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14. ABSTRACT
To carry out this effort, a team consisting of ISEN, NUWC Newport Division, and the Applied Research Laboratory (ARL) at the Pennsylvania State University has been assembled. ISEN will be responsible for generating the enhancements to the ATILA code. NUWC Newport will develop and execute the models for verification and validation and ARL will measure and provide experimental data to construct the constitutive laws and for model validation. This report addresses the measurement results obtained in experiments at ARL to determine the effects of the dynamic and static stress, and temperature on material properties and device behavior and provide feedback and validation of the new modeling capabilities.

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Final Report

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Transducer Analysis and ATILA++ Model Development

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LONG-TERM GOALS

Increased power and duty cycle demands on SONAR transducers push these devices closer to their stress and thermal limits. Work has been done to understand the stress and temperature dependent properties of the active materials involved. Predicting performance of these devices under demanding environments is also difficult due to changes in material properties. New single crystal piezoelectrics that are being explored for compact, high power, and broadband SONAR transducers have larger degrees of non-linearity in both stress and temperature than typical ceramics, such as PZT-8. This effort addresses the need to predict the performance of these devices by considering the highly non-linear behavior with a fully non-linear solution procedure in the ATILA finite element software package. This will greatly enhance the state-of-the-art in transducer performance prediction and provide a tool for more accurately predicting the behavior of single crystal piezoelectric devices.

OBJECTIVES

To carry out this effort, a team consisting of ISEN, NUWC Divison Newport, and the Applied Research Laboratory (ARL) at the Pennsylvania State University has been assembled. ISEN will be responsible for generating the enhancements to the ATILA code. NUWC Newport will develop and execute the models for verification and validation and ARL will measure and provide experimental data to construct the constitutive laws and for model validation. This report addresses the measurement results obtained in experiments at the Applied Research Laboratory to determine the effects of the dynamic and static stress, and temperature on material properties and device behavior and provide feedback and validation of the new modeling capabilities.

APPROACH

Utilize equipment at ARL facilities purchased under ONR DURIP (Contract N00014-09-1-0830) to measure the dynamic stress/strain behavior relative to the applied electric field and the effects of static preload or compressive stress or temperature (alone and in combination) in order to characterize the non-linear material and device parameters and performance, and provide measured device performance for comparison to modeled outputs.

WORK COMPLETED

Dynamic stress and strain measurements were made on unconstrained 33-mode bar samples for binary, ternary, acceptor-doped, and domain-engineered single crystals and high-Q_M ceramics. National Instruments NI-DAQ PXI-1033 hardware was used for signal generation and measurement. Sample displacements were measured with a Polytec OFV-525 single point laser Doppler vibrometer. Dielectric constant and loss versus field measurements were performed using an IET 1621 Precision Capacitance Measurement System, a manual balancing bridge with up to 10^{-18}F resolution.

Preload and thermal effects were determined using symmetrically loaded "dumbbell" transducers made with PZT 8 ceramics and PMNT, PIMNT and Mn doped PIMNT single crystals under increasing preloads and increasing ambient temperatures and both preload and temperature changes simultaneously (Figure 1). The Polytec equipment was used with the laser focused through the "laser-transparent" glass door of the envrionmental chamber to obtain the *effective* d_{33} of the entire device by measuring displacement at the face of the endmass.

Figure 1 "Dumbbell" transducers shown as-modeled and fabricated

Stress-Strain Relationships An apparatus and control system have been developed for measuring the stress/strain relationship of samples under compressive preload and high electric fields (Figure 2).

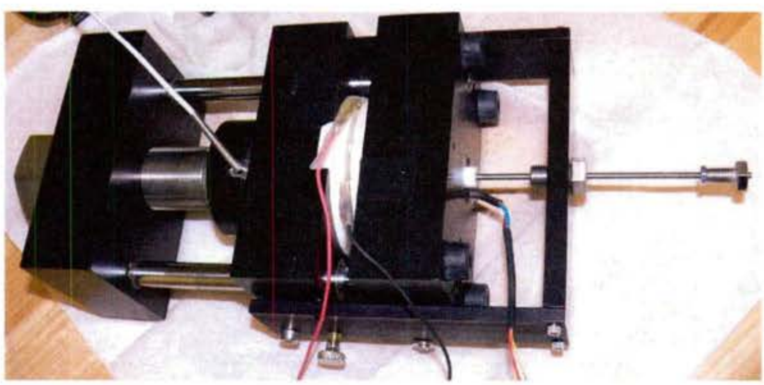


Figure 2 Strain/Field measurement apparatus

Thermal and frequency dependence of properties of passive materials A technique was developed to adapt Resonant Ultrasound Spectroscopy (RUS) to the evaluation of elastic properties of low Q passive materials such as polyurethanes and epoxies, which are very difficult to measure by other means. RUS provides information on both c_{11} and c_{44} elastic coefficients, and can therefore yield both Young's modulus and Poisson's ratio for the material. Samples made in different sizes yield the frequency dependence. An environmental chamber is used to characterize the temperature dependence of properties.

