HIGH POWER EVALUATION OF TEXTURED PIEZOELECTRIC CERAMICS FOR SONAR PROJECTORS

A Thesis in
Acoustics
by
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Textured ceramics of the relaxor ferroelectric [(1-x)Pb(Mg_{1/3}Nb_{2/3})O_3-xPbTiO_3] (PMN-PT or PMNT) have shown piezoelectric properties suitable for high power SONAR projectors. The piezoelectric coefficient ($d_{33}$>800pm/V), the electromechanical coupling coefficient ($k_{33}$>0.80), and the mechanical quality factor ($Q_m$>90) in various forms of PMN-PT showcase the potential for these textured ceramics to be implemented in a high power, broad bandwidth acoustic projector. This work attempted to devise a set of experiments to quickly characterize the electromechanical performance of these materials in relevant devices in order to provide feedback to both the material developers and the user community. In this effort, the performance of textured PMNT and Manganese doped PMNT (Mn:PMNT) was compared to conventional lead zirconate titanate (PZT) ceramics.

Two primary transducer designs were investigated: the Langevin sandwich and the Tonpilz. Modeling was first carried out through the GiD-ATILA finite element software package to predict the transducer behavior in air and in water. Transducers were then fabricated using piezoelectric rings of dimensions specified by the modeling results. The Langevin sandwich transducers underwent a series of preload and temperature tests, monitoring key electromechanical properties over a range of preload stresses and temperatures. Results from this experiment showed significantly reduced $d_{33}$ (660pC/N for PMNT and 410pC/N for Mn:PMNT), lower $k_{33}$ (0.38 for PMNT and <0.35 for Mn:PMNT), and increased resonance frequency shifts as a function of stress (>6% for PMNT and Mn:PMNT at 25MPa) compared to the modeling results.

Tonpilz transducers were fabricated and tested in air and in water using the anechoic test facility and high pressure test facility at the Applied Research Laboratory (ARL) at Pennsylvania State University. Small signal measurements in air showed similar poor electromechanical material properties for PMNT and Mn:PMNT as the sandwich transducers. Linearity and harmonic distortion measurements in water revealed reduced source levels, increased harmonic distortion, and unstable behavior at high drive levels both on and off resonance for PMNT and Mn:PMNT.
compared to modeled results. Isothermal measurements were made at 50°C and source levels were monitored as a function of duty cycle. PZT4 and PZT8 showed source levels greater than 5dB higher compared to PMNT and Mn:PMNT for all duty cycles measured. The primary cause for lower than expected performance from textured PMNT can be traced back to the increased PT composition and reduced texture fraction in the material (30% and 85%, respectively). This elevated PT concentration resulted in increased thermal instability at lower temperatures, resulting in domain reconfiguration and poorer electromechanical properties at the operating temperatures for these experiments. The reduced texture fraction decreased the piezoelectric response in PMNT, causing reductions in the expected source levels produced from the devices. The results found from this work suggest modifications need to be made to the PT composition and texture fraction in the textured materials in order to unlock the true potential for use in high power SONAR projectors. Despite these results, the method used to rapidly fabricate, test, and evaluate the performance of these SONAR projectors could be directly used to carry out similar device evaluations for different piezoelectric materials, providing rapid feedback to the material developers in order to optimize the material properties for future studies of textured piezoelectric ceramics.
# Table of Contents

List of Figures vii  
List of Tables xi  
Acknowledgments xii  

## Chapter 1  
**Introduction** 1  
1.1 Introduction .................................................. 1  
1.2 Previous Studies ............................................. 3  
1.3 Outline of Thesis ............................................ 3  

## Chapter 2  
**Background On Piezoelectric Materials** 5  
2.1 Introduction .................................................. 5  
2.2 PZT Ceramics ................................................ 7  
2.3 Relaxor-PT Ferroelectrics .................................. 10  
2.4 Piezoelectric Material Property Comparison ............... 12  
2.5 Summary .................................................... 14  

## Chapter 3  
**Underwater Transducers** 16  
3.1 Background ................................................... 16  
3.1.1 Directivity ................................................. 19  
3.1.2 Source Level ............................................... 20  
3.2 SONAR Projector Designs .................................... 22  
3.2.1 Langevin Sandwich ....................................... 22  
3.2.2 Tonpilz ................................................... 24  
3.3 Material Property Definitions ............................... 26
List of Figures

1.1 Phase diagram for PMN-xPT where x represents the mole fraction of PbTiO$_3$. C represents the paraelectric cubic phase, $M_C$ represents the monoclinic phase, R represents the rhombohedral phase, and T represents the tetragonal phase [3].

2.1 Schematic of unit cell geometry in lead titanate for paraelectric behavior (left) and ferroelectric behavior (right). Above the Curie temperature, the material adopts a centrosymmetric cubic cell geometry, where there is no net dipole moment. Below the Curie temperature, the material displays a lower symmetry unit cell geometry, where the Ti/Zr ions located in the center of the unit cell displace, giving rise to a net dipole moment and overall polarization $P$ [8].

2.2 Typical polarization $P$ versus electric field $E$ hysteresis behavior for ferroelectric materials. The coercive field, $E_C$, denotes the electric field required to reorient the polarization in the material. $P_r$ represents the amount of polarization in the material with no applied field, or the remnant polarization. At some value of electric field $E_{sat}$, this causes the polarization to saturate, denoted as $P_{sat}$ [9].

2.3 Phase diagram for PMN-PT where x represents the mole fraction of PbTiO$_3$. C represents the paraelectric cubic phase, $M_C$ represents the monoclinic phase, T represents the tetragonal phase, and R represents the rhombohedral phase. Image from Brosnan [3].

2.4 Strain response of textured PMN-PT compared to PMN-PT and PZN-PT single crystal ceramics [3].

2.5 Schematic of sample geometries for piezoelectric materials. Reference axis is shown in the bottom left. The three sample geometries shown are (a) length extensional (33-mode), (b) transverse (31-mode), and (c) shear (15-mode) [1].
3.1 Normalized radiation resistance and reactance functions as a function of $ka$. At low frequencies, the reactance term dominates, but as frequency increases, the radiation resistance dominates and energy is radiated as acoustic wave propagation. 18

3.2 Directivity plot for sonar projector using PMNT, taken from the anechoic test facility (ATF). Frequency is shown normalized to the resonance frequency, and the acoustic output is normalized to 0dB. 19

3.3 Idealized TVR plot for a underwater projector versus frequency [15]. 21

3.4 Schematic of elements in a Langevin sandwich transducer [21]. Four piezoelectric ceramic rings are shown in this transducer, although this could be any number of rings (an even number is more common). An insulator is usually placed in between the end masses and the piezoelectric stack. 23

3.5 Schematic of elements in a Tonpilz Transducer. The piezoelectric ceramic material is in green, segmented by electrodes seen in gold. This stack is sandwiched between a head mass and a tail mass. A stress bolt runs through the transducer to apply a compressive stress bias. [1]. 24

4.1 Schematic of a Langevin sandwich transducer modeled in ATILA. 30

4.2 Schematic of a Tonpilz transducer modeled in ATILA. 30

4.3 Schematic of planes of mirror symmetry in ATILA. Boundary conditions can then be input for any of these planes to model the entire device. 32

4.4 Schematic of Tonpilz transducer in a simulated water load modeled in ATILA. 33

4.5 Impedance magnitude, top, and impedance phase, bottom, for Tonpilz transducers, modeled in ATILA. 35

4.6 Exaggerated schematic of motion of Tonpilz transducer during operation (not to scale). The figure is seen at rest in (a), then undergoes a strain, lengthening the device in (b), then returning to it’s original state in (c) before compressing in (d), then finally returning to its original state again. This motion back and forth from the transducer results in the head mass radiating acoustic energy into the surrounding medium. 37

4.7 Displacement of Mn:PMNT transducer along the length of the device (x-direction) at resonance (a) and off resonance (b). Notice the areas of high displacement are at the head in both cases, indicating effective radiation into the medium. 38
4.8 Impedance magnitude, top, and impedance phase, bottom, for Tonpilz transducers under a simulated water load, modeled in ATILA. 39
4.9 Transmit Voltage Response for Tonpilz transducers, modeled in ATILA. 40
4.10 Transmit Voltage Response for Tonpilz transducers normalized to ring thickness, modeled in ATILA. 41

5.1 Impedance magnitude and phase of PZT8. The magnitude is shown in blue while the phase is shown in red. The resonance and anti-resonance frequencies are labeled by $f_r$ and $f_a$, respectively. 46
5.2 Completed fabricated Langevin sandwich transducers using PMNT and Mn:PMNT rings. End masses and insulator rings are labeled. 50
5.3 Change in resonance frequency versus preload stress level. Soft piezoelectrics like undoped PMNT and PZT5H show higher change in the resonance frequency as more stress is applied, while hard PZT4 and PZT8 show little to no change as the stress is increased. 52
5.4 Mechanical quality factor as a function of temperature and stress. 53
5.5 Electromechanical coupling coefficient as a function of temperature and stress. Mn:PMNT is not shown here as the sample started to depole during experiment. 54
5.6 Impedance magnitude for PMNT, top, and Mn:PMNT, bottom for various temperatures and stresses during preload tests. Notice the resonance peak magnitudes decrease as stress is increased, indicating the material is starting to de-pole. 57

6.1 Completed Tonpilz transducers fabricated from PZT8 (left), and PMNT (right). Kapton tape is used at the tail mass to secure the high and low side wires to each other. Notice the stack length difference, due to different ring thicknesses shown in Table 6.1. 61
6.2 Impedance magnitude, top, and impedance phase, bottom, for Tonpilz transducers measured in air. 62
6.3 Suspended housing cylinder for single-element testing of Tonpilz transducer. The anechoic tank test facility is shown in the background [3]. 64
6.4 TVR plot for PMNT (top) and Mn:PMNT (bottom), along with modeled TVR curves. 65
6.5 Schematic of test setup in the HPT facility. Wires seen here connect to preamplifiers, voltage/current monitors, function generators, signal analyzers, etc. to drive and collect data from the device. Image from Sherlock [1]. 66
6.6 Source level measured as a function of drive level at resonance for Tonpilz transducers. Grid spacing is 5dB in both the x and y axis.

6.7 PZT5H transducer after testing in HPT. The device was driven to failure, as indicated by the hole produced in the piezoelectric ring.

6.8 Current total harmonic distortion as a function of source level at resonance.

6.9 Source level total harmonic distortion as a function of source level at resonance.

6.10 Source level measured as a function of drive level off resonance ($1.5f_0$) for Tonpilz transducers. Grid spacing is 5dB in both the x and y axis.

6.11 Current total harmonic distortion as a function of source level off resonance.

6.12 Source level total harmonic distortion as a function of source level off resonance.

6.13 Electric field required to maintain 50°C isotherm at resonance as a function of duty cycle. Hard piezoelectrics require higher electric fields to maintain an elevated operating temperature.

6.14 Acoustic source level as a function of duty cycle under isothermal operating conditions at resonance.

1 Capacitance as a function of temperature and preload stress.

2 Piezoelectric coefficient $d_{33}$ as a function of temperature and preload stress.

3 Loss factor $\tan \delta$ as a function of temperature and preload stress.
## List of Tables

2.1 Property comparisons between conventional PZT (soft and hard) ceramics, single crystal PMN-PT, and textured PMN-PT (undoped and doped). .................................................. 13

4.1 Passive component material properties input into ATILA. .......... 33
4.2 Active piezoelectric material properties input into ATILA [2,25]. .. 34
4.3 Modeled electromechanical coupling coefficient and quality factor for Tonpilz Transducers. .............................................. 38

5.1 Small signal material properties measured for piezoelectric materials. The dielectric permittivity and piezoelectric coefficient were measured at 1kHz, while the rest of the material parameters were measured at resonance. ................................................. 48
5.2 Comparison of modeled $d_{33}$ and tan $\delta$ values compared to measured results for the five piezoelectric materials investigated. ............. 55

6.1 Normalized ring thicknesses used for each material in their respective Tonpilz transducer. .................................................. 59
6.2 Small signal material properties for rings used in Tonpilz transducers. 60
6.3 Small signal material properties measured for Tonpilz transducers. The capacitance was measured at 1kHz, while the rest of the material parameters were measured at resonance. ................. 63
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Chapter 1
Introduction

1.1 Introduction

Perovskite piezoelectric ceramics have shown potential for use in SONAR and ultrasonic transducers, actuators, piezoelectric energy harvesters, and medical ultrasound, due to their high piezoelectric response and high electromechanical coupling coefficient. In particular, textured ceramics of the relaxor-ferroelectric [(1-x)Pb(Mg\textsubscript{1/3}Nb\textsubscript{2/3})O\textsubscript{3}-xPbTiO\textsubscript{3}] (PMN-PT) solid solutions have displayed desirable electromechanical properties suitable for high power use. Compared to conventional lead-zirconate titanate (Pb(Zr\textsubscript{x}Ti\textsubscript{1-x})O\textsubscript{3}) (PZT) ceramics, <001>\textsubscript{c} poled textured ceramics display much higher 33-mode properties (e.g. $d_{33}=855\text{pm/V}$, $k_{33}=0.83$) and higher mechanical quality factor ($Q_{m}=94$), allowing for lower losses and reduced heat generation during operation [1, 2].

The optimal piezoelectric properties exhibited by PMN-PT occur near the morphotropic phase boundary (MPB) between the rhombohedral and tetragonal phases in the material. This phase transition occurs at different temperatures depending on the weight fraction of each component (PMN or PT) in the material, shown in the phase diagram in Figure 1.1. A weight fraction of x=0.28 would correspond to a phase transition temperature ($T_{R-T}$) of 368 K or 95 °C, while a PT weight fraction of x=0.32 would correspond to a $T_{R-T}$ of 333 K or 60 °C. At this phase transition temperature, the domains in the crystal structure begin to reconfigure to the tetragonal phase, which has significantly reduced electromechanical performance. As a result, x=0.28, or 0.72PMN-0.28PT is primarily used for higher power applications due to the greater temperature stability [1].
Figure 1.1: Phase diagram for PMN-xPT where x represents the mole fraction of PbTiO$_3$. C represents the paraelectric cubic phase, M$_C$ represents the monoclinic phase, R represents the rhombohedral phase, and T represents the tetragonal phase [3].

PZT ceramics have been implemented in SONAR transducers due to the ability to tailor the material properties to fit specific applications. Through the use of donor or acceptor dopants, the piezoelectric response or the degree of domain wall motion can be altered. PZT is often classified into one of two groups: "soft" or "hard." A soft piezoelectric refers to a material with higher piezoelectric response but higher losses. A hard piezoelectric refers to a material with lower piezoelectric response but lower losses. The versatility of PZT has led to widespread implementation in many SONAR transducer applications. The goal of this research is to characterize the electromechanical performance of SONAR transducers using textured relaxor-PT ferroelectric ceramics, and compare the performance to commonly used soft and hard PZTs (PZT4/PZT8 and PZT5H, respectively).
1.2 Previous Studies

There have been numerous instrumental studies performed on the electromechanical performance of SONAR transducers. In particular, the work characterizing the performance of SONAR projectors using different piezoelectric materials and characterizing the electromechanical performance of relaxor-PT ferroelectric ceramics was of utmost relevance to this work. The work of Sherlock [1] laid the foundation for thorough testing of the electromechanical performance of SONAR projectors for relaxor-PT based ceramics, both in air and in water. Many of the fabrication, testing, and modeling procedures used in this thesis are based after this work. The work of Brosnan [3] was one of the first forays into characterizing the performance of textured ceramics in SONAR transducers. Similar methods of testing used in this work was carried out in the underwater tanks at the Applied Research Laboratory (ARL) at Pennsylvania State University. Finally, the work of Poterala [2] showcased the potential for textured PMN-PT for use in high power applications. The electromechanical properties of these materials from this work directly led to this study of the performance of textured PMN-PT in SONAR projectors. Similar materials used from Poterala [2] are investigated in this thesis.

