely used to study the modal parameters of vibrating structures. This technique is being used to understand the vibration response of ultrasonic transducers with their impedance trace and validate the FEA predictions. This method will be used in the present work to calculate the Qm from the modal parameters and to locate the nodal plane for all the transducers, whether it is in the middle of the stack or away from it.

III. RESULTSANDDISCUSSION

The vibrational amplitude of the transducer, the electromechanical coupling coefficient, the mechanical quality factor, and the transducer's damping can be considerably impacted by the longitudinal position of the piezoelectric stack incorporated in cylindrical transducers. In this work, the piezoelectric rings are located in the middle of the stack, to ensure that all the transducers have the lowest impedance magnitude, the highest strain at the stack, the lowest displacement at the stack, and the maximum vibration amplitude at the tip. All the transducers are tuned and operated at the L1 mode, which constrains them to have only one nodal plane.

A. Impedance Magnitude

The cylindrical BLTs were assembled, in a similar structure to the simulated model design. Thus, the lengths of the BLTs to achieve approximately 20.5 kHz, are 116.4 mm (Pz24), 113.4 mm (Pz26), 116.4 mm (PIC181), and 105.4 mm (Mn: PIN-PMN-PT), with a reduction in overall length between 7.6% to 10.4%. The resonance frequency, Keff and QM for the transducers were compared to the simulated key performance metrics, in Table II. For all the piezoceramic transducers, the damping for their simulation is defined to be higher than in corresponding experimental transducers as the damping factor provided in the supplier material datasheets, does not correspond to the measured ring properties. Thus, the corresponding impedance magnitude is lower than the exper- imental impedance magnitude. Each transducer's impedance is between 1 and 840 Ω, and the PiezoDrive device has multiple sets of transformers allowing it to be matched to any impedance magnitude below 840 Ω.

Table II
COMPARESISON OF THE SIMULATED AND MEASURED RESONANCE FREQUENCIES, INCLUDING SOME KEY PERFORMANCE METRICS

Performance metrics	Pz24 (CTS Ferroperm)	Pz26 (CTS Ferroperm)	PIC181 (PI Ceramics)	Mn: PIN-PMN-PT
Simulation resonance (kHz)	20.43	20.52	20.35	20.42
Experiment resonance (kHz)	20.63	20.98	20.38	21.24
Error (%)	0.97	2.19	0.15	3.86
Simulation impedance magnitude (Ω)	201.0	38.77	76.88	50.33
Experiment impedance magnitude (Ω)	623.10	167.70	147.60	40.38
Error (%)	67.74	76.88	47.91	24.64
k_{eff}	0.18	0.23	0.23	0.24
Q_M	375.1	381.5	452.4	424.8
FoM($Q_M k_{eff}$)	67.52	87.75	104.05	101.95

B. Harmonic Analysis

The cylindrical transducer tip normal-to-surface harmonic analysis for the L1 mode was measured as shown in Figure 1. For all the piezoceramic transducers, the vibration-frequency traces exhibit a softening nonlinear characteristic, where the resonance frequency of all transducers decreases as the exci- tation level increases, starting from low excitation level (10 VRMS) and low vibration amplitude, 1.37 µm, 2.10 µm, 2.56 µm, respectively. The resonance frequencies were shifted by 345 Hz (1.67%), 550 Hz (2.62%), and 445 Hz (2.18%), respectively, after excitation up to 100 VRMS. The PIC181 has the highest tip vibrational amplitude, with a lower non- linearity effect compared to Pz26. Also, there are clear notches for both Pz26 and PIC181, excited at 30 VRMS and 70 VRMS, respectively. These notches could be due to the long bolts used for the assembly. The tip vibration amplitude responses for all the transducers are very steep, which reflects a high QM for all transducers.

Figure 1 (d), shows that the Gen. III single crystal cylin- drical transducer has a different non-linearity effect compared to piezoceramics transducers. Thus, the vibration-frequency trace exhibits a softening nonlinear characteristic for up to 40 VRMS, followed by a hardening non-linear characteristic between 40 VRMS and 70 VRMS, followed by softening nonlinear characteristic between 70 VRMS and 100 VRMS. Also, the hysteresis effect is clear when the excitation level reaches 100 VRMS. This observation illustrates that the Mn: PIN-PMN-PT rings material may have modified properties at high excitation or the rings might be depolarised, as it is a softener material compared to the piezoceramics. Another observation from Figure 1 (d) is that the vibration-frequency traces exhibit a wide blunt peak (damped peak), which means QM values for all piezocrystal transducers are low and the tip vibrational amplitude compared to piezoceramics transducers is found to be high.