Unlike other methods that yield only Young's Modulus and loss, RUS provides data on the full set of elastic constants, yielding c_{11}, c_{44}, Young's Modulus, Poisson's Ratio and loss.

RESULTS

A. Crystal Dumbbell Static Preload and Thermal Effects

Dumbbell preload/static compressive stress results are shown in Figure 3 and Figure 4 for PZT8 ceramic, binary ternary, domain-engineered, and acceptor doped ternary single crystals. The calibration voltages and effective d33 vs preload are shown in Figure 3. The PMNT crystal version shows an apparent phase change at high static stress levels observable in the drop in effective d33.

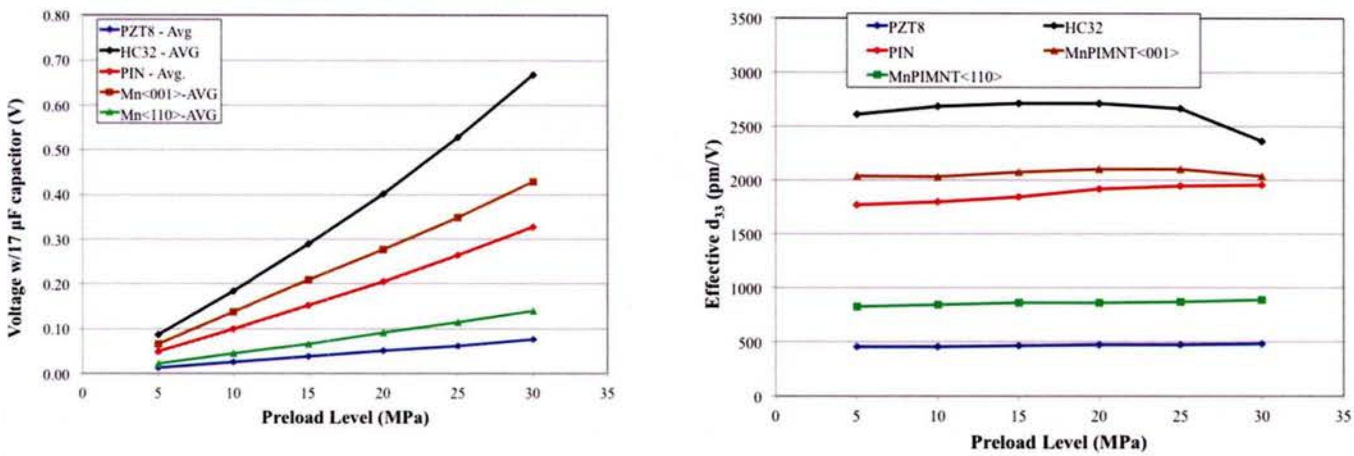


Figure 3 Calibration voltage and effective d33 vs. preload level – "Dumbbell" sample

Figure 4 shows the percent change in resonance frequency and dielectric constant with increasing static preload. All of the materials became stiffer with increasing static stress. The free dielectric constants for soft crystals show significant change with preload which affects device impedance and amplifier considerations; modified crystals have smaller percent change.