1.3 Outline of Thesis

A background on piezoelectric materials and the piezoelectric effect will be presented in Chapter 2. The mechanisms driving piezoelectricity in ceramics will be discussed. Conventional PZT ceramics will be compared with relaxor-PT based ferroelectric ceramics. Finally, an initial comparison of some key material and piezoelectric properties will be made for various PZTs and PMN-PT materials.

A background on underwater transducers will be presented in Chapter 3. The radiation mechanism behind SONAR (SOnund Navigation And Ranging) projectors will be derived and discussed. Important metrics to describe SONAR projector performance will be introduced. An overview of the two primary transducer designs used in this thesis will be presented. Finally, vital electromechanical material property definitions will be discussed to better understand the performance of these devices and to identify properties discussed at length throughout the thesis.

Chapter 4 presents an overview of the modeling performed for these transducers
studied. Using the GiD-ATILA software package, the modeling set up and materials used in the design are shown. The modeling results are performed, which include in air and in water characterization, from impedance plots to TVR plots for each transducer.

In Chapter 5, the electromechanical characterization of fabricated piezoelectric rings will be presented. Small signal measurements such as complex impedance and piezoelectric coefficient measurements are described. A comparison of the electromechanical properties of fabricated rings to be used in the SONAR projectors are shown here. Finally, the performance of Langevin sandwich transducers is investigated through the use of preload tests, subjecting the transducers to different amounts of stress and temperature and monitoring key electromechanical behavior.

Chapter 6 is an evaluation of the device performance for Tonpilz transducers, both in air and in water. The fabrication procedure is described, and the resulting performance of the build devices are presented in air. Then, in-water characterization is presented for experiments in the Anechoic Test Facility (ATF) and High Pressure Test Facility (HPT). Linearity and harmonic distortion behavior is presented both on resonance and off resonance for each device. Finally, isothermal behavior is analyzed for each transducer, presenting results on drive voltage and source levels produced from these transducers under various duty cycles.

Chapter 7 summarizes the work presented in this thesis. The electromechanical performance of each device studied is compared and evaluated against one another. Future work is also presented here, including modifications to these experiments to pursue and additional experiments proposed to further legitimize the results found in this thesis.
Chapter 2 | Background On Piezoelectric Materials

2.1 Introduction

Piezoelectric materials are a class of solid materials which convert mechanical energy to electrical energy (and vice versa). The first known discovery of piezoelectric materials came in 1880 by the Curie brothers, who demonstrated the relationship between mechanical strain and electric charge in quartz and Rochelle salt. For several decades, these materials were primarily studied in a laboratory setting, until World War I when Paul Langevin utilized quartz in an ultrasonic submarine detector [4]. In the 1940’s, the discovery of ferroelectric and electrostrictive properties in barium titanate accelerated the interest in discovering new piezoelectric materials to be used in a variety of different applications. Currently, these materials have been implemented in numerous applications, such as medical ultrasound devices, actuators, timing circuits, loudspeakers, and sonar transducers.

Piezoelectric materials utilize the phenomenon known as the piezoelectric effect. This effect is a type of electromechanical coupling, existing in two domains, direct, and converse. The direct piezoelectric effect describes a material’s ability to transform mechanical strain into electrical charge, typically utilized in generator or sensor applications. The converse effect describes a material’s ability to convert an applied electrical potential into mechanical strain energy, typically utilized in actuator applications [1, 5]. Piezoelectric coupling can be described by a linear relationship between a first-rank tensor or vector (electric charge density displacement D or...
electric field $E$) and a second-rank tensor (applied stress $T$ or induced mechanical strain $S$). Equations 2.1 and 2.2 show the relationship in tensor form for the direct and converse piezoelectric effects, respectively.

\[ D_i = d_{ikj} T_{jk} \quad (2.1) \]

\[ S_{ij} = d_{ikj} E_k \quad (2.2) \]

where $d$ is the piezoelectric coefficient. The subscripts $i,j,k=1,2,3$, and describe the relative direction of input and output. The piezoelectric coefficient $d$ is often expressed in reduced tensor notation $d_{jk}$, where $j$ represents the electrical axis and $k$ represents the mechanical axis. These equations can be combined into coupled equations of strain-charge matrix form [6]. Equations 2.3 and 2.4 show the direct and converse piezoelectric effect in said form, respectively.

\[ \{D\} = [d]\{T\} + [\epsilon^T]\{E\} \quad (2.3) \]

\[ \{S\} = [s^E]\{T\} + [d]^t\{E\} \quad (2.4) \]

where $\{D\}$ is the three-dimensional electric displacement vector, $\{E\}$ is the electric field vector, $\{T\}$ is the stress vector, $\{S\}$ is the six-component strain vector, $[s^E]$ is the six by six compliance matrix evaluated at constant electric field, $[\epsilon^T]$ is the three by three dielectric permittivity matrix at constant mechanical stress, and $[d]$ is the three by six matrix of piezoelectric constants.

The response to an externally applied electric field is a vital concept to understanding piezoelectric behavior in materials. When a solid is placed in an externally applied electric field, the disturbance in the medium forces a dynamical change to the positions of the nuclei and the electrons within the material, creating what are known as electric dipole moments [6]. This process of dipole formation is known as polarization. Three main sources of polarization exist: electronic, ionic, and dipolar. Electronic polarization, found in all dielectric materials, results only when an electric field is present, and involves the separation of the center of the electron cloud around an atom with respect to the center of its nucleus. Ionic polarization occurs only in materials which are ionic, resulting from a displacement of cations
and anions in opposite directions, leading to a net dipole moment. Dipolar polarization occurs only in substances which possess permanent dipole moments, resulting from an orientation of the molecular dipoles in the direction of the applied field.

Piezoelectric materials belong to a larger class of materials known as ferroelectrics. In ferroelectric materials, the piezoelectric behavior is related to asymmetries in the unit cell geometry which are temperature dependent [1]. Ferroelectrics will exhibit spontaneous polarization even in the absence of an electric field below a certain temperature, known as the Curie temperature, $T_c$. At this Curie temperature, ferroelectrics undergo a structural phase transition, changing from a paraelectric phase above the Curie temperature to a ferroelectric phase below this temperature. In the paraelectric phase, the material displays cubic unit cell geometry, resulting in no net dipole moments nor ferroelectric behavior. Below $T_c$, however, slight displacements of the charged ions within the unit cell give rise to a crystal class that lacks a center of symmetry [7]. An example of these two conditions is shown in Figure 2.1. This asymmetry in the unit cell gives rise to a net dipole moment, and multiplied over many unit cells, this remnant polarization results in ferroelectric behavior. Additionally, ferroelectrics exhibit the ability to reorient their polarization through an applied electric field, which displays hysteresis type behavior shown in Figure 2.2.

### 2.2 PZT Ceramics

The discovery of Barium Titanate (BaTiO$_3$) stimulated the search for new ceramic materials which had superior piezoelectric properties. One such material that was discovered in the 1960’s was lead zirconate-lead titanate mixtures, which would later be known as PZT (Pb(Zr$_x$Ti$_{1-x}$)O$_3$, where $x$ is an atom composition between 0 and 1). PZT has now become one of the world’s most widely used piezoelectric ceramic material, because of its high piezoelectric response, high strength, chemical inertness, and low cost to manufacture. PZT has a perovskite crystal structure, where each unit cell consists of a small tetravalent metal ion in a lattice of large divalent metal ions. In the case of PZT, the small tetravalent ion is usually titanium or zirconium, while the large divalent ion is lead [10]. A schematic of the atoms in a unit cell for PZT is shown in Figure 2.1.

One of the main contributing factors to the piezoelectric properties of PZT is
Figure 2.1: Schematic of unit cell geometry in lead titanate for paraelectric behavior (left) and ferroelectric behavior (right). Above the Curie temperature, the material adopts a centrosymmetric cubic cell geometry, where there is no net dipole moment. Below the Curie temperature, the material displays a lower symmetry unit cell geometry, where the Ti/Zr ions located in the center of the unit cell displace, giving rise to a net dipole moment and overall polarization $P$.

Its high dielectric response at the morphotropic tetragonal-rhombohedral phase boundary (MPB) near a composition of $x=0.52$. At this composition, there is an increased piezoelectric response and poling efficiency due to the increased number of allowable domain states [11]. Six possible domain states exist from the tetragonal phase ($<100>$), where Ti or Zr cations displace towards the unit cell faces, and eight possible domain states exist from the rhombohedral phase ($<111>$), where the Ti or Zr cations displace towards the corners of the unit cell. Because these domain states are all equally favorable energetically, this maximizes the number of allowable polarization vectors.

Another favorable characteristic of PZT is the ability to change the degree of domain wall motion as a function of applied electric field by incorporating donor (net negative charge) or acceptor (net positive charge) dopants. Donor doping involves replacing $\text{Pb}^{2+}$ with elements like $\text{La}^{3+}$, which creates openings within the unit cell, thereby reducing the energy barrier for the B-site ions ($\text{Ti}^{4+}$ or $\text{Zr}^{4+}$) to displace and thus, increases domain wall motion. Conversely, acceptor doping involves replacing the B-site ions with cations of low valence, e.g. $\text{Fe}^{3+}$. This results in oxygen vacancies, creating re-orientable dipoles which align in the direction of...
Figure 2.2: Typical polarization $P$ versus electric field $E$ hysteresis behavior for ferroelectric materials. The coercive field, $E_C$, denotes the electric field required to reorient the polarization in the material. $P_r$ represents the amount of polarization in the material with no applied field, or the remnant polarization. At some value of electric field $E_{sat}$, this causes the polarization to saturate, denoted as $P_{sat}$ [9].

the polarization vector within domains, which produces internal fields that stabilize the domain configuration and reduce domain wall motion [12].

The degree of domain wall motion plays a key role in the piezoelectric properties of PZT. When donor dopants are introduced, the increased ferroelectric domain switching consumes energy and increases the electromechanical losses, thus deemed a 'soft' PZT. These type of high response, high loss PZTs are therefore often used in low power, high sensitivity applications such as ultrasound transducers, pressure sensors, and actuators. When acceptor dopants are introduced, the reduced domain wall motion decreases the piezoelectric response, but also decreases the losses in the ceramic, thus deemed a "hard" PZT. The low response and low losses of these PZTs facilitate their use in higher operating conditions, allowing for implementing in high power applications [1]. A comparison of the piezoelectric properties of different types of "hard" and "soft" PZTs is further discussed in Section 2.4.
2.3 Relaxor-PT Ferroelectrics

While PZT has dominated the commercial piezoelectric market, recently there have been advancements made in the investigation of materials with property improvements beyond that of PZT. One such class of materials is relaxor-based ferroelectric ceramics. Relaxor ferroelectrics are a type of ferroelectric material which exhibits high electrostriction. This phenomena was first discovered in lead magnesium niobate, [Pb(Mg_{1/3}Nb_{2/3})O_3], or PMN. The mechanism behind relaxor behavior is still being investigated, but some researchers believe it is due to the formation of polar micro-regions or polar nano-regions within the material [13]. These regions cause a diffuse and frequency-dependent broad dielectric maximum and aging behaviors at low temperatures. Relaxor-based ferroelectric materials are generally solid solutions of a relaxor (PMN or PZN [(1-x)PbZn_{1/3}Nb_{2/3}O_3]) with PbTiO_3, which is usually represented as "relaxor-PT." These relaxor-PT ceramics, through domain engineering, have shown the ability to generate extremely large piezoelectric coefficients (>2000 pC/N) and electromechanical coupling coefficients (>0.9). These exceptional properties occur often at the rhombohedral-tetragonal phase transition, similar to PZT ceramics. A phase diagram of the PMN-PT system is shown in Figure 2.3. This temperature (denoted as $T_{R-T}$) is often lower than the Curie temperature and dictates the usable temperature range in these materials, so this temperature is also often referred to as $T_{\text{max}}$ [3].

The piezoelectric properties of relaxor-PT ferroelectrics can be further manipulated and enhanced through domain engineering. By varying the degree of the distribution of crystallographic orientations in the polycrystalline sample, or texture, vastly different material properties can be achieved. If a material has fully random orientation, this is said to have no texture, and displays isotropic properties. On the other hand, if a sample is fully textured, this is said to be single crystal, and displays anisotropic properties. Relaxor-PT single crystals have shown extremely high piezoelectric responses as a result of the lack of defects associated with grain boundaries. However, as a result of the extremely high strains produced in single crystals, the losses are often very high, which limit the feasibility in implementing these materials in high power operations.

The templated grain growth (TGG) method is primarily used to develop crystallographic texture in polycrystalline samples. This growth method uses aligned
Figure 2.3: Phase diagram for PMN-PT where $x$ represents the mole fraction of PbTiO$_3$. C represents the paraelectric cubic phase, $M_C$ represents the monoclinic phase, $T$ represents the tetragonal phase, and $R$ represents the rhombohedral phase. Image from Brosnan [3].

template particles in a ceramic matrix, effectively changing the surface free energy between the matrix grains and the larger, template particles during heat treatment [3]. The templates are typically micron-sized perovskite crystals with platelet morphology, enabling alignment via shear forming techniques such as tape casting or extrusion [2]. A high temperature anneal is performed to promote growth of the templated grains in the aligned direction of the particles. The amount of texture in a sample is given by the Lotgering degree, or by comparing the relative x-ray diffraction peak heights.

For a relaxor-PT ferroelectric to have the necessary properties required in high power operations, varying the degree of texture in the sample is currently being investigated. Recent work from Poterala, et. al has shown that textured relaxor-PT ferroelectrics demonstrate piezoelectric properties intermediate to that of single crystals and ceramics, and show the material properties necessary to withstand high drive levels [2]. Textured ceramics have shown exceptional piezoelectric properties
at the MPB due to the increased poling efficiency by more efficient alignment of polar vectors in lower symmetry crystal classes. A higher degree of texture, in general, has been shown to exhibit higher piezoelectric response [3]. Furthermore, these textured ceramics have shown to exhibit lower losses compared to single crystals and higher response compared to ceramics, allowing for better high power performance. The strain response as a function of electric field is shown for various textured PMN-PT ferroelectrics, comparing to single crystals, in Figure 2.4. From this figure, it is apparent that textured ceramics exhibit the ability to undergo higher drive levels for the same strain response compared to single crystals. In addition, the work by Poterala et. al showed that adding acceptor dopants to the textured samples (e.g. 2 at% Mn) reduced the mechanical losses to further improve high power performance. A more detailed comparison of piezoelectric properties between textured ceramics, single crystals, and PZT ceramics is shown in Section 2.4.

2.4 Piezoelectric Material Property Comparison

From the work of Poterala, Brosnan, and Sherlock, a more thorough comparison of the piezoelectric properties between textured relaxor-PT ceramics, single crystals,
Table 2.1: Property comparisons between conventional PZT (soft and hard) ceramics, single crystal PMN-PT, and textured PMN-PT (undoped and doped).