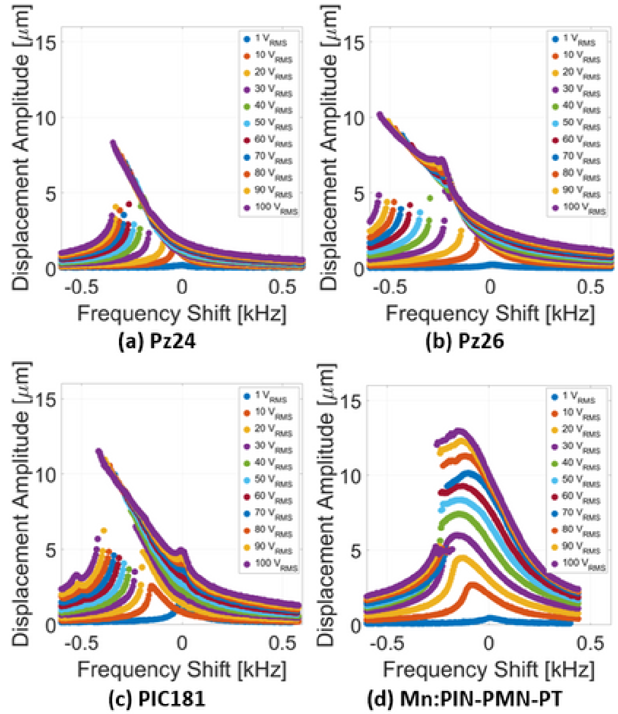

Figure 1. The harmonic analysis responses for all the cylindrical transducers, at excitation levels incremented 1, 10, 20, ..., 100 VRMS.

C. Vibrational Amplitude

The tip normal-to-surface vibration responses at the L1 mode for all transducers have been measured using 1D LDV and the PiezoDrive as shown in Figure 2. The Mn: PIN-PMN-PT provides the highest vibrational amplitude at up to 19.76 µm at 150 mARMS. However, after reaching this amplitude and shutting down the current supplied to the transducer, the transducer subsequently generated very low vibrational amplitude responses. This indicates that the rings have been depolarised. The single-crystal device test was followed by PIC181, Pz26, and then Pz24 in terms of maximum vibration. Also, as illustrated in the harmonic analysis test, PIC181 was found to be the next stable material, in terms of frequency change, followed by Pz24, then Pz26, as the least stable, as it has the highest change of frequency.

D. Experimental Modal Analysis

Figure 3 shows the normalised displacement along the length of all the transducers at the L1 mode and corresponding simulated results. It seems, that the nodal planes for all the transducers are at the middle of the stack. Thus, these transduc- ers should have the highest possible mechanical quality factor. The corresponding QM values are 450 (Pz24), 536 (Pz26), 832 (PIC181), and 352 (Mn: PIN-PMN-PT). This shows that the PIC181 transducer has the highest efficiency compared to other transducers.

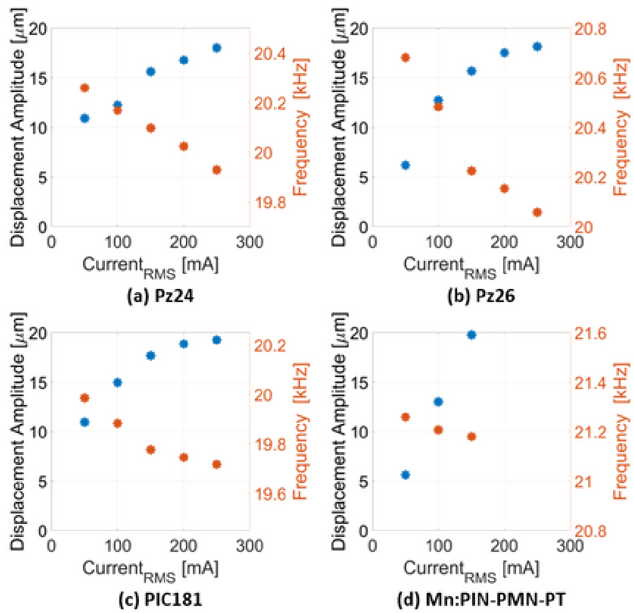

Figure 2. The harmonic analysis of two TPF transducers: (a) TPF transducer with titanium back mass; (b) TPF transducer with stainless-steel back mass