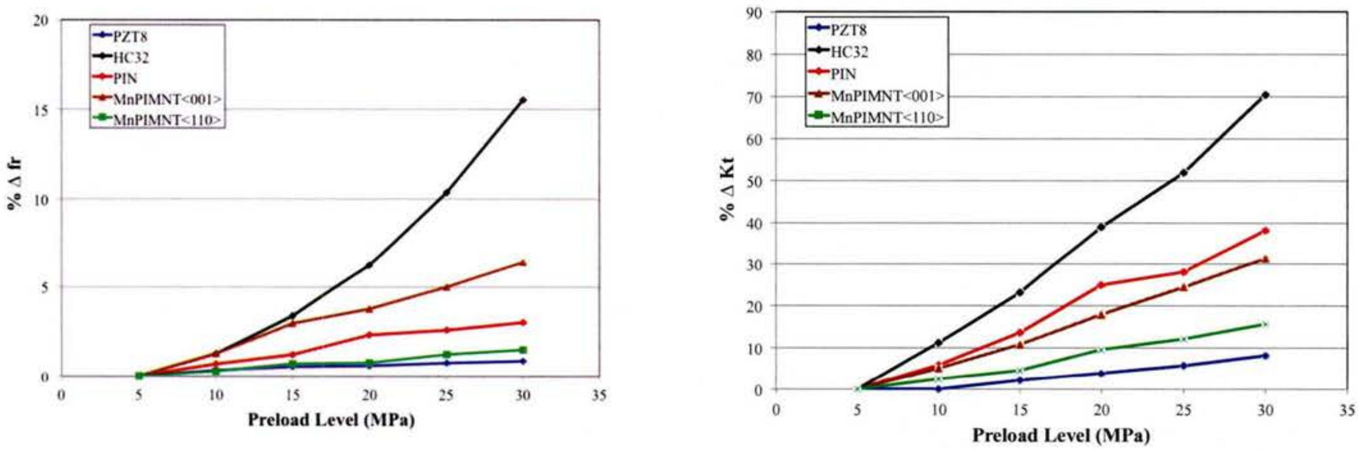


Figure 4 Change in resonance frequency and dielectric constant with increasing static preload – "Dumbbell" samples

The graphs in Figure 5 through Figure 7 illustrate the combined effects of prelaod stress and elevated ambient temperature. The PMNT crystal dumbbell shows increasing magnitude of effects vs. temperature as the static preload is increased. The percent changes in properties of the other compositions were modest in comparison.

Averaged values of small signal properties for specific samples of single crystals with multiple modifications are shown in Table 1.

Table 1 Small Signal Properties

Material/Category	Measured at 1 kHz			Measured at f_0		
	$K_{33}^T(\varepsilon_0)$	$\tan\delta$ (%)	d_{33}(pm/V)	Y_r (GPa)	Q_M	k_{33}
Conventional Ceramics						
PZT-4	1627	0.3	340	67	373	0.73
PZT-8	1155	0.23	243	77	932	0.67
Single Crystal						
PMNT	5622	0.24	1593	21.5	240	0.91
PIMNT	4370	0.13	1465	22.5	212	0.92
Mn:PIMNT <001>	3675	0.17		20.9	750	0.9
Mn:PIMNT <110>	3145	0.19	880	32	955	0.89
High Q_M Ceramics						
APC-840	1403	0.06	367	65	352	0.68
APC-841	1140	0.38	291	73	710	0.65
APC-880	1150	0.06	300	70	570	0.66
NEC TOKIN N61	1344	0.1	310	69	242	0.58
SUNNYTEC S42	1317	0.1	324	72	340	0.64