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_{R-T}$ (°C)</th>
<th>$T_C$ (°C)</th>
<th>$d_{33}$ (pm/V)</th>
<th>$k_{33}$</th>
<th>$Q_M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PZT 4 (hard PZT)</td>
<td>150</td>
<td>275</td>
<td>0.70</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>PZT 8 (hard PZT)</td>
<td>300</td>
<td>220</td>
<td>0.70</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>PZT 5H (soft PZT)</td>
<td>193</td>
<td>795</td>
<td>0.75</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>PMN-28PT (single crystal) [1]</td>
<td>95</td>
<td>145</td>
<td>1700</td>
<td>0.90</td>
<td>65</td>
</tr>
<tr>
<td>PMN-28PT (undoped textured) [2]</td>
<td>76</td>
<td>129</td>
<td>855</td>
<td>0.83</td>
<td>94</td>
</tr>
<tr>
<td>PMN-28PT (2 at% Mn doped textured) [2]</td>
<td>-*</td>
<td>130</td>
<td>517</td>
<td>0.76</td>
<td>714</td>
</tr>
</tbody>
</table>

*The $T_{R-T}$ could not be clearly identified for doped PMN-28PT. This transition may be broadened over a wider temperature range due to dopant heterogeneity in this material [2].

and conventional ceramics (PZTs) can be made. Table 2.1 shows a comparison of important material properties between these materials, including the phase transition temperature, composition, piezoelectric coefficient, electromechanical coupling coefficient, and mechanical quality factor. Undoped textured PMN-28PT and 2 at% Mn doped textured PMN-28PT properties were reported from Poterala [2]. Properties of single crystal PMN-28PT are reported from Sherlock [1]. Finally, properties for PZT4, PZT8, and PZT5H were reported using measurements from this current research. The properties given are all using the same measurement method and frequency, although it is expected that there were differences in equipment used and operating conditions at the time of measurement. From Figure 2.3, it is shown that the MPB for PMN-PT lies at x=0.325. However, at this composition, there is limited temperature stability, so for high power operations, compositions of x=0.28 are primarily used [1].

From Table 2.1, some critical conclusions can be made. First, the piezoelectric coefficient and the electromechanical coupling coefficient for undoped and doped textured PMN-PT lies intermediate to that of PZTs and single crystal ceramics. This indicates better piezoelectric response and larger bandwidth for textured materials compared to PZTs, but lower than single crystal PMN-28PT. Second, the quality factor for undoped textured PMN-28PT is slightly higher than that...
of soft PZT and single crystal, indicating slightly lower losses. In doped textured PMN-28PT, the mechanical quality factor is similar to that of hard PZT, indicating very low losses and optimal for high power applications. Finally, it is shown that the $T_{R-T}$ for single crystal and textured ceramics are much lower than the Curie temperature for PZT, limiting the useable temperature range. A more detailed list of important material properties along with their definitions is shown in Section 3.3.

Table 2.1 shows the electromechanical properties using generalized subscripts, with no correspondence to any particular sample geometry. However, this must be addressed, as the particular sample geometry can lead to vastly different material properties. For all piezoelectric materials, whenever a material is stressed, electric voltage can be recovered along any surface of the material (via electrodes), so piezoelectric properties must contain a sign convention to facilitate the recovery of the electric potential [14]. The main sample geometries that exist for piezoelectrics are extensional, transverse, and shear modes. A schematic of these geometries is shown in Figure 2.5, along with a reference axis for the directions of motion. In the length extensional mode, the poling direction, applied electric field, and primary mechanical response direction are all parallel to each other in the "3" direction, thus a 33-mode designation is made [1]. From previous research it has been shown that the length extensional mode offers superior electromechanical coupling coefficients and piezoelectric coefficients compared to the transverse ("31") or shear ("15") modes. In addition, the sample geometry of the sonar projector transducers necessitate use of the 33-mode for optimal performance, so for these reasons, it is most prudent for the work in this research to be presented using 33-mode designation.

## 2.5 Summary

Piezoelectric materials are a diverse class of materials which have been implemented in a variety of different applications. Initially just a laboratory curiosity, the use of piezoelectricity in sonar using quartz spurned a fascination in discovering new materials to be used with superior performance. One such material that was discovered was lead zirconate titanate, or PZT. Due to the high strength, chemical inertness, low cost to manufacture, and the ability to tailor the material
properties by adding dopants to fit specific needs, PZT has become one of the world’s most widely used ceramic material. Recently, research has been performed on materials which offer superior piezoelectric response to PZT. One such class of materials has been relaxor-PT based ferroelectrics, of the form PMN-PT or PZN-PT. These materials offer extremely high electromechanical coupling coefficients and piezoelectric coefficients compared to those of PZT. Another benefit of these materials is the ability to manipulate and tailor the properties through domain engineering. By varying the amount of crystallographic orientations in the sample, or the texture, vastly different piezoelectric performance can be achieved. A sample which is fully textured in a given orientation is said to be single crystal. These samples offer outstanding piezoelectric response due to the lack of grain boundaries, however, due to the high domain wall motion, this increases the losses in the system, limiting the feasibility in implementing into high power operations. Textured materials with volume percent of texture amount between 50 and 90 percent show the ability to be implemented in high power applications, due to their high piezoelectric response compared to PZT, but lower losses compared to single crystal.
Chapter 3  
Underwater Transducers

3.1 Background

A transducer is a device which converts energy from one form to another. Hence, an electroacoustic transducer is a device which converts electrical energy to acoustical energy, or vice versa. Electroacoustic transduction is the basis for underwater transducers in SONAR (SOund Navigation And Ranging), which utilizes acoustic propagation and wave reflection to navigate, communicate, and detect objects under the surface of water. There are two primary types of sonar used: active and passive. Active sonar creates a pulse of sound, then listens for the reflections or echoes of the pulse, while passive sonar just listens for signals without transmitting. An underwater transducer which converts electrical energy into acoustic propagation is deemed a projector, or the in-water equivalent to a loudspeaker. Conversely, an underwater transducer which converts acoustic energy to electrical energy is known as a hydrophone, or the in-water equivalent to a microphone. For this research, underwater transducers used for SONAR projectors will be investigated.

Since Langevin first incorporated quartz into a submarine detector in WWI, piezoelectric materials have been a vital ingredient to these transducers, for their ability to convert electrical energy into mechanical strain, which can then be turned into acoustic wave propagation. For underwater projectors, this requires piezoelectrics which can sustain high drive levels, as a key aspect of device performance is the acoustic output, or source level. To determine the overall acoustic output of the transducer, we must first investigate the effect of water loading on a transducer, and how that impacts the radiation efficiency. The radiation impedance of a transducer
can be given by

\[ Z_r = R_r + jX_r = R_r + j\omega M_r \] (3.1)

where \( R_r \) is the radiation resistance, \( X_r \) is the radiation reactance, \( \omega \) is frequency, and \( M_r \) is the radiation mass. It is seen that the radiation resistance is completely real, and the radiation mass is net imaginary (where the imaginary component of \( Z_r \) is proportional to radiation mass). From the definition of impedance, thus, the power dissipated in \( R_r \) represents the far-field acoustic output of the device, while \( M_r \) represents the stored near-field acoustical energy in the transducer [15].

The most common assumption for projectors is to assume circular piston type radiation. The radiation impedance of a circular piston is given as [16]

\[ Z_r = \rho c \pi a^2 \left[ R_1(2ka) + jX_1(2ka) \right] \] (3.2)

where \( \rho \) is the density, \( c \) is the speed of sound, \( a \) is the piston radius, \( k \) is the wavenumber, \( R_1 \) is the radiation resistance function, and \( X_1 \) is the radiation reactance function, given in Equations 3.3 and 3.4 below, respectively.

\[ R_r = \rho c \pi a^2 \left[ 1 - \frac{2 * J_1(2ka)}{2ka} \right] \] (3.3)

\[ X_r = \rho c \pi a^2 \left[ \frac{2H_1(2ka)}{2ka} \right] \] (3.4)

where \( J_1 \) and \( H_1 \) are the Bessel and Struve functions of the first kind, respectively. The normalized radiation resistance and reactance functions for a circular piston are shown in Figure 3.1. From this figure, it is seen that as \( ka >> 1 \), or the frequency or the size of the source is large, the radiation resistance approaches a value of \( \rho c \pi a^2 \) and the radiation reactance approaches 0. At this point, the transducer is said to be "\( \rho c \) loaded" and the radiation efficiency into the surrounding medium is maximized [15]. Conversely, if \( ka << 1 \), or the size of the piston is small or operation is at low frequencies, then the radiation impedance acts as an added mass to the transducer of magnitude

\[ M_r = \frac{X_r}{\omega} = \pi a^2 \rho \left[ \frac{X_1(2ka)}{k} \right] \] (3.5)
which is approximately equal to a constant value of \((8/3)\rho a^3\). In a lightweight acoustic medium such as air, this added mass term is very small and sometimes negligible. However, when in water, this added mass can significantly reduce the resonance frequency of the device [15].

From the radiation resistance and the transducer velocity, one can obtain the expression for the acoustic power output of the device, shown in Equation 3.6,

\[
P_a = \frac{1}{2} u^2 R_r = \frac{1}{2} \omega^2 x^2 R_r,
\] (3.6)

where \(P_a\) is the acoustic power, \(u\) is the transducer velocity, \(R_r\) is the radiation resistance, \(x\) is the transducer displacement, and \(\omega\) is the frequency. From Equation 3.3 and Figure 3.1, it is seen that when \(ka\) is small, \(R_r\) is small, so relatively small acoustic output is achieved. When \(ka\) is large, the \(R_r\) term and hence the acoustic output is maximized. This shows that it is difficult to achieve large acoustic outputs with small transducers at low operating frequencies. There is a trade off between transducer size and operating frequency. This is an important design consideration.
to be addressed when choosing a piezoelectric material for a particular transducer.

### 3.1.1 Directivity

In addition to the overall acoustic output of the device, it is important to characterize the directionality of the projector. The directivity pattern of a transducer shows the relative acoustic pressure generated as a function of angle relative to the output face of the transducer [15]. To characterize the directivity of a SONAR projector, the device is typically driven at a constant drive level and rotated 360 degrees, while hydrophones are placed around the transducer to receive the signal. Figure 3.2 shows a directivity plot for a SONAR projector. These plots are typically normalized to a specific acoustic output (0 dB re: 1\mu Pa in Figure 3.2), showing the relative source strength as a function of angle and frequency.

Several key characteristics of the transducer output behavior can be determined from the directivity plot. First, the direction where the acoustic pressure has its
maximum value is known as the acoustic axis [15]. Second, the beam angle of a transducer is given as the angular width (in degrees) of the primary beam of the transducer, measured by the total 'arch' encompassed by the beam between the two points 3 dB lower on either side of the main acoustic axis [17]. A source that has the same acoustic pressure at all angles is said to be an omni-directional source. Finally, the directivity index (DI) is a measure of the acoustic strength relative to an omni-directional source, and indicates the relative amount of directionality of the device at a given frequency. This can be calculated for any given frequency, and for a piston type source, the expression is shown below in Equation 3.7 [18],

\[
DI = 10 \log \left[ \frac{(kr)^2}{1 - \frac{J_1(2kr)}{kr}} \right]
\]  

(3.7)

where \( k \) is the wavenumber, or radian frequency divided by sound speed, \( r \) is the effective radius of the head mass of the piston, and \( J_1 \) is the Bessel function of the first kind and first order.

### 3.1.2 Source Level

A more comprehensive assessment of the transducer acoustic output can be given by combining the directivity and the source strength. This quantity is often presented as the transmitting voltage response (TVR), which is simply the source level per unit of applied voltage, referenced to a distance 1 m away from face of transducer and using an input of 1 V\(_{\text{rms}}\). The TVR is calculated from the conductance, directivity, and the efficiency, given as [19]

\[
TVR = 10 \log(G_p) + DI + \eta + 170.9 \quad \text{dB ref: } 1 \mu\text{Pa/V at 1 m}
\]  

(3.8)

where \( G_p \) is the conductance, \( DI \) is the directivity index, and \( \eta \) is the projector efficiency, defined as the ratio of the acoustic power generated to the total electrical power input.

A normalized plot of the TVR for an idealized SONAR projector is shown in Figure 3.3. The TVR is shown to increase at +12 dB per octave below the resonance frequency before reaching a maximum at resonance, then drops at -12 dB per octave above resonance before flattening out above 2\( f_s \).
Since the projector will most likely be driven at levels above $1V_{\text{rms}}$ for high power operations, it is more useful to present the acoustic output as a source level (SL). The source level is a measure of the acoustic output again referenced to 1 m away from the face of the transducer for a given applied rms voltage. The SL is given as

\[
SL = 10\log W_e + \eta + DI + 170.9 \quad \text{dB ref: 1\mu Pa at 1 m} \quad (3.9)
\]

where $W_e$ is the input electrical power, $\eta$ is the electroacoustic efficiency, and $DI$ is the directivity index. Knowing that the efficiency is just a ratio of the acoustic power generated to input electrical power, Equation 3.7 can be simplified to

\[
SL = 10\log W_a + DI + 170.9 \quad \text{dB ref: 1\mu Pa at 1 m} \quad (3.10)
\]

where $W_a$ is the acoustic power. The SL can therefore be related to the TVR using the following relationship:

\[
SL = TVR + 20\log(V) \quad \text{dB ref: 1\mu Pa at 1 m} \quad (3.11)
\]

where $V$ is the applied voltage to the transducer.

Another important metric of transducer performance is the bandwidth of the device. The bandwidth is the frequency range over which the transducer can
effectively operate [15]. This is often presented as an effective electromechanical
coupling factor of the device, or $k_{\text{eff}}$. It is also sometimes reported as $1/\text{Q}_{m}$, or the
frequency range which the impedance phase is between -45 and 45 degrees, thereby
indicating a large component of the input electrical power is being converted to
acoustic radiation [1]. In order to optimize the bandwidth of the device, Stans-
field has stated that the transducer should be designed such that its $\text{Q}_{m} \ast k_{\text{eff}}$ is
approximately equal to 1.2 [20]. This condition provides the best coupling between
frequency and power output of the device. This is an important design consideration
when evaluating different piezoelectric materials, as the choice of material plays a
vital role in the overall bandwidth and acoustic output of the device. Additional
important metrics of transducer performance are highlighted in Section 3.3.

3.2 SONAR Projector Designs

SONAR projectors can take a wide variety of geometrical shapes, depending on the
system requirements. These can take the form of spheres, cylinders, rings, or piston
radiators, among others [19]. Reviewing all of the different types of geometries is
beyond the scope of this work. Consequently, the two main projector designs used
in this research, Langevin Sandwich and Tonpilz, are presented in this section.

3.2.1 Langevin Sandwich

One common geometry of SONAR projectors is the Langevin sandwich transducer.
Consisting of piezoelectric elements sandwiched between two identical end masses,
this transducer is a simple geometry utilized for narrow-band operation, typically
in the range of 20-100 kHz [19, 22]. The piezoelectric elements are typically in
the form of a disc or ring, segmented into equal pieces and polarized in opposite
directions. Electrodes are placed in between the piezoelectric elements and an
insulator is typically implemented in the design between the piezoelectric elements
and the end masses. A stress bolt connects the pieces and induces coupling between
the stack and the end masses, and allows a compressive pre-stress to be applied to
the assembly, increasing the tensile strength of the transducer [22]. This geometry
results in length extensional or 33 mode operation. Figure 3.4 shows a schematic
of a Langevin sandwich transducer.
Figure 3.4: Schematic of elements in a Langevin sandwich transducer [21]. Four piezoelectric ceramic rings are shown in this transducer, although this could be any number of rings (an even number is more common). An insulator is usually placed in between the end masses and the piezoelectric stack.