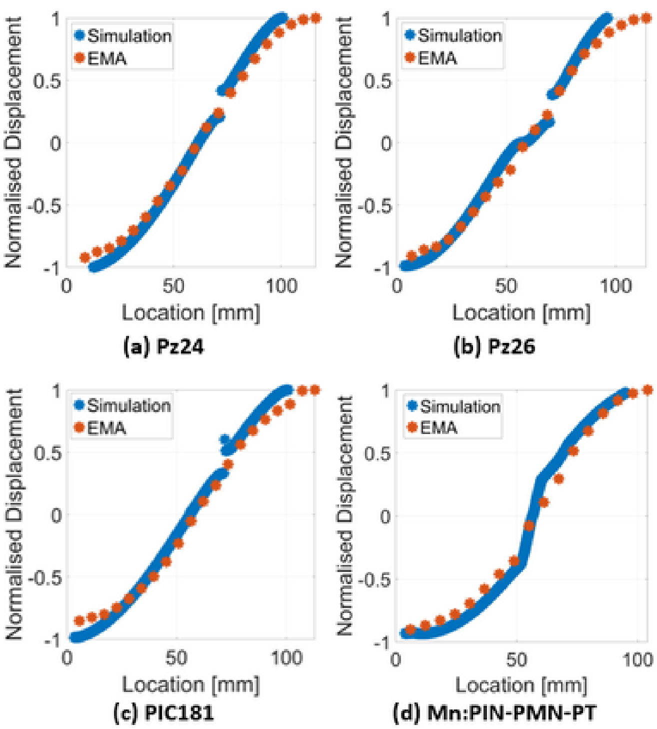

Figure 3. The harmonic analysis of two TPF transducers: (a) TPF transducer with titanium back mass; (b) TPF transducer with stainless-steel back mass

E. Single crystal transducer rings after measurement

The Gen. III single crystal transducer was disassembled to examine the status of the ring after excitation with a high voltage level. Figure 4 shows that the impedance magnitude was diminished after high voltage excitation was applied to the rings compared to before assembling the transducer. Thus, the radial mode, wall thickness mode and thickness mode are not clear for the rings after being assembled and disassembled.

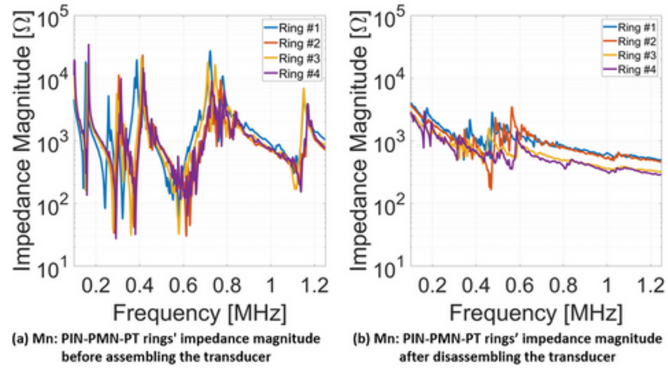

Figure 4. This plot shows the impedance magnitude of Gen. III single crystal rings before the assembling process and after the assembling process. and how the rings' impedance has been diminished.

IV. CONCLUSIONS

Understanding the material properties of the piezoelectric material is crucial to reflect the efficiency of the rings, and the transducers and for the accuracy of simulation models. In terms of FoM, the PIC181 transducer was found to be the highest, followed by the Gen. III single crystal transducer. The Gen. III single crystal transducer allowed a reduction in the overall length of the transducer by 11 mm (9.1%), making it a promising material for miniaturisation. However, the Gen. III single crystal transducer has unpredictable non-linearity compared to the piezoceramic transducers, and exciting it with a high current might lead to depolarisation of the rings. It is concluded that the performance of the material is promising for miniaturisation, but the material used in this study is preliminary and the manufacturing process may have caused problems. Further work is required to carry out tests with optimised crystal growth and manufacturing potentially with alternative compositions.

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