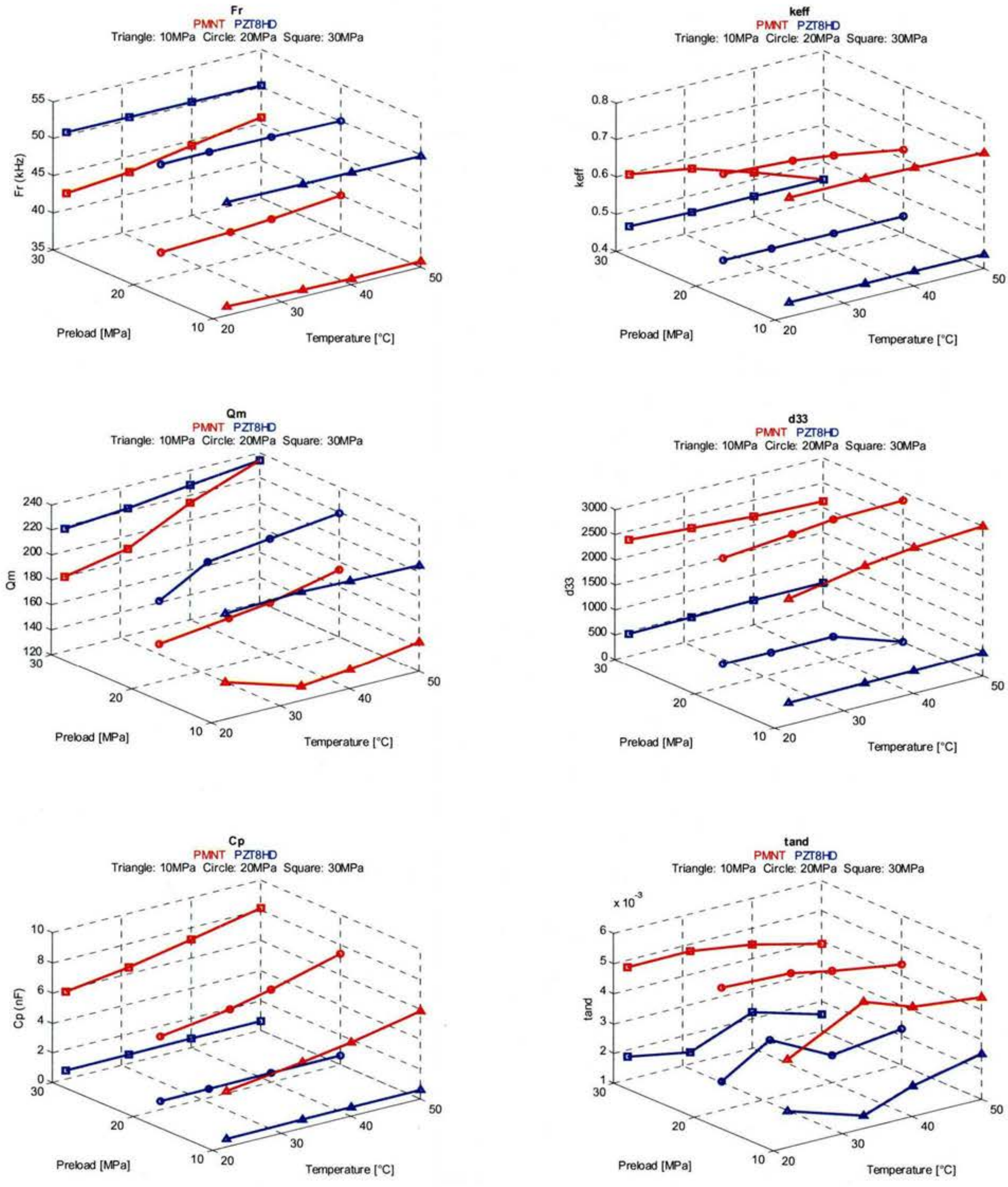


Figure 5 Combined effects of preload and temperature on dumbbells made with PZT8 ceramic and PMNT single crystal