Several design considerations must be made to achieve optimal performance of the Langevin sandwich transducer. First, the end masses are typically made from steel or tungsten, to increase the vibration amplitude at the radiating faces, and improve the matching to the applied load, thus increasing the acoustic output of the device. By including end masses of different densities to the piezoelectric stack, the resonance frequency of the device will be lower than that of the unloaded piezoelectric ceramics. Second, the piezoelectric ceramics chosen will be dependent on the application being used for, but to achieve high acoustic output at high drive levels, the piezoelectrics should have high electromechanical coupling factors, high MPB phase transition temperature or high Curie temperature, low dielectric loss, and a high piezoelectric coefficient [22].

Within this research, these transducers will be utilized to distinguish differences in properties of the device using different piezoelectric ceramic materials, when varying the temperature and the pre-stress amount. Transducers will be built for each piezoelectric material and different stack lengths will be used to obtain the same device resonance frequency. Then, the effect of different applied pre-stresses and different temperatures will be investigated for each transducer. A more detailed
Figure 3.5: Schematic of elements in a Tonpilz Transducer. The piezoelectric ceramic material is in green, segmented by electrodes seen in gold. This stack is sandwiched between a head mass and a tail mass. A stress bolt runs through the transducer to apply a compressive stress bias. [1].

description of this experiment and the results will be presented in Chapter 5.

3.2.2 Tonpilz

One of the most common projector geometries for mid-frequency operation is the Tonpilz transducer. Unlike the ring projectors, Tonpilz transducers can be modeled as piston-type sources, radiating sound in one direction. These are one of the most common geometries used in underwater acoustics, often implemented in large arrays to create highly-directional and high intensity sound radiation into a particular area [19]. Tonpilz transducers are typically designed for operation between 1 kHz and 100 kHz. A schematic of the components involved in a Tonpilz transducer is shown in Figure 3.5.

The Tonpilz element consists of a stack of piezoelectric ceramic rings sandwiched between a large piston head mass and a heavy inertial tail mass. The device is
driven along the polarization of the piezoelectric stack via the sandwiched electrodes, causing the stack to produce a strain and actuate the head mass, resulting in radiating acoustic energy into the surrounding medium. Including a heavy tail mass lowers the resonance frequency of the device and allows for obtaining high acoustic output at mid-frequencies without the need for excessively long piezoelectric stack lengths [1,19]. A stress bolt is included to prevent device operation in tension under high drive levels. Ceramic materials have a much smaller tolerance to tensile stresses compared to compressive stresses, so by applying a compressive stress bias, the bolt prevents operating in tension and allows for operation at much higher drive levels [1].

In order to attain the greatest acoustic output from the device, several design considerations must be made. First, a large tail to head mass ratio is desirable as it yields a large head velocity, and as seen in equation 3.6, results in a larger acoustic power produced by the projector. The head mass is typically a material with a high stiffness to weight ratio, such as magnesium or aluminum. To avoid undesirable flexural modes from the head mass, the thickness is determined by setting its flexural resonance to about 2 times the fundamental resonance of the transducer. The tail mass is typically stainless steel or tungsten, and is usually less than a quarter wavelength in length to provide a rigid baffle condition, yielding greater acoustic radiation. The tail mass is also typically 3-5 times the mass of the head, to minimize radiation from the back of the transducer and allow for more efficient radiation from the head. The stress bolt is usually comprised of a material whose stiffness is less than 20% of the stack to avoid impeding the motion of the tail mass and to prevent significant reduction in the effective coupling coefficient of the device [1,15,19].

Due to its capability of handling high drive levels and having high acoustic outputs, the Tonpilz transducer was chosen as the primary projector geometry for this research. In this geometry, the polarization of the stack results in length extensional, or 33 mode operation. The goal of this research is to characterize the electromechanical performance of Tonpilz transducers using textured relaxor-PT ferroelectric ceramics, and compare the performance to commonly used ceramics, such as polycrystalline PZT and single crystal.
3.3 Material Property Definitions

It is important to discuss the critical material properties which affect performance of transducer. While it is a goal to optimize as many material properties as possible, there are trade-offs for many which limit the ability to optimize them all. The properties presented will be prudent for the design of a Tonpilz SONAR projector, operating in the length extensional (33) mode. Not all material properties will be shown, just the primary ones which will be discussed at length throughout the thesis and ones most critical to achieving high performance of the device [10]. The properties shown here are in reduced tensor notation, or $X_{jk}$, where $j$ represents the electrical axis and $k$ represents the mechanical axis. Only definitions are discussed here; more detailed equations and calculations for these piezoelectric properties will be presented in Chapter 5.

$d_{33}$ Piezoelectric coefficient, which quantifies the induced polarization when a piezoelectric material is subject to a given stress, given in units of pC/N for the direct piezoelectric effect, and pm/V for the converse piezoelectric effect. This third rank tensor property quantifies response of a piezo material. Higher $d_{33}$ values are desirable to produce higher acoustic source levels.

$s_{33}^E$ Elastic compliance, strain produced in the material for a given amount of stress applied, under constant electric field. Compliance is a fourth rank tensor. Higher elastic compliance is desirable to achieve higher displacement from the material, producing higher source levels. In addition, higher $s_{33}^E$ allows for smaller package or stack length size for a given resonance frequency.
**$k_{33}$** Electromechanical coupling factor, indicates effectiveness with which a piezo material converts electrical energy into mechanical energy. For a transducer, this is often given as $k_{\text{eff}}$, or an effective coupling factor. A higher coupling factor is desirable as this indicates greater bandwidth available for the transducer, increasing frequency range of operation [23].

**$Q_m$** Mechanical quality factor, characterizes 'sharpness of resonance' of piezoelectric response. Often defined as a loss metric, a higher $Q_m$ is desired as this indicates a lower rate of energy loss in the transducer.

**$\tan \delta$** Loss tangent, analogous to the quality factor, describes the losses in the system. Subscripts $\delta_m$, $\delta_p$, and $\delta_d$, characterize the energy loss due to mechanical motion, energy loss due to electrical-mechanical energy conversion, and energy loss due to charge mobility, respectively. Lower $\tan \delta$ values are desired to prevent heat generation and temperature rise during high power operation.

**$T_{R-T}/T_C$** Rhombohedral-tetragonal phase transition temperature. For single crystal and textured ceramics, this temperature is the limiting temperature for optimal piezo response. For PZT, $T_C$ or the Curie temperature is the limiting temperature of piezoelectric behavior. Higher $T_{R-T}/T_C$ allows for wider temperature range of operation, and results in less material property variation over a constant temperature range [1].

**$E_c$** Coercive field, the measure of a piezoelectric materials’ ability to withstand an external electric field without becoming depolarized. This value determines maximum drive amplitude a transducer can withstand, so higher coercive field value is desired to enable higher power operation.

**$K_{33}^T$** Dielectric constant measured under constant stress, which corresponds to the overall electrical impedance of the transducer. Higher values are desired to reduce the impedance of the transducer.
3.4 Summary

Underwater transducers are the key components in SONAR. A SONAR projector converts electrical energy into acoustical energy, and are the subject of this work. To evaluate the performance of a SONAR projector, the primary metric used is source level, which is dependent on the directivity, or directionality, and the acoustical power generated by the source. Projectors can take the form of numerous geometries, from cymbals to rings to spheres. For the context of this research, only the Langevin sandwich and Tonpilz type geometries were investigated. The Langevin sandwich type transducer was only used to determine the effect of pre-stress and temperature on different device properties. The Tonpilz design was utilized more intensively to comprehend the overall effect of different piezoelectric ceramics on acoustical output. Key properties were discussed which affect the performance for a projector. Trade-offs between several important properties make it difficult to optimize the devices for all uses, but by taking careful consideration of these properties, optimal results can be achieved for the specific application of choice.
4.1 Electromechanical Transducer Model

In this chapter, the performance of generic Langevin sandwich and tonpilz transducers were modeled using the GiD-ATILA finite element modeling software package. ATILA was developed to specifically aid in the design of piezoelectric devices, particularly for SONAR applications. The finite element code is able to perform modal analysis of axisymmetrical and three-dimensional transducers, providing their harmonic response under various radiating conditions, such as transmitting voltage response, directivity pattern, electrical impedance, and stress contours, among others [24]. ATILA uses linear mathematics to model the response in a given system, either in air or in a simulated water load [1]. Using the complete property matrices, ATILA can model all resonance modes, further aiding in the design of the transducer. The predicted electromechanical response determined from modeling can then be compared with the dynamic measurements made for these transducers, shown in Chapter 6.

Each material investigated was modeled using both the Langevin sandwich and tonpilz designs. In total, five transducers were modeled for each design. Material matrix property values were taken from various literature for PZTs and Poterala’s paper for the textured materials [2, 25]. PZT4, PZT8, and PZT5H were used as a reference or baseline to compare the performance of the textured ceramics. A schematic depiction of the Langevin sandwich and tonpilz transducers modeled in the GiD-ATILA package are shown in Figures 4.1 and 4.2, respectively.

From these figures, it is apparent that both transducers exhibit the same design
Figure 4.1: Schematic of a Langevin sandwich transducer modeled in ATILA.

Figure 4.2: Schematic of a Tonpilz transducer modeled in ATILA.
considerations as discussed in Chapter 3, including end masses, insulators, a bolt, and the stack of piezoelectric material. The transducers have multiple rings of equal thickness of piezoelectric material to allow for higher operating voltages, by reducing the overall electrical impedance of the device. Not shown in the transducer model are the electrodes at each joint between the rings and the insulators. The degree of segmentation (number of rings) and ring thickness can be adjusted to accommodate the specific drive levels needed for a particular application. For these materials, the PZT tonpilz transducers were modeled using 4 rings and the textured materials were modeled using 2 rings. The thicknesses of the rings were modified to produce the same resonance frequency for all the devices.

The materials shown in these models are all chosen to facilitate the best performance of the devices. For the tonpilz transducers, Tungsten is used as the material in the tail mass because of its large mass, needed to limit displacement towards the rear of the stack. Magnesium is used as the material in the head mass because of its lower weight but high stiffness, needed to effectively radiate energy into the surrounding medium. 303 and 316 stainless steel are used as the materials in the bolts for the sandwich and tonpilz transducers, respectively, for their high mechanical strength needed to apply compressive stress biases in the devices. The insulator rings are used to provide added electrical insulation and a mechanical impedance match between the piezoelectric stack and the end masses [1].

In addition, note that only one eighth and one quarter of the actual devices are shown in Figures 4.1 and 4.2, respectively. Due to symmetry conditions, a portion of the device can be modeled and appropriate boundary conditions can be applied in ATILA. A schematic of these symmetry planes is shown in Figure 4.3. For the Langevin sandwich transducer, there are three mirror planes present along the device, while in the tonpilz transducer, there are two mirror planes present. Both the displacements and the electric field for the devices had these mirror planes implemented in the calculations for the modeled transducers.

For the tonpilz elements, these devices would ultimately be tested in water as well as air, so additional modeling of the water boundary must be performed. A schematic of a tonpilz transducer and the surrounding water boundary is shown in Figure 4.4. The water boundary is also modeled with the same symmetry conditions as the transducer, so only a quarter of the full boundary is shown here. The water boundary is directly connected to the head mass, extending away from
Figure 4.3: Schematic of planes of mirror symmetry in ATILA. Boundary conditions can then be input for any of these planes to model the entire device.

the transducer in a spherical manner. An appropriate size of the water boundary must be considered, as too small a volume will result in near-field abnormalities in the response, while too big a volume will result in long computation times for the model. For these devices, a water boundary with radius of about 4x the length of the device was chosen as the optimal condition.

To model the transducer performance under an applied electric field, material properties must be input into ATILA for each material in the transducer. There are two primary types of materials in the design: passive component materials and active materials. Passive component materials are not piezoelectric and exhibit isotropic behavior, and therefore only require a few mechanical properties to be input into the model. In addition, no electric field will be applied to these components, so the dielectric constant is not needed. The mechanical losses of these materials will be negligible compared to the active materials in the transducer, so these parameters are also neglected. The passive component material properties are shown in Table 4.1. The active materials are the piezoelectric materials in the device. The properties input into ATILA are split into five categories: mechanical compliance \( s_{ij}^E \), piezoelectric coupling \( d_{ij} \), dielectric \( \epsilon_{ij}^T \), loss values \( \tan \delta \), and density \( \rho \). All material properties reported were taken directly from relevant literature [2, 25]. The material properties for the active piezoelectric materials are

32
Figure 4.4: Schematic of Tonpilz transducer in a simulated water load modeled in ATILA.

Table 4.1: Passive component material properties input into ATILA.

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus (GPa)</th>
<th>Density (kg/m³)</th>
<th>Poisson’s Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten</td>
<td>342</td>
<td>17459</td>
<td>0.26</td>
</tr>
<tr>
<td>Insulator</td>
<td>48.3</td>
<td>7580</td>
<td>0.31</td>
</tr>
<tr>
<td>Magnesium</td>
<td>39.0</td>
<td>1798</td>
<td>0.35</td>
</tr>
<tr>
<td>316SS</td>
<td>185</td>
<td>7920</td>
<td>0.29</td>
</tr>
<tr>
<td>303SS</td>
<td>193</td>
<td>8000</td>
<td>0.25</td>
</tr>
</tbody>
</table>

shown in Table 4.2.

4.2 Finite Element Modeling Results

The Langevin sandwich transducers were only modeled in air, as these devices were only going to be tested as described in Section 5.2. The Tonpilz devices were first modeled in air then under a simulated water load. The ring thicknesses were first adjusted for each material to produce approximately the same resonance frequency (within +/- 3%). A general trend seen was that larger stack lengths were required for lower elastic compliance materials. Thus, the order of stack lengths for these
Table 4.2: Active piezoelectric material properties input into ATILA [2,25].

<table>
<thead>
<tr>
<th></th>
<th>PZT4</th>
<th>PZT5H</th>
<th>PZT8</th>
<th>PMNT</th>
<th>Mn:PMNT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s_{ij}^E$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$s_{11}$</td>
<td>12.3</td>
<td>16.4</td>
<td>11.1</td>
<td>17.4</td>
<td>11.5</td>
</tr>
<tr>
<td>$s_{12}$</td>
<td>-4.05</td>
<td>-4.7</td>
<td>-3.7</td>
<td>0.1</td>
<td>-0.5</td>
</tr>
<tr>
<td>$s_{13}$</td>
<td>-5.31</td>
<td>-7.22</td>
<td>-4.8</td>
<td>-14.3</td>
<td>-8.0</td>
</tr>
<tr>
<td>$s_{33}$</td>
<td>15.5</td>
<td>20.8</td>
<td>13.9</td>
<td>34.1</td>
<td>23.5</td>
</tr>
<tr>
<td>$s_{44}$</td>
<td>39.0</td>
<td>47.5</td>
<td>35.0</td>
<td>22.5</td>
<td>23.3</td>
</tr>
<tr>
<td>$s_{66}$</td>
<td></td>
<td></td>
<td></td>
<td>34.5</td>
<td>24.0</td>
</tr>
<tr>
<td>$x10^{-12}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m^2/N$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$d_{ij}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$d_{15}$</td>
<td>496</td>
<td>741</td>
<td>400</td>
<td>423</td>
<td>419</td>
</tr>
<tr>
<td>$d_{31}$</td>
<td>-123</td>
<td>-274</td>
<td>-93</td>
<td>-393</td>
<td>-207</td>
</tr>
<tr>
<td>$d_{33}$</td>
<td>289</td>
<td>593</td>
<td>218</td>
<td>855</td>
<td>517</td>
</tr>
<tr>
<td>Losses</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tan \delta_m$</td>
<td>0.002</td>
<td>0.013</td>
<td>0.001</td>
<td>0.0011</td>
<td>0.0011</td>
</tr>
<tr>
<td>$\tan \delta_p$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\tan \delta_d$</td>
<td>0.04</td>
<td>0.02</td>
<td>0.004</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Density</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$kg/m^3$</td>
<td>7500</td>
<td>7500</td>
<td>7600</td>
<td>8068</td>
<td>8050</td>
</tr>
</tbody>
</table>

Electrical Impedance

The electrical impedance of the Tonpilz devices was then modeled in air. The complex impedance magnitude and phase for each device is shown in Figures 4.5 and 4.6, respectively. The frequencies are normalized to the first resonance frequency, and frequencies up to the third harmonic ($4f_0$) are modeled. All the materials show similar trends in the impedance magnitude and phase spectrums. Some key differences, however, include the sharpness of the peaks and the frequencies of peaks above $3f_0$, and the bandwidth of the devices at resonance (seen as the broadness of the peak in the phase plot). The deviation in performance at higher frequencies

devices, from smallest to largest, was: PMNT → PZT5H → Mn: PMNT → PZT4 → PZT8.
Figure 4.5: Impedance magnitude, top, and impedance phase, bottom, for Tonpilz transducers, modeled in ATILA.
may be due to resonance modes predicted by the model. These modes are likely to be too weak to make an impact on the in-water behavior of the device, and in addition, these higher order modes are well beyond the intended bandwidth for these projectors.