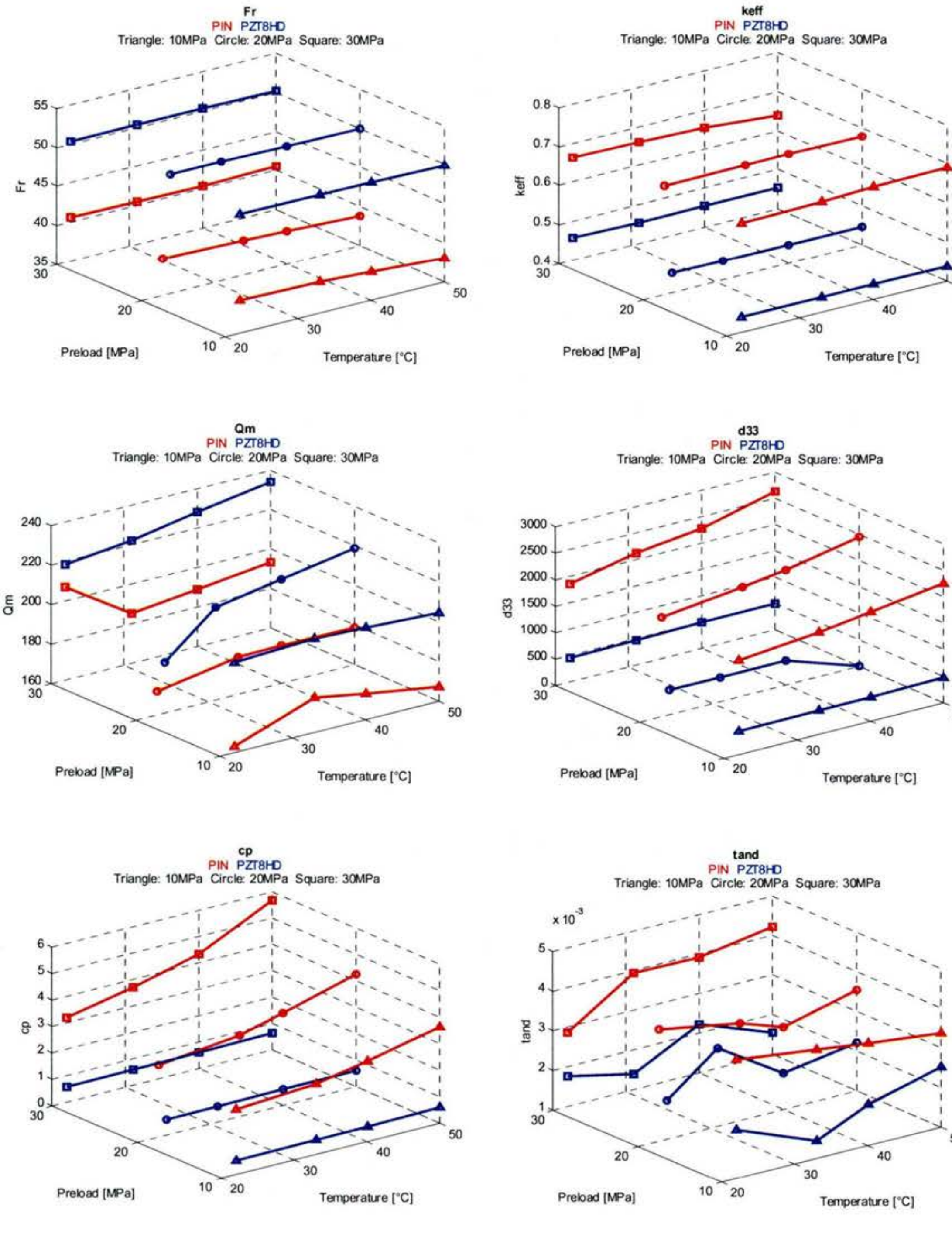


Figure 6 Combined effects of preload and temperature on dumbbells made with PZT8 ceramic and PIN single crystal

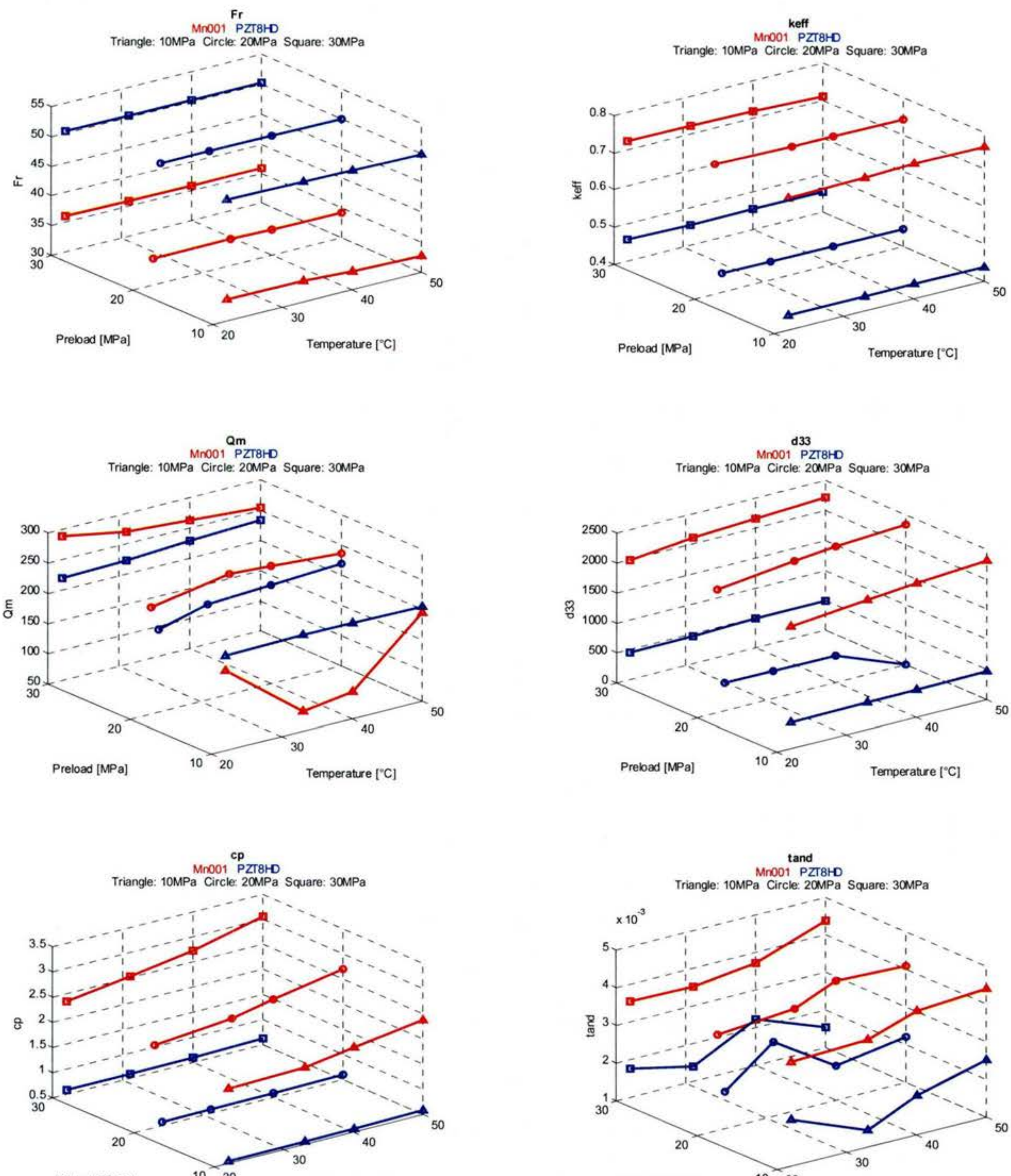


Figure 7 Combined effects of preload and temperature on dumbbells made with PZT8 ceramic and Mn001 single crystal

B. High Qm Ceramic Materials

Dielectric constant and loss versus field measurements were performed using an IET 1621 Precision Capacitance Measurement System, a manual balancing bridge with up to 10^{-18}F resolution. Results for various High Qm at 1 kHz and room temperature can be seen in Figure 8 Dielectric constant and dissipation for five high-QM ceramic materials. The NEC Tokin N61 material shows a greater sensitivity to increased field than the other materials listed.

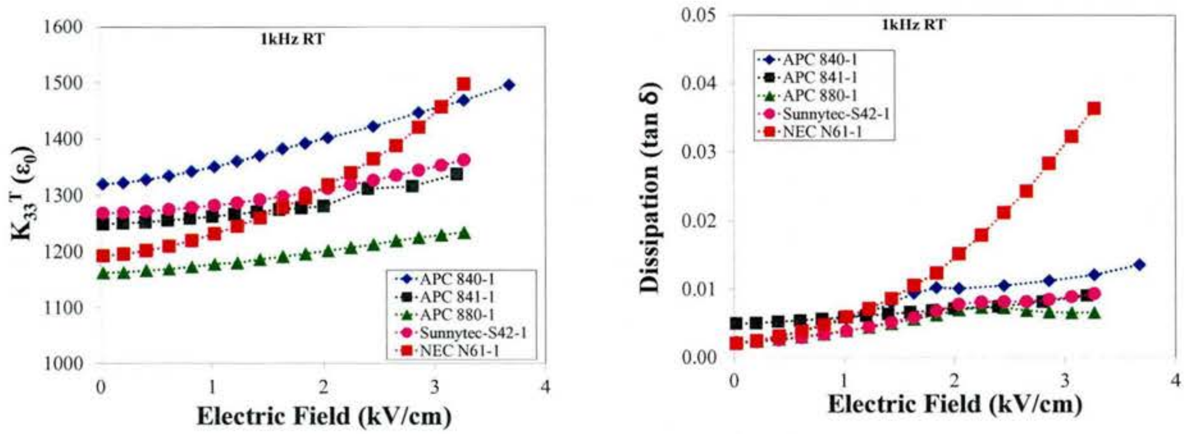


Figure 8 Dielectric constant and dissipation for five high-QM ceramic materials

Dynamic stress and strain measurements results are shown graphically in Figure 9 and Figure 10 with a summary of each result in the figure caption.