**Acoustic Output**

The acoustic output of the Tonpilz projectors was also modeled in ATILA. These devices, when driven under an applied voltage, will radiate energy into the surrounding water volume. When a voltage is applied to the device, the piezoelectric rings undergo the converse piezoelectric effect, producing a mechanical strain and subsequent deformation of the rings. The rings are oriented such that maximum displacement occurs at the ends of the rings near the insulators. An exaggerated schematic of the four step process the transducers undergo to produce an acoustic output is shown in Figure 4.6. This figure shows how the transducer undergoes a strain, effectively stretching the device, then relaxing to the unstressed state, then compressing, then finally returning back to the original state. This repeated motion of the device at a particular frequency will result in acoustic wave propagation into the surrounding water. The design of the Tonpilz transducer is then optimized to efficiently convert this motion into radiated acoustic energy into the surrounding medium.

To further illustrate the resulting displacement along the device during operation, a displacement contour map is shown in Figure 4.7. Here, it is clearly visible where the areas of high and low displacement occur along the device. At the center of the device, the displacement is at a minimum, while at the head, the displacement is at a maximum. This shows maximum radiation efficiency of the device, as most of the motion in the device results in propagating acoustic waves through the water. At resonance, this difference is almost ten-fold shown in the example device in Figure 4.7 (Mn:PMNT). Off resonance, the displacements seen are lower, which is to be expected, but the same trend holds that maximum displacement occurs at the head.

Before modeling the acoustic source level of the devices, the impedance magnitude and phase were modeled in water. These spectra can be found in Figure 4.8. Several interesting results are seen from these plots. First, as a result of water
loading, the sharpness of the peaks or the quality factor has decreased for all the transducers. The same general trend still is seen in the impedance magnitudes, however, with PZT5H showing the broadest peak or lowest quality factor, and PZT8 and Mn:PMNT showing the sharpest peak or highest quality factor. This agrees with theory that soft piezoelectrics will show higher response but higher losses, and vice versa for hard piezoelectrics. What is even more illuminating, however, is the phase response for these different materials. The transducer bandwidth is often defined as the frequency range where the phase is between -45 degrees and +45 degrees, indicating a large amount of the input electrical power is dissipated as real power [1]. Here, it is clearly seen that the textured materials have greater bandwidths than all the PZT materials. This shows the promise of these materials exhibiting large bandwidths of radiation, to combat any heat generation trade-offs that may occur. Values for the in-air and in-water electromechanical coupling coefficient ($k_{eff}$) and the mechanical quality factor ($Q_m$) calculated from these models are presented in Table 4.3. The quality factor in air is not reported as this...
Figure 4.7: Displacement of Mn:PMNT transducer along the length of the device (x-direction) at resonance (a) and off resonance (b). Notice the areas of high displacement are at the head in both cases, indicating effective radiation into the medium.

Table 4.3: Modeled electromechanical coupling coefficient and quality factor for Tonpilz Transducers.

<table>
<thead>
<tr>
<th>Material</th>
<th>In-Air $k_{eff}$</th>
<th>In-Water $k_{eff}$</th>
<th>In-Water $Q_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PZT4</td>
<td>0.60</td>
<td>0.61</td>
<td>9.5±0.9</td>
</tr>
<tr>
<td>PZT8</td>
<td>0.55</td>
<td>0.56</td>
<td>9.5±0.9</td>
</tr>
<tr>
<td>PZT5H</td>
<td>0.62</td>
<td>0.66</td>
<td>7.4±0.7</td>
</tr>
<tr>
<td>PMNT</td>
<td>0.71</td>
<td>0.72</td>
<td>6.3±0.5</td>
</tr>
<tr>
<td>Mn:PMNT</td>
<td>0.66</td>
<td>0.69</td>
<td>7.4±0.7</td>
</tr>
</tbody>
</table>

value would fluctuate drastically depending on the losses input into the model, and the fact that glue joints were not accounted for in the model.

The resulting propagation of acoustic waves into the water can be quantified as the acoustic source level (SL). This level is typically reported at a distance of 1 m away from the radiating transducer, and is typically expressed on a logarithmic scale, normalized to the reference pressure in water of 1µPa. When modeling the devices, it is often more useful to report the source level as a transmit voltage response (TVR), which is the source level per unit of applied voltage. The modeled TVR for these devices, normalized to their resonance frequency, is shown in Figure 4.9.

The TVR plot shows a general trend of higher response for higher piezoelectric response (d33) materials. In this case, PZT5H and the Undoped PMNT show the
Figure 4.8: Impedance magnitude, top, and impedance phase, bottom, for Tonpilz transducers under a simulated water load, modeled in ATILA.
highest TVR, in addition to having large piezoelectric coefficients. In addition to the strong peak at resonance, these materials all show similar behaviors above resonance. The peaks seen above $3f_0$ are again a result of higher order modes, but these effects fall outside the frequency band of intended operation. The dips in the TVR around $2f_0$ are caused by the breathing modes of the transducer. Often out of phase with the piezoelectric stack, these modes cause deep nulls in the acoustic output. In addition, the effective bandwidth can also be seen by comparing the TVR behavior around these frequencies. For the undoped textured PMNT, there is a small dip in the response around $2.4f_0$, then a much more intense null around $2.7f_0$. Compared to the deep nulls for PZT, which occur from 2.2-2.5$f_0$, this suggests that the useable frequency range is higher for the undoped textured PMNT, further illustrating the result found from the impedance phase plot in Figure 4.8. For the Mn doped textured PMNT, while the TVR is lower than the other materials, the sharp peak indicated a higher quality factor and thus lower heat generation during operation.

The TVR can also be presented normalized to ring thickness, shown in Figure
Figure 4.10: Transmit Voltage Response for Tonpilz transducers normalized to ring thickness, modeled in ATILA.

4.10. This normalized plot shows much more significant separation between the materials in terms of acoustic response at resonance. Since the textured materials require much smaller ring thicknesses than PZT, the output relative to the thickness is much higher. The TVR of PMNT and Mn:PMNT are seen to be upwards of 5 to 10 dB higher than PZT4 or PZT8 at $f_0$. This plot, along with the impedance spectrum, further illustrates the potential for textured ceramics to be a suitable candidate for SONAR applications due to their high bandwidth and high source levels produced.

4.3 Summary

The performance of Langevin sandwich and Tonpilz transducers using different piezoelectric materials was modeled using the GiD-ATILA finite element software package. Transducers using PZT4, PZT5H, PZT8, PMNT, and Mn:PMNT as
the piezoelectric stack materials were modeled in this software package. Proper consideration was made to the choice of head, tail, bolt, and insulator materials to optimize the radiation efficiency of the devices. Knowing the material properties for the passive and active materials in the transducer, the performance of these devices were modeled in air and under a simulated water load. The thicknesses of the piezoelectric stack were adjusted to produce the same resonance frequency in all the devices. As a result of higher compliances, PMNT and Mn:PMNT required significantly smaller ring thicknesses to produce the same resonance frequency as the PZT materials. As a result these textured materials could be used to produce compact high-power SONAR projectors, mitigating a common limitation in high power applications of device dimensions.

The Tonpilz transducers were modeled for their response of several important characteristics, including the complex impedance and the transmit voltage response (TVR). The impedance of the devices in air agreed with theory, as the peak magnitudes were the greatest for materials with highest piezoelectric response. In addition, materials with the highest electromechanical coupling coefficients corresponded to higher bandwidths available for operation, indicated by the frequency range at which the phase was \(-45 < \phi < +45\). The in-water response for the Tonpilz transducer showed maximum displacement along the device at the head, indicating efficient radiation into the surrounding fluid. The acoustic source level was modeled using the TVR, or the source level per applied voltage. The TVR of these devices also correlated well with piezoelectric response. The bandwidth and heat generation was illuminated through this plot as well, from the location in frequency of the nulls in the response and the sharpness of the peaks (mechanical quality factor), respectively. The modeling of these transducers only further reinforced the potential that textured PMNT has in being a viable option for high power applications for SONAR projectors.
Chapter 5  
Electromechanical Characterization

5.1 Experimental Setup

The electromechanical properties of \textit{\langle 001\rangle}_c\text{ textured undoped PMN-xPT and }\textit{\langle 001\rangle}_c\text{ textured 2 at\% Mn doped PMN-xPT} were measured and compared to the properties of PZT4, PZT8, and PZT5H. The properties were measured under small and large signal conditions. Small signal conditions are indicated by drive amplitudes where the electromechanical output is directly proportional to the input signal, indicating linear response. Large signal conditions are indicated by nonlinear behaviors starting to take place at higher drive levels. Since the feasibility of use under high power conditions is to be determined, it is vital to understand the characteristics of the properties over a wide range of drive levels. The relationship between key electrical and mechanical parameters will be presented here for each material investigated.

5.1.1 Materials of Interest

The primary material of interest for this work is \textit{\langle 001\rangle}_c\text{ textured \(1-x\)Pb(Mg}_{1/3}\text{Nb}_{2/3}\text{)}TiO}_3-x\text{PbTiO}_3.\text{ For this research, a mole fraction of }x=0.302\text{ was used for both textured materials. A lotgering factor or texture fraction of 85\% and 80\% were obtained for undoped PMN-PT and Mn doped PMN-PT, respectively. For simplicity, the undoped textured PMN-PT material will be referred to as PMNT and the 2 at\% Mn doped PMN-PT material will be referred to as Mn:PMNT. All textured}
materials were produced by ARL-Freeport using tape casting and the templated grain growth method (TGG).

Modifications to this binary PMN-PT system can be introduced to obtain different material properties. The first modification is adding Mn$^{2+}$ as an acceptor dopant. Analogous to acceptor doping PZT, adding Mn ions displace the B-site Zr$^{4+}$ and Ti$^{4+}$ ions, creating oxygen vacancies and thereby increasing the energy barrier to B-site motion. This decreases domain wall motion and decreases losses, effectively "hardening" the material. Increasing the amount of doping reduces the domain wall motion even further. In this work, 2 at% Mn was used for the acceptor doped composition of 69.8PMN-30.2PT.

These textured materials were compared to commonly used PZT materials implemented in SONAR projector transducers. For this work, PZT4, PZT5H, and PZT8 were used. These three PZT materials represented a good range of "hard" and "soft" piezoelectric response which could be compared to in the evaluation of the textured ceramics. The PZT materials were obtained from Piezo Kinetics, Incorporated (Bellefonte, PA) and CTS Corporation (Horsham, PA).

5.1.2 Sample Preparation

Rings of PMNT,Mn:PMNT, PZT4, PZT5H, and PZT8 were used for both the Langevin sandwich and Tonpilz transducers. The rings all had the same outer diameter and inner diameter. The thickness was modified for each based on the modeling results from ATILA, which was detailed in Chapter 5, to obtain the same resonance frequency for each material. Completed rings were then poled at various electric fields depending on the coercive fields for each material. PMNT was poled at 10kV/cm and Mn:PMNT was poled at 12kV/cm. The Langevin sandwich and Tonpilz transducer build procedures are outlined in Section 5.3 and 6.1, respectively.

5.2 Small Signal Measurements

Small signal measurements were first performed for each piezoelectric material investigated. All measurements were carried out in accordance with the IEEE Standard on Piezoelectricity and any significant deviations from these methods are noted [26]. Measurements were first made on individual piezoelectric rings to
confirm correct dimensions and accurate modeling results. Then, transducers were
built using these rings and additional measurements were made under the small
signal regime. The parameters could often be measured very precisely, to greater
than four significant figures in most cases. As a result, most of the precision in the
measurements is limited by sample to sample variation, and not from equipment
error. Therefore, many of the measured parameters are reported as averages over a
representative sample for each material.

**Complex Impedance**

The complex impedance (expressed as a magnitude and phase) is a vital measure-
ment that contains a wealth of information about the material. The impedance
of the sample was measured using an impedance/gain analyzer (Agilent 4294A
Precision Impedance Analyzer, Santa Clara, CA). Two sweeps were performed for
each sample. First, a coarse frequency sweep over the range \( f \ll f_s \) to \( f \gg f_p \),
where \( f_s \) and \( f_p \) are the series and parallel resonance frequencies, respectively. Then,
a fine frequency sweep near resonance was performed to capture the resonance
frequency and the 3-dB down points with greater precision. An example impedance
spectrum for PZT4 is shown in Figure 5.1.

The series and parallel resonance frequencies were determined from the maximum
of the real part of the conductance (\( G \)) and the maximum real part of the resistance
(\( R \)), respectively, from the impedance spectrum. The equations for the resistance,
and conductance are given in Equations 5.1 and 5.2, respectively.

\[
R = Z \ast \cos \left( \text{Phase} \ast \frac{\pi}{180} \right) \quad (5.1)
\]

\[
G = \frac{R}{\left( R^2 + X^2 \right)} \quad (5.2)
\]

Where \( R \) is the resistance, \( Z \) is the impedance magnitude, \( \text{Phase} \) is the impedance
phase, \( G \) is the conductance, and \( X \) is the reactance, given in Equation 5.3.

\[
X = Z \ast \sin \left( \text{Phase} \ast \frac{\pi}{180} \right) \quad (5.3)
\]

The mechanical quality factor can also be computed from the impedance
Figure 5.1: Impedance magnitude and phase of PZT8. The magnitude is shown in blue while the phase is shown in red. The resonance and anti-resonance frequencies are labeled by $f_r$ and $f_a$, respectively.

Knowing the susceptance, $B$, one can accurately calculate the quality factor. The susceptance and mechanical quality factor is given in Equations 5.4 and 5.5, respectively

$$B = -\frac{X}{(R^2 + X^2)} \quad (5.4)$$

$$Q_m = \frac{f_s}{f_2 - f_1} \quad (5.5)$$

where $f_1$ and $f_2$ are the frequencies which correspond to the minimum and maximum susceptance, respectively. This is equivalent to defining $f_1$ and $f_2$ as the 3dB down points from the peak admittance. For low loss systems, it is a valid approximation to take $f_1$ and $f_2$ as the frequencies at which the phase angle is -45 degrees and
+45 degrees, respectively.