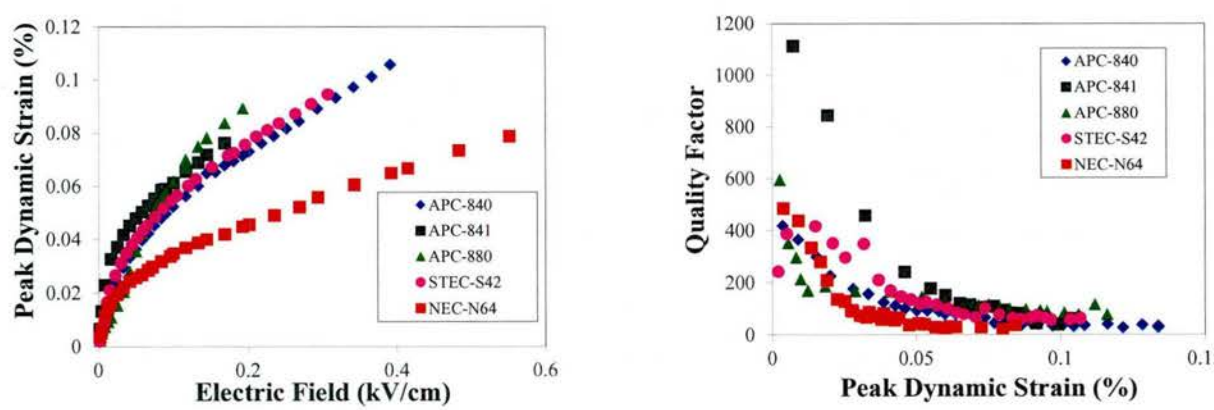
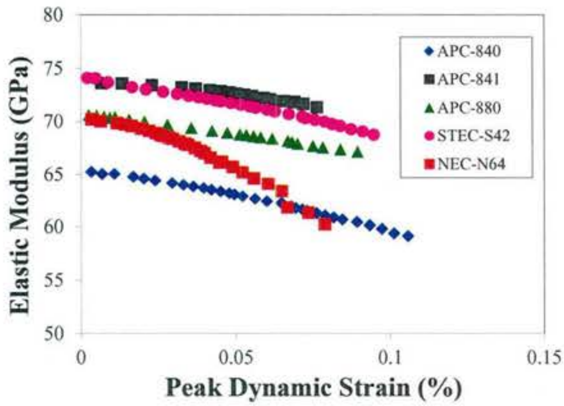


Figure 9 Peak dynamic strain vs. field and mechanical quality factor for high-QM ceramic materials

- **NEC-N64 is in the middle of the group at low field, but its peak dynamic strain rapidly drops off as the field is increased**



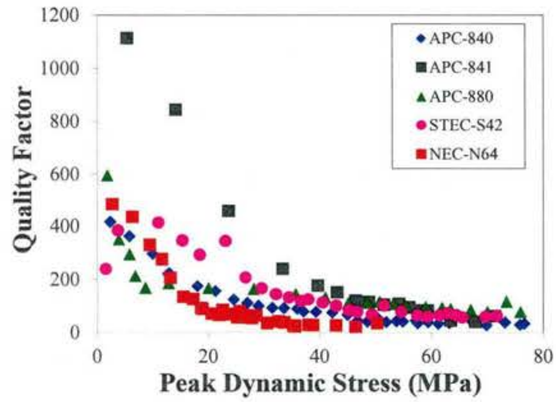


Figure 10 Elastic modulus vs. strain and mechanical quality factor vs. stress for high-QM ceramic materials

- **The modulus of the NEC-N64 sample can be seen to decrease more rapidly than the other materials with increasing field.**

C. Strain versus Field Measurements under Static Preload

An apparatus and software control system have been fabricated and developed for evaluating the behavior of materials under high electric fields while being subjected to compressive loading forces. The apparatus (shown in Figure 11) consists of two parallel platens with a series load cell and a fine-thread hex-head stud to measure and apply the compressive force (stress), and a Linear Variable Displacement Transducer (LVDT) coupled with a lock-in amplifier to measure displacement (strain). A NIDAQ System generates a drive signal. The resulting displacement and voltage are measured simultaneously with the data acquisition system. The system also monitors the charge across a reference capacitor to measure polarization as a function of applied field.

Quasi-static strain /field hysteresis loops can be generated for materials under varying preload. Pre-loads of up 1000 lbs. can be applied with the maximum pressure dependent on the sample area. In addition, polarization versus field data can also be generated with this equipment. Example results for PIMNT single crystal are shown in Figure 12 and Figure 13.