The elastic compliance can be measured from these impedance measurements using the following relationship

\[ Y_r = \rho c = 4\rho(f_0 \ast l)^2 \] (5.6)

where the sound speed \( c \) is calculated from the product of the series resonance frequency \( f_s \) and the wavelength, or \( 2l \) for this resonance mode. For this sample geometry, \( Y_r = c_{33}^E \), therefore the elastic compliance can be simplified to

\[ s_{33}^E = \frac{1}{Y_r}. \] (5.7)

The electromechanical coupling coefficient can also be calculated from \( f_s \) and \( f_p \), using the relationship shown in Equation 5.8.

\[ k_{33} = \sqrt{\frac{\pi}{2} \left( \frac{f_s}{f_p} \right) \cot \left( \frac{\pi f_s}{2 f_p} \right)} \] (5.8)

Using the same Agilent 4294A impedance analyzer, the dielectric permittivity and the dielectric loss could be determined. Using a 1 Volt drive at 1 kHz the dielectric permittivity was computed from the parallel capacitance and the sample dimensions, shown in Equation 5.9.

\[ K_{33}^T = \frac{C_p}{\epsilon_0 A} \] (5.9)

where \( C_p \) is the parallel capacitance, \( \epsilon_0 \) is the permittivity of free space, \( t \) is the thickness of the sample, and \( A \) is the cross-sectional area of the sample. The dielectric loss was measured from the dielectric dissipation at 1 kHz and 1 V drive. Since this frequency was well below the resonance frequency of the materials, the mechanical losses were considered to be negligible compared to the dielectric losses. Therefore, the dielectric losses were reported as tan\( \delta \) values. These material properties for each material can be seen in Table 5.1.
Table 5.1: Small signal material properties measured for piezoelectric materials. The dielectric permittivity and piezoelectric coefficient were measured at 1kHz, while the rest of the material parameters were measured at resonance.

<table>
<thead>
<tr>
<th>Material</th>
<th>$K_{33}^T (\epsilon_0)$</th>
<th>$s_{33}^E$ (pm²/N)</th>
<th>$k_{33}$</th>
<th>$d_{33}$ (pC/N)</th>
<th>$Q_m$</th>
<th>$\tan \delta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PZT4</td>
<td>1177</td>
<td>78.7</td>
<td>0.44</td>
<td>270</td>
<td>1209</td>
<td>0.14</td>
</tr>
<tr>
<td>PZT8</td>
<td>1043</td>
<td>67.0</td>
<td>0.49</td>
<td>290</td>
<td>1479</td>
<td>0.18</td>
</tr>
<tr>
<td>PZT5H</td>
<td>3682</td>
<td>147</td>
<td>0.57</td>
<td>755</td>
<td>53.4</td>
<td>1.63</td>
</tr>
<tr>
<td>PMNT</td>
<td>3686</td>
<td>228</td>
<td>0.52</td>
<td>662</td>
<td>65.1</td>
<td>1.37</td>
</tr>
<tr>
<td>Mn:PMNT</td>
<td>2566</td>
<td>165</td>
<td>0.42</td>
<td>410</td>
<td>639</td>
<td>1.04</td>
</tr>
</tbody>
</table>

**Piezoelectric Coefficient**

One of the most important material parameters which dictates performance of a SONAR projector is the piezoelectric coefficient. There are several methods that exist which can be used to measure the piezoelectric coefficient for each material, such as using the slope of the unipolar strain-field response, using a Berlincourt $d_{33}$ meter measuring induced polarization under constant force, or calculating directly from the resonance measurements and Equations 5.7, 5.8, and 5.9, using the relationship shown in Equation 4.10 [1].

$$d_{33} = \sqrt{k_{33}^2 \times K_{33}^T \times s_{33}^E}$$  \hspace{1cm} (5.10)

where $k_{33}$ is the electromechanical coefficient, $K_{33}^T$ is the free dielectric constant, and $s_{33}^E$ is the elastic compliance.

For this work, the piezoelectric coefficient was directly measured using a non-contact laser vibrometry method. A function generator was used to output a continuous sinusoidal waveform at 1 kHz. This frequency was used as it fell well below the resonance frequency for any of the materials, allowing to avoid any possible resonance phenomena. The waveform was amplified to 2 V$_{pk}$ and applied to the sample electrodes. A low distortion variable input transformer (Instruments Inc., Model VIT-13, San Diego, CA) was used to measure the voltage drop across the sample. The vibration velocity of the sample was then measured using a Polytec OFV-505 laser head and a Polytec OFV-5000 laser controller. A Krohn-Hite Corporation low pass/high pass Butterworth/Bessel dual channel filter was
used to filter out unwanted frequencies from the waveform. All these elements were then fed into a National Instruments PXIE-1073 DAQ which ran a Virtual Instrument (VI) program on the computer. This program set the sample rate, window%, number of cycles, and voltage and current settings for each measurement.

After measuring the vibration velocity, the piezoelectric coefficient could be calculated using the relationship

\[ d_{33} = \frac{S}{E}, \quad (5.11) \]

where \( S \) is the strain and \( E \) is the electric field. The strain is given by \( \delta l/l \), where \( \delta l \) is given by

\[ \delta l = \frac{v}{\omega} = \frac{v}{2\pi f}, \quad (5.12) \]

where \( v \) is the vibration velocity and \( f \) is the frequency. Substitution for this result into the the piezoelectric coefficient expression results in

\[ d_{33} = \frac{v}{V f}, \quad (5.13) \]

where \( V \) is the applied voltage. In this measured experiment, the vibration velocity and applied voltage are directly measured, and the signal is applied at 1 kHz frequency. By measuring all three parameters to a fine precision, an accurate result for the piezoelectric coefficient can be obtained. A comparison of piezoelectric coefficients for each material studied is presented in Table 5.1.

5.3 Preload Tests

Langevin Sandwich Transducer Fabrication

Langevin sandwich transducers were fabricated from two rings of each material and tested under different preload stresses and temperatures to determine the electromechanical response due to varying those conditions. All parts of the transducer underwent a three-step cleaning in Methyl Ethyl Ketone, Ethyl Alcohol, and Acetone (in that order) prior to assembly. After drying for a sufficient amount of time to remove any solvents in the materials, the end masses, insulator rings,
Figure 5.2: Completed fabricated Langevin sandwich transducers using PMNT and Mn:PMNT rings. End masses and insulator rings are labeled.

electrodes, and piezoelectric rings were all axially aligned using a bolt and bonded to each other using a EPON 828-Epicure 1440 epoxy. Washers and nuts were placed on either side of the end masses and tightened to a preload stress of 1000 psi, calculated using Equation 5.14.

\[ V = g_{33} \sigma_{33} t n C \left[ n C + C_{ref} \right] \]  

(5.14)

Where \( g_{33} \) is the piezoelectric voltage coefficient of the rings in Vm/N, \( \sigma_{33} \) is the desired preload stress, \( t \) is the ring thickness, \( n \) is the number of rings, \( C \) is the ring capacitance, and \( C_{ref} \) is the parallel reference capacitor. The transducers were then shorted and placed in an oven at 60 C to cure overnight. A picture of completed PMNT and Mn:PMNT Langevin sandwich transducers is shown in Figure 5.2.
Preload Test Procedure

After relieving the compressive stress bias, the transducers were stressed to 5MPa to begin the experiment. A thermocouple was placed on the transducers and reflective tape was attached to one of the faces of the transducers. They were then placed in a Delta 9039 oven/temperature control chamber. The temperature of the oven was controlled by a Matlab script. The first run was at room temperature (around 23 degrees Celsius). An impedance sweep was performed using the Agilent 4924A impedance analyzer, in the same fashion as discussed above. Then, the piezoelectric coefficient was measured using the laser vibrometry method discussed above. The laser was pointed at the reflective tape to achieve maximum signal to noise ratio. The oven was then increased to 30 degrees Celsius, and the measurements were repeated for each transducer. The thermocouple was used to give an accurate representation of the sample temperature inside the oven. Two more temperatures were tested, at 40 degrees and 50 degrees Celsius. After completion of the last temperature, the oven was turned off and samples were cooled to room temperature. The transducers were then taken out of the oven and the preload stress was increased to 10 MPa. The experiment was run in similar fashion for this preload stress. The preload was increased to a final stress of 25 MPa in 5 MPa intervals, for a total of 5 stress amounts tested. A few key material parameters are discussed in this section. Additional material parameters investigated can be found in Appendix A.

Preload Test Results

Several interesting trends were seen from this experiment. First, the change in resonance frequency as a function of stress is shown in Figure 5.2. These measurements were taken at room temperature (24 degrees Celsius). In this figure, it is clear that the effect of preload stress has a profound difference in shifting the resonance frequency for hard versus soft piezoelectrics. In soft or high response piezoelectrics like PZT5H and PMNT, the resonance frequency changes much more than hard piezoelectrics like PZT4 and PZT8 as the stress amount is increased. The behavior of Mn:PMNT is rather puzzling, from what modeling suggested. For a material with a piezoelectric response in between that of PMNT and PZT4, one would expect the curve to fall between these two materials. One hypothesis could
Figure 5.3: Change in resonance frequency versus preload stress level. Soft piezoelectrics like undoped PMNT and PZT5H show higher change in the resonance frequency as more stress is applied, while hard PZT4 and PZT8 show little to no change as the stress is increased.

be that the PT content in this material is higher than expected, which would lead to the material being closer to the MPB phase transition temperature, leading to polarity instability. As a result, this would allow the material to act similar to a soft piezoelectric and thus have a higher change in resonance frequency as stress is increased. This thermal instability of PMNT and Mn:PMNT will be a frequent topic of discussion during the device evaluation shown in Chapter 6.

Another parameter investigated as a function of temperature and stress was the quality factor, $Q_m$. A 3D plot of the quality factor as a function of temperature and stress is shown in Figure 5.4. A general trend of increasing quality factor as temperature increases is seen for each material investigated. In addition, there appears to be a slight increase in $Q_m$ as stress is increased for a given temperature. This effect is more pronounced in the softer piezoelectrics (PMNT/PZT5H), which agrees with theory. Quality factors for PZT8 and PZT4 are higher over all temperatures and stresses compared to PMNT and PZT5H, which also agrees with theory.
Another important parameter investigated was the electromechanical coupling coefficient, $k_{33}$. A plot of $k_{33}$ versus temperature and stress is shown in Figure 5.5. Mn:PMNT was not plotted here as the thermal instability caused the sample to depole, resulting in an incomplete data set being acquired. The electromechanical coupling coefficient is seen to be very stable as temperature and stress is increased for all PZT materials. PZT5H is seen to have the highest coupling coefficient, or highest bandwidth available, which agrees with theory. The behavior of PMNT is unexpected according to theory, as their $k_{33}$ values should be similar to those of PZT5H. The shift in $k_{33}$ downwards after 40 degrees Celsius in PMNT was common for all preload levels. The same thermal instability which plagued Mn-doped PMNT is hypothesized to be the culprit here as well, as the sample appeared to slightly depolarize at this temperature. The combination of increased stress and temperature also caused the coupling factor to decrease over the duration of the experiment. This behavior is typical for a material showing signs of depolarizing, which was confirmed through the successive impedance plots taken for this material.
with the magnitudes slowly decreasing as temperature and stress were increased. The impedance magnitude for PMNT for various temperatures and stresses is shown in Figure 5.5.

5.4 Summary

The electromechanical behavior of the five piezoelectric materials implemented in the Langevin sandwich transducers were investigated. The complex impedance was taken for each material to extract additional key material properties, including mechanical quality factor, electromechanical coupling factor, and the dielectric permittivity. The piezoelectric coefficient was measured using a non-contact laser vibrometry method. The measured piezoelectric coefficients for these materials agreed with modeling and theory, with hard PZTs (PZT4/8) showing the lowest \( d_{33} \), the soft piezoelectrics (PZT5H/PMNT) showing the highest \( d_{33} \), and Mn:PMNT
Table 5.2: Comparison of modeled $d_{33}$ and $\tan \delta$ values compared to measured results for the five piezoelectric materials investigated.

<table>
<thead>
<tr>
<th>Material</th>
<th>Modeled $d_{33}$ (pC/N)</th>
<th>Measured $d_{33}$ (pC/N)</th>
<th>Modeled $\tan \delta$ (%)</th>
<th>Measured $\tan \delta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PZT4</td>
<td>289</td>
<td>270</td>
<td>0.20</td>
<td>0.14</td>
</tr>
<tr>
<td>PZT8</td>
<td>218</td>
<td>290</td>
<td>0.10</td>
<td>0.18</td>
</tr>
<tr>
<td>PZT5H</td>
<td>593</td>
<td>755</td>
<td>1.30</td>
<td>1.63</td>
</tr>
<tr>
<td>PMNT</td>
<td>855</td>
<td>662</td>
<td>0.11</td>
<td>1.37</td>
</tr>
<tr>
<td>Mn:PMNT</td>
<td>517</td>
<td>410</td>
<td>0.11</td>
<td>1.04</td>
</tr>
</tbody>
</table>

falling in the middle of these two extremes. However, the measured $d_{33}$ and $\tan \delta$ values for PMNT and Mn:PMNT deviated from the modeled results. The $d_{33}$ measured was about 75% of the modeled values and the measured $\tan \delta$ was an order of magnitude increased for PMNT and Mn:PMNT compared to the modeled values. Since texture fraction is directly proportional to piezoelectric response, this could suggest that the textured piezoelectric materials produced had a lower texture fraction than what was modeled. In addition, an increased PT concentration would increase the losses in the system due to increased thermal instability, further suggesting that these measured textured materials had a higher PT concentration, which is indeed what was discovered.

Preload tests were performed on the Langevin sandwich transducers to investigate several material properties as a function of temperature and stress. The resonance frequency was seen to shift the most for soft piezoelectrics, with a change of almost 10% seen at 25 MPa preload level for PMNT. The quality factor and electromechanical coupling factor were investigated as a function of temperature and stress. The quality factor appeared to be directly proportional to both temperature and stress for all materials. The electromechanical coupling coefficient was relatively stable for all temperatures and stresses in PZT, which agreed with theory. The behavior of PMNT and Mn:PMNT was unexpected for these preload tests. Both materials showed thermal instability at 50 degrees Celsius, which was below the expected $T_{R-T}$. The higher amount of PT concentration in both materials would lead to a lower phase transition temperature, causing the sample to de-pole at a lower temperature than expected. This behavior was illustrated in the plot of $k_{33}$. 

55
with the Mn:PMNT sample completely de-poling before data could be collected, and PMNT showing decreasing $k_{33}$ as temperature and stress were increased. The behavior of these textured ceramics is further investigated in Tonpilz transducers in Chapter 6.
Figure 5.6: Impedance magnitude for PMNT, top, and Mn:PMNT, bottom for various temperatures and stresses during preload tests. Notice the resonance peak magnitudes decrease as stress is increased, indicating the material is starting to de-pole.
6.1 Transducer Fabrication

In this chapter, the performance of Tonpilz transducers using textured piezoelectrics and conventional PZT ceramics is investigated. Tonpilz transducers were fabricated and experimentally tested in air and in water in an anechoic test facility and a high pressure test facility. Using the modeling results from GiD-ATILA in Chapter 5, transducers were fabricated using the specified materials and geometries intended to produce optimal performance of the devices. A total of five Tonpilz transducers were fabricated, using PZT4, PZT8, PZT5H, PMNT, and Mn:PMNT.

Rings of PZT were prepared and machined from CTS Corporation (Albuquerque, NM) and rings of PMNT were prepared and machined at ARL-Freeport (Freeport, PA). All rings had the same outer and inner diameter. Thicknesses of the rings were varied using the modeling results used to produce (approximately) the same resonance frequency for each device. The normalized ring thicknesses (to the smallest ring thickness, undoped PMNT) used for each material are shown in Table 6.1. All inactive materials/components (insulator rings, head masses, tail masses, bolts, electrodes) used in the devices were the same, and had the same inner diameter to match the piezoelectric rings.

The rings were first characterized using the Agilent 4294A impedance analyzer to confirm similar capacitances and resonance frequencies were used for each ring in the devices. Small signal material properties for the rings used in each device are shown in Table 6.2. Rings were selected based on similarity of their capacitance and resonance frequencies. The ring data shown here agrees with what was seen in
Table 6.1: Normalized ring thicknesses used for each material in their respective Tonpilz transducer.

<table>
<thead>
<tr>
<th>Material</th>
<th>Ring Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>PZT4</td>
<td>$1.6t_0$</td>
</tr>
<tr>
<td>PZT8</td>
<td>$1.7t_0$</td>
</tr>
<tr>
<td>PZT5H</td>
<td>$1.3t_0$</td>
</tr>
<tr>
<td>PMNT</td>
<td>$t_0$</td>
</tr>
<tr>
<td>Mn:PMNT</td>
<td>$1.1t_0$</td>
</tr>
</tbody>
</table>

modeling and in the measurements made in Chapter 5, with soft piezoelectrics like PZT5H and PMNT showing high capacitance and low mechanical quality factors, while hard piezoelectrics like PZT4 and PZT8 show low $C_p$ and high $Q_m$ values. The Manganese-doped PMNT shows values for these quantities in between these two extremes, also confirming what was seen in modeling.

After the appropriate rings were selected, the transducer fabrication began. First, the head and tail masses were de-greased then grit blasted using Aluminum Oxide grit. Then, all the materials in the transducer underwent a three-step cleaning procedure using Methyl Ethyl Ketone (MEK), Ethyl Alcohol, and Acetone, in that order. Samples were dried for a sufficient amount to remove solvents from the materials. Then, the tail mass, insulator rings, electrodes, and piezoelectric rings were axially aligned using a build bolt and bonded to each other using a EPON 828-Epicure 1440 epoxy mixture. After curing overnight at 60°C, the stacks underwent a preload test similar to the procedure shown in Section 5.3. After using equation 4.8 to determine the voltage required to stress the sample a certain amount, the head mass was bonded to the stack and a final bolt was inserted with a compressive stress bias of 17.2 MPa (2500 psi) applied to each transducer, and cured at 60°C overnight. A K-type thermocouple was then epoxied on using a 5 minute epoxy to monitor temperature of the devices when operating. The completed transducers using PZT8 and PMNT rings are shown in Figure 6.1.

The completed transducers were then analyzed under small signal conditions in air. The complex impedance was first measured for each device. The impedance magnitude and phase for each transducer are shown in Figure 6.2. The impedance magnitude and phase for the PZT transducers agreed well with modeling. However,
Table 6.2: Small signal material properties for rings used in Tonpilz transducers.

<table>
<thead>
<tr>
<th>Ring</th>
<th>$C_p$ (nF)</th>
<th>$f_r$ (kHz)</th>
<th>$Q_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PZT4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.208</td>
<td>159.3</td>
<td>1284</td>
</tr>
<tr>
<td>2</td>
<td>0.220</td>
<td>159.7</td>
<td>1212</td>
</tr>
<tr>
<td>3</td>
<td>0.228</td>
<td>159.2</td>
<td>1133</td>
</tr>
<tr>
<td>4</td>
<td>0.219</td>
<td>160.0</td>
<td>1207</td>
</tr>
<tr>
<td>PZT8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.173</td>
<td>159.3</td>
<td>1460</td>
</tr>
<tr>
<td>2</td>
<td>0.178</td>
<td>158.9</td>
<td>1480</td>
</tr>
<tr>
<td>3</td>
<td>0.182</td>
<td>158.4</td>
<td>1476</td>
</tr>
<tr>
<td>4</td>
<td>0.182</td>
<td>158.5</td>
<td>1443</td>
</tr>
<tr>
<td>PZT5H</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.840</td>
<td>135.5</td>
<td>54.0</td>
</tr>
<tr>
<td>2</td>
<td>0.837</td>
<td>135.4</td>
<td>53.8</td>
</tr>
<tr>
<td>3</td>
<td>0.821</td>
<td>135.1</td>
<td>52.4</td>
</tr>
<tr>
<td>4</td>
<td>0.821</td>
<td>135.3</td>
<td>51.9</td>
</tr>
<tr>
<td>PMNT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.069</td>
<td>140.8</td>
<td>68.1</td>
</tr>
<tr>
<td>2</td>
<td>1.091</td>
<td>141.5</td>
<td>66.6</td>
</tr>
<tr>
<td>3</td>
<td>1.056</td>
<td>141.8</td>
<td>64.7</td>
</tr>
<tr>
<td>4</td>
<td>1.091</td>
<td>141.9</td>
<td>63.9</td>
</tr>
<tr>
<td>Mn:PMNT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.662</td>
<td>150.5</td>
<td>634</td>
</tr>
<tr>
<td>2</td>
<td>0.655</td>
<td>150.1</td>
<td>656</td>
</tr>
<tr>
<td>3</td>
<td>0.655</td>
<td>150.1</td>
<td>635</td>
</tr>
<tr>
<td>4</td>
<td>0.664</td>
<td>150.5</td>
<td>627</td>
</tr>
</tbody>
</table>

The textured PMNT and Mn:PMNT showed significant deviations in the impedance phase spectrum. The phase of these transducers indicate a lower available bandwidth than expected. The higher than expected lead titanate (PT) concentration combined with lower texture fraction in these samples could result in more thermal instability and poorer piezoelectric response. It is seen here that these devices do not have the operating frequency range as expected from modeling due to the measured composition and texture fraction vs the property set reported in literature. This is an important result and one to pay closer attention to as these devices are further evaluated underwater.
Figure 6.1: Completed Tonpilz transducers fabricated from PZT8 (left), and PMNT (right). Kapton tape is used at the tail mass to secure the high and low side wires to each other. Notice the stack length difference, due to different ring thicknesses shown in Table 6.1.

The same small signal properties measured for the piezoelectric rings were measured for these Tonpilz transducers. These properties for each transducer are shown in Table 6.3. These properties confirm the behavior seen in the impedance spectra. The devices fabricated using PZT all correlate well with the ring data, as capacitances, electromechanical coupling coefficients, and quality factors all agree with expectations. These properties for textured PMNT and Mn:PMNT show similar abnormalities seen in the impedance spectrum. The electromechanical coupling coefficients for these devices are much smaller than those for PZT, which is also indicated in the impedance phase plot. In addition, the capacitance values are much higher than expected, indicated in the impedance magnitude plot. The mechanical quality factors and tanδ values also deviate significantly from the modeled response. This would result in more heat generation and temperature rise during operation, a concern when exposing these devices to high drive levels.
Figure 6.2: Impedance magnitude, top, and impedance phase, bottom, for Tonpilz transducers measured in air.
Table 6.3: Small signal material properties measured for Tonpilz transducers. The capacitance was measured at 1kHz, while the rest of the material parameters were measured at resonance.

<table>
<thead>
<tr>
<th></th>
<th>$C_p$ (nF)</th>
<th>$f_0$</th>
<th>$k_{eff}$</th>
<th>$Q_m$</th>
<th>tanδ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PZT4</td>
<td>0.957</td>
<td>1.00</td>
<td>0.55</td>
<td>237</td>
<td>0.17</td>
</tr>
<tr>
<td>PZT8</td>
<td>0.792</td>
<td>0.94</td>
<td>0.59</td>
<td>321</td>
<td>0.19</td>
</tr>
<tr>
<td>PZT5H</td>
<td>3.63</td>
<td>0.99</td>
<td>0.65</td>
<td>44.4</td>
<td>1.35</td>
</tr>
<tr>
<td>PMNT</td>
<td>5.53</td>
<td>1.21</td>
<td>0.35</td>
<td>80.8</td>
<td>1.06</td>
</tr>
<tr>
<td>Mn:PMNT</td>
<td>3.40</td>
<td>1.11</td>
<td>0.38</td>
<td>132</td>
<td>1.20</td>
</tr>
</tbody>
</table>

6.2 Anechoic Test Facility

After these devices were evaluated in air, the transducers were placed in a housing for underwater testing in the anechoic test facility (ATF) at ARL. A rubber neoprene acoustic window was bonded to the head mass of the transducers using a Loctite 410 super glue. This assembly was allowed to set overnight at room temperature and then placed on top of a housing cylinder, shown in Figure 6.3. This housing was then suspended in the anechoic water tank at a depth of 9 ft, and a calibrated hydrophone was placed at the same depth 3 m away from the housing.

The acoustic source level from the transducers was first measured in the tank, from the measured transmitted pressure at the hydrophone. The transducers were driven at a constant 30 dBV at three frequencies, $0.9f_0$, $f_0$, and $1.1f_0$. The source level was measured at a reference of 1 meter away and at 1 $\mu$Pa, the reference pressure in water. The source level was measured as a function of beam angle, with the transducer being rotated a full 360 degrees using a rotating transducer mount and a calibrated goniometer. The response was measured in 0.25 degree step sizes, relative to the acoustic axis of the transducer.

The acoustic source level was also presented as a transmit voltage response. The transducers were driven on axis at 30 dBV over a wide frequency range. Two hydrophones were used to capture the response over entire frequency range accurately, one providing better accuracy for lower frequencies and one providing better accuracy for higher frequencies. A plot of the TVR for PMNT and Mn:PMNT, along with the comparison to the modeled response, is shown in Figure 6.4.
From this figure, it is apparent that the measured TVR near resonance (+/- 0.5\(f_0\)) is close to what the model predicted. The peaks at resonance appear to be sharper in the modeled response compared to the measured response, which agrees with what was seen experimentally from the mechanical quality factor. It is not inherently clear as to why the measured response is higher in PMNT compared to the model at resonance. The deviations at higher frequencies are not concerning as this will be outside the operating frequency range for these devices. This TVR will be directly used as a calibration for the high pressure test response.

### 6.3 High Pressure Test Facility

The same transducer housing seen in Figure 6.3 was placed in the High Pressure Tank (HPT) Facility at ARL. The tank was a large pressurized vessel measuring 168in in working depth and 60in in diameter. A calibrated hydrophone was placed at the bottom of the tank, and the transducer housing was placed 13ft above. Insulated cables were used to transmit the data to a National Instruments DAQ, collect the hydrophone data, and drive the transducer. A 10 M\(\Omega\) resistor was used inside the transducer housing as a leak detector, ensuring that no water entered into
Figure 6.4: TVR plot for PMNT (top) and Mn:PMNT (bottom), along with modeled TVR curves.

The temperature of the water was monitored by a thermometer placed in the water, which maintained at 24+/−1 °C throughout the testing. A schematic of the test setup is shown in Figure 6.5.
Figure 6.5: Schematic of test setup in the HPT facility. Wires seen here connect to preamplifiers, voltage/current monitors, function generators, signal analyzers, etc. to drive and collect data from the device. Image from Sherlock [1].

6.3.1 Linearity and Harmonic Distortion Measurements

The first measurements made to the transducers were linearity and harmonic distortion measurements. By applying a pure tone electrical drive to the transducers, the acoustic output could be measured by the hydrophone. Both the magnitude of the source level and the harmonic distortion of the acoustic output were analyzed. The drive levels used initially for this measurement were low enough to fall in the linear response regime for all the transducers. Later, after the isothermal measurements (seen in Section 6.3.2), the drive levels were increased so that non-linear behavior started to appear for all the transducers and the devices were pushed to failure (or in some cases, was limited to the maximum achievable voltage from the amplifier). Data are shown here for all drive levels used, up to failure or the maximum voltage achieved. The transition from linear to non-linear behavior is vital to understanding the capabilities of each device under high power conditions.

The harmonic distortion is an important quantity produced from this experiment as well. Harmonic distortion is defined as the ratio of the sum of all the powers of
all harmonic components to the fundamental frequency. The input sinusoid is a single tone, but the device will excite overtones which are whole number multiples of the frequency. Higher harmonic distortion will be indicated by more energy in the higher order harmonics of the signal. This can be problematic in high power transducers, as more energy being placed in these overtones reduce the overall efficiency of the device. To accurately determine the energy in these harmonics, the hydrophone captured signals up to $4f_0$.

**Resonance Behavior**

Transducer performance was first evaluated at the resonance frequency of the devices, indicated by the TVR from the low drive level tests in the ATF. The source level measured from the hydrophone is presented as a decibel referenced to 1 μPa, the reference pressure of water. Source levels are plotted as a function of drive level (dB referenced to 1 V/m) for the transducers, presented in Figure 6.6. Source
Figure 6.7: PZT5H transducer after testing in HPT. The device was driven to failure, as indicated by the hole produced in the piezoelectric ring.

levels are seen to increase linearly for all transducers for much of the drive levels. As soon as non-linear behaviors start to take place, the source levels are seen to decrease, indicating the maximum optimal drive level has been achieved for the transducer. The onset of this non-linear behavior can be attributed to a couple possible causes: The harmonic distortion increase caused by higher drive levels reduces energy at the operating frequency due to the rapidly changing slopes of the polarization and strain versus electric field curves, and the resonance frequency shifts with increasing drive (the frequency was kept constant for each device during operation). As the drive levels are increased, the polarization and strain start to reach the nonlinear regime and undergo non-reversible changes in their behavior, such as depolarization, thereby contributing to higher harmonic distortion at higher drive levels. The only device to fail during testing was PZT5H. An image of the PZT5H transducer after removing from the housing shows the failure point on the ceramic ring, shown in Figure 6.7. In all other devices, the experiment was concluded by either reaching the maximum allowable voltage from the amplifier (PZT4 and PZT8), or a decrease seen in the source levels (PMNT and Mn:PMNT).

The source levels seen in Figure 6.6 confirm what was theorized based on
piezoelectric coefficient. The soft piezoelectrics, or high $d_{33}$ materials, result in higher source levels obtained. However, the performance of these devices degrade significantly (or in the case of PZT5H, results in failure) at high drive levels. In the case of hard piezoelectrics such as PZT 4 and PZT8, the device performs better at higher drive levels due to the reduced heat generation and lower losses for these materials. The behavior of Mn:PMNT is worse than expected, as the source levels were predicted to be in between that of PZT5H and PZT8. The linear response of Mn:PMNT is seen to occur at higher drive levels than PZT4 or PZT8, however, at that point, the source level drops significantly, which would be worrisome for high power applications.

The harmonic distortion was also monitored in the current and source levels produced by these transducers. The total harmonic distortion (THD) in the current and the source level as a function of source level is presented in Figures 6.8 and 6.9, respectively. The THD in the current shows some interesting trends. First, all the transducers show relatively similar amounts of distortion at low drive levels. The primary difference in the current THD trends among these five different materials is the ramp up at higher source levels. Hard PZTs appear to have a sudden and rapid
increase in THD, while PZT5H and PMNT have a slower, more gradual increase. What is puzzling is the high THD values occurring at relatively low drive levels in Mn:PMNT. Again, due to the thermal instability of the piezoelectric with PT weight concentrations near the MPB, this could be a cause of this phenomenon seen. If more losses are occurring within the piezoelectric, more energy is being spent exciting the higher order harmonics and less energy is being put into the fundamental frequency output. The source level THD plot shows similar distinctions between hard and soft piezoelectrics. What is more peculiar, in this plot, is the relatively low THD seen at high source levels for PMNT. The low THD levels suggest this material might be better suited for high power operation than Mn:PMNT, even with lower quality factor and higher losses present. However, there is a sudden increase in THD in the source level for PMNT at a particular point, which would be worrisome for high power applications as one would not want to be operating close to that regime. Therefore, when strictly comparing transducer performance on resonance for THD, PZT8 looks to be a superior choice for high power application because of the low THD exhibited over a wide range of drive/source levels.
Figure 6.10: Source level measured as a function of drive level off resonance ($1.5f_0$) for Tonpilz transducers. Grid spacing is 5dB in both the x and y axis.

**Off Resonance Behavior**

The transducers were also evaluated at a frequency above resonance, around $1.5f_0$, to analyze the off resonance behavior of the device. The same measurements took place at this frequency as the on resonance frequency measurements, and the responses were compared to each other. Source levels were first measured as a function of drive level, shown in Figure 6.10.

The source levels seen in this plot show a much clearer distinction in response between the materials. The source levels produced match the order of $d_{33}$ values seen in each material, from smallest to largest (seen in Table 5.1). The levels are also seen to be very linear throughout the experiment, with only minor changes in SL occurring along the way. While the overall levels seen here are lower than at resonance, the source level behavior in these textured piezoelectrics show the potential for use over a wider frequency range compared to conventional PZTs. The discontinuities seen could be a result of the material property changes oc-
curring due to the isothermal measurements, described further in Section 6.3.2. These measurements were first carried out at low drive levels, then the isothermal measurements took place, then the transducers were driven at high levels. These discontinuities in this source level versus drive level plot all occurred after the isothermal measurements took place, indicating a material property shift following these measurements.

The off-resonance current and source level THD were also plotted, shown in Figures 6.11 and 6.12, respectively. These plots show vastly different trends compared to the on resonance behavior. In the current THD, the textured PMNT and Mn:PMNT show much higher levels at higher source levels, and a much more varied and unstable response at high source levels. The thermal instability in both these materials due to the higher PT concentration could again be the cause of this behavior, as higher source/drive levels would lead to a temperature rise in the device and cause more energy to be lost and spread into higher order harmonics. The source level THD off resonance also shows very different behavior off resonance compared to on resonance. First, in PZT4 and PZT8, even at low source levels, the THD starts to rapidly increase and fluctuate widely. The abnormal decrease in source level seen in PZT4 could be a result of the isothermal measurements, as after these measurements took place the source level decreased for the same drive levels measured in the linear regime. This result could mean that these hard PZTs are best suited on resonance at high drive levels. PMNT and Mn:PMNT show similar low THD values in the source level up until very high drive, when the THD of PMNT starts to rise rapidly. The lower SL THD values for textured materials show that they have potential for use over a wider frequency range compared to PZT4 and PZT8, although limited to lower drive levels to maintain a steady response. PZT5H shows the most potential for high power use off resonance, with the lowest current and source level THDs seen across the entire range of source levels tested.

### 6.3.2 Isothermal Behavior

The second experiment carried out in the HPT was to measure the isothermal behavior of the transducers. Due to self-heating, the transducers often operate at elevated temperatures during high power operation. Thus, to better characterize performance of the device under these circumstances, transducer behavior at an
Figure 6.11: Current total harmonic distortion as a function of source level off resonance.

Figure 6.12: Source level total harmonic distortion as a function of source level off resonance.
elevated temperature was monitored. For these experiments, a temperature of 50+/-1 °C was chosen at which to monitor the transducers, chosen as a generic temperature which Tonpilz transducers have previously shown to operate at.

The experimental setup was similar to that described in Section 6.3.1. The thermocouple mounted on the sample was used to monitor the temperature of the sample and ensure operation took place at the proper temperature. To self-heat the transducers to 50 °C, a 1ms pulse at the resonance frequency of the device (denoted by the maximum current) was transmitted to the device, and the drive level was adjusted so that the heat generation of all the loss mechanisms present in the transducer reached an equilibrium with the heat flow out of the transducer, such that the temperature remained at 50+/-1 °C. The frequency was adjusted as needed when driving to higher levels, as it would often shift when driving to higher levels. Once equilibrium was reached, the transducers were driven for an additional 5 minutes at this level to ensure steady state response was being measured. This procedure was repeated for various amounts of duty cycles, or the amount of time an AC pulse is applied over a given time period. For example, a 50% duty cycle would refer to an AC pulse of 0.5ms "on" and 0.5ms "off". Thus, for a lower duty cycle, the transducers were subjected to a smaller and smaller amount of time being driven by the pulse, requiring higher drive levels needed to self-heat the transducers to the specified temperature. A plot of the drive voltage required to maintain the 50 °C isotherm at resonance as a function of duty cycle for each transducer is shown in Figure 6.13.

From Figure 6.15, it is apparent that hard piezoelectrics require higher drive voltages to maintain the elevated temperature during operation, and vice versa for soft piezoelectrics. This agrees with theory, as there will be more heat generation and losses occurring in a higher response material like PMNT and PZT5H. The behavior of Mn:PMNT is promising in terms of a high power use potential material. The drive voltages required to self heat the material are higher than PZT4 and PZT8 at high duty cycles, until the levels dip below those of PZT4 and PZT8 at very low duty cycle levels. This performance drop at very low duty cycles could also be due to the thermal instability, as operating at elevated temperatures close to the $T_{R-T}$ will push the material closer to depoling, permanently degrading the performance and increasing the losses. If the PT weight fraction was closer to 0.28, as modeled, this material could have performance even better than PZT4 or PZT8.
Figure 6.13: Electric field required to maintain 50°C isotherm at resonance as a function of duty cycle. Hard piezoelectrics require higher electric fields to maintain an elevated operating temperature.

Additionally, the acoustic source level was measured as a function of duty cycle under these isothermal conditions, shown in Figure 6.14. The same hyperbolic shape of the curves are seen in this plot as those seen in Figure 6.13, as the drive levels will be higher at lower duty cycles, leading to greater acoustic output. Several interesting trends are seen from this plot. First, the source levels in PZT4 and PZT8 are much higher at all duty cycles compared to the other transducers tested. PZT4 especially shows superior performance at all duty cycles, making it a suitable choice for high power operation. The performance of Mn:PMNT is again unexpected, especially when comparing to the drive levels required for isothermal operation. The temperature instability would be a clear culprit for this behavior, as any depoling would significantly reduce the piezoelectric response, thus decreasing the measured source level from the device. These textured materials still show promise for operation under high power conditions, but the PT composition in the materials must be addressed in order to unlock the true potential for these
Figure 6.14: Acoustic source level as a function of duty cycle under isothermal operating conditions at resonance.

piezoelectric ceramics.

6.4 Summary

Five tonpilz transducers were fabricated using rings of different materials: PZT4, PZT8, PZT5H, PMNT, and Mn:PMNT. These transducers were then tested underwater using an Anechoic Test Facility (ATF) and a High Pressure Test (HPT) facility at ARL. Linearity and harmonic distortion measurements were made to monitor acoustic source level and harmonic distortion as a function of drive level both on and off resonance \((f_0\) and \(1.5f_0\)). The source levels seen both on and off resonance corresponded fairly well with the overall piezoelectric coefficients of each material. Nonlinear behavior was much more dramatic and apparent for textured PMNT and Mn:PMNT, with sharp drops in the source levels seen at high drive levels. This behavior was further confirmed from the harmonic distortion
measurements, both in the current and the source level. The THD increased significantly at higher drive levels for PMNT and Mn:PMNT, indicating more energy was being put into the overtones and less energy being input into the fundamental frequency. The thermal instability of these textured materials could be a cause of these increased losses, as the mole fraction of PT in the PMN-PT materials were higher than modeled (0.3 as opposed to 0.28) and resulted in a composition closer to the MPB. In addition, combined with a lower texture fraction in these textured ceramics, the source levels achieved were lower than expected.

The isothermal behavior of the transducers was also analyzed as a function of duty cycle, or the duration the transducers underwent an AC pulse. A temperature of 50+/-1°C was maintained for each transducer. Higher drive levels were required for lower duty cycles, and was prevalent in both the electric field and acoustic source levels measured. The thermal instability of PMNT and Mn:PMNT was again prevalent during these measurements, as lower than expected source levels were achieved for both materials over all duty cycles measured. The increased losses and heat generation could push the materials to depole, as operation near the $T_{R-T}$ would result in significant decreases in piezoelectric response due to this non-reversible change to the polarization. From these measurements, it is more apparent that PZT4 or PZT8 are better suited for high power operation from these materials currently constructed. Changes to the PT composition and the texture fraction must be made to PMNT and Mn:PMNT in order to show better electromechanical performance for high power operating conditions.
Chapter 7  
Conclusions and Future Work

7.1 Device Performance

The performance of Langevin sandwich and Tonpilz transducers was analyzed for PZT4, PZT8, PZT5H, textured <001>_c [Pb(Mg_{1/3}Nb_{2/3})O_3] (PMNT) and 2 at% doped PMN-PT (Mn:PMNT). Langevin sandwich transducers were characterized through a series of preload tests in air, varying the stress and temperature and evaluating the electromechanical behavior. Tonpilz transducers were characterized in air and in water, measuring small signal parameters in air, linearity and harmonic distortion in water, and analyzing the isothermal behavior in water.

Transducers were first modeled in the GiD-ATILA finite element software package prior to fabricating the devices. Using material properties found in literature, the performance of Langevin sandwich and Tonpilz transducers was modeled in air and under a simulated water load. Modeled results showed a high quality factor and bandwidth for PMNT and Mn:PMNT compared to PZT, through the impedance magnitude and phase plots. The transmit voltage response (TVR) was modeled for each transducer as well, with both textured ceramics showing similar acoustic output to the PZTs studied.

Transducers were fabricated from the design considerations made through modeling. Ring thickness varied for each transducer so that similar resonance frequencies were obtained for each device. Small signal measurements made in air of the devices indicated several deviations from the results seen from modeling for PMNT and Mn:PMNT. First, the impedance magnitudes of both materials was significantly reduced from the model, indicating poorer piezoelectric response
(d_{33}). In addition, the impedance phase showed lower bandwidth available (smaller frequency range where phase was \(-45°<\phi<+45°\)) compared to the modeled results. The quality factor and subsequent tanδ values deviated by about 15% from the modeled results as well.

In-water testing of the transducers further illustrated these deviations seen from the modeling results for PMNT and Mn:PMNT. Linearity and harmonic distortion measurements showed reduced source levels and increased harmonic distortion than what was expected for these textured ceramics. The source levels produced for PMNT was on par with PZT5H and the source level for Mn:PMNT was on par with PZT4, and PZT8, both of which was expected to exceed based on the material properties. This behavior was seen both on and off resonance, with no clear bandwidth increase for the textured ceramics compared to PZT. Finally, isothermal measurements showed significant heat generation in the textured PMNT and Mn:PMNT transducers, indicated by the lower than expected source levels produced over the range of duty cycles tested.

The poor performance of these textured ceramics could be pinpointed on a few key factors. First, the mole fraction of PT in PMNT and Mn:PMNT was 0.302, closer to the MPB and not what was measured from the results of Poterala [2] or the modeled results (0.28). Recalling from Chapter 1, a mole fraction closer to the MPB forces domain reconfiguration into the poorer piezoelectric performing rhombohedral phase at a lower temperature $T_{R-T}$. As a result, the effective temperature range of these devices would decrease and performance would degrade in a non-recoverable fashion. Both the piezoelectric coefficient and electromechanical coupling coefficient ($k_{33}$) are much lower in the rhombohedral phase, and this behavior was noticed after curing the transducers at just 60°C. This temperature was still below the $T_{R-T}$, but it has been observed that in a case with PMNT, the temperature of the device is limited to 50°C even with a $T_{R-T}=95°C$, due to the large material property changes as a function of temperature [1,27]. As a result, this lower phase transition temperature in the PMNT and Mn:PMNT would lower the optimal temperature to below what was performed in these experiments. Any self heating that would occur for these devices would degrade the electromechanical behavior, thereby producing unsatisfactory results. In addition, the texture fraction of PMNT and Mn:PMNT were measured to be lower than the material results from Poterala and the modeled results. A lower texture fraction would result in lower piezoelectric and
electromechanical coefficients, pushing the response closer to random polycrystalline ceramics. For these reasons, the mole fraction of PT and texture fraction in these materials must be addressed in order for future experiments to showcase the true potential of the use of textured ceramics in high power SONAR projectors.

The test procedure used in this work could be directly used to compare and contrast the electromechanical performance of different piezoelectric materials. The procedure of fabricating and evaluating these SONAR projectors was carried out in a streamlined and efficient manner, allowing for the feedback of the material performance to be relayed back to the material developers in a rapid fashion. As a result, utilizing this same test procedure could allow for evaluation of many different compositions of textured materials, allowing for a quick implementation of these desired parameters in order to optimize the material properties to fit any specific application.

7.2 Future Work

The conclusions reached in this work indicate some clear next steps and future work that need to be addressed before unlocking the true potential of textured PMNT ceramics. First, it will be necessary to manufacture piezoelectric rings for PMNT and Mn:PMNT with weight fractions of PT equal to 0.28. Second, it would also be necessary for these rings to have texture fractions or Lotgering factors as close to the values reported in Poterala’s work [2]. This would result in a clear comparison between the modeled transducers and the fabricated transducers. Finally, it would be recommended to manufacture rings with deviations in measured $C_p$ and $f_r$ no more than 2%. This would ensure transducers built have stable resonance behavior and optimal performance over a wider frequency range, and all devices built would show similar performance.

Additional textured materials have recently been produced which show viability for evaluating the performance in a SONAR projector. An additional modification has been introduced recently by adding an additional component to the binary PMN-PT system, known as a ternary component. A ternary system is used to assuage the low phase stability of PMN-PT, as a result of the low phase transition temperature and low coercive field [28,29]. The ternary component is thus selected such that it is thermally stable and has a high coercive field [1]. $\text{Pb(In}_{1/2}\text{Nb}_{1/2}\text{O}_3$
has been incorporated as the ternary component in previous studies, giving rise to \((1-x-y)\text{Pb(In}_{1/2}\text{Nb}_{1/2})O_3-x\text{Pb(Mg}_{1/3}\text{Nb}_{2/3})O_3-y\text{PbTiO}_3\), or PIN-PMN-PT or PIMNT \[29,30\]. An additional modification can be made to the growth template in the binary system. For this work, a lead titanate (PT) seed was used to grow the textured ceramic. Additional materials, such as strontium titanate (ST) and barium titanate (BT) templates can be used to alter the electromechanical properties of the ceramic. It would be worthwhile to study the behavior of these materials in SONAR projectors and compare their performance to PMNT with a PT template.

Transducer fatigue behavior was not investigated for these devices. Monitoring the performance of the device at a typical operating drive level for an extended amount of time would generate noteworthy results. The voltage, current, impedance phase, and displacement could be monitored as a function of cycles, and could be performed in air or in a simulated water load. These results would be instrumental in understanding the behavior of the transducers over time and the longevity of the devices.
Appendix
Preload Versus Temperature Plots

Introduction

Additional plots of parameters tested as a function of temperature and preload stress for sandwich transducers, as described in Section 5.3, are shown here.

Figure 1: Capacitance as a function of temperature and preload stress.
Figure 2: Piezoelectric coefficient $d_{33}$ as a function of temperature and preload stress.

Figure 3: Loss factor $\tan \delta$ as a function of temperature and preload stress.
Bibliography


URL https://www.google.com/patents/US7554343