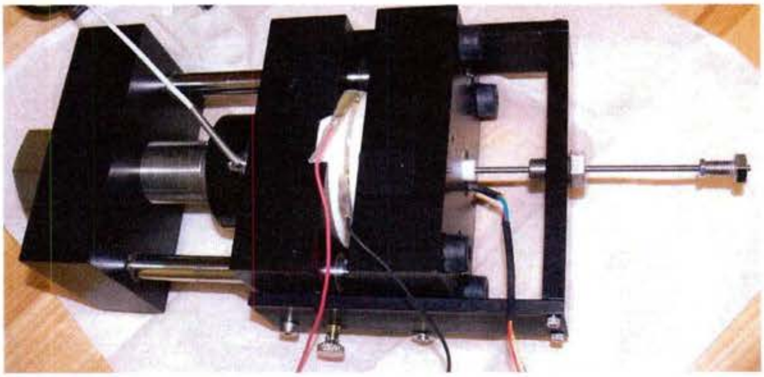


Figure 11 Strain/Field measurement apparatus

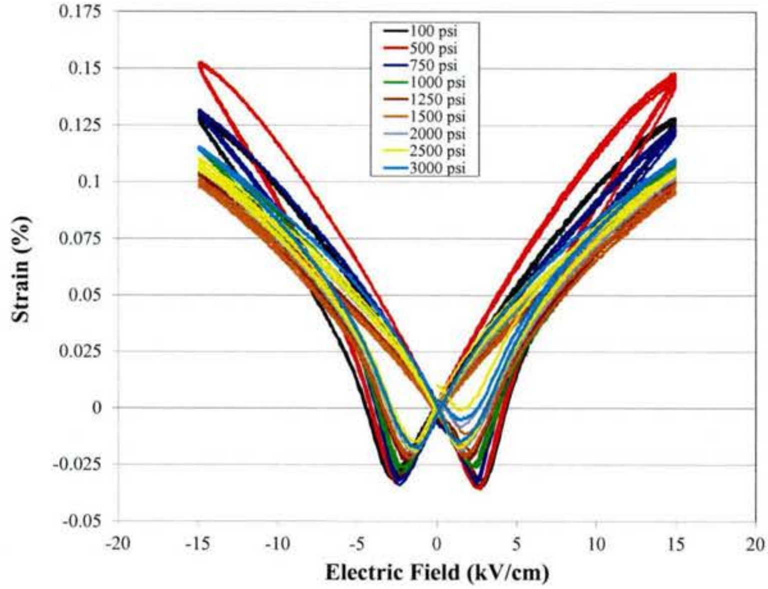


Figure 12 Strain vs. Field plot for PIMNT crystal

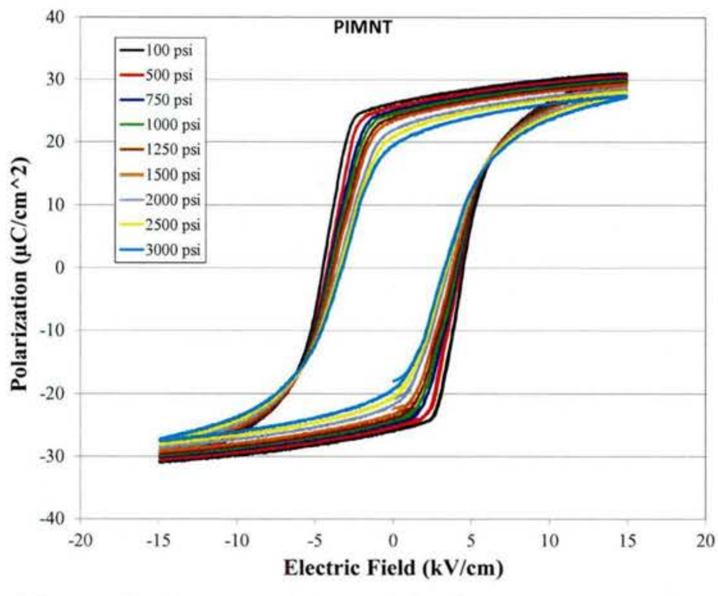


Figure 13 Polarization vs. Field for PIMNT crystal

D. Thermal and frequency dependence of properties of passive materials RUS involves vibrating the sample with a driving transducer on one side or corner and recording the vibration displacements on the opposite surface of the sample with a second receiving transducer. A software program is used to curve-fit the resonance peaks by varying the elastic constants with least-squares difference fitting of the data to adjust the input properties and repeat the analysis in a loop until the desired quality of fit is achieved.

The technique has, in the past, been successfully used to determine properties of metals and crystal materials. In the present study, techniques were adapted to permit determination of properties of viscoelastic materials that are very low Qm. The challenge then is to resolve resonant frequencies of known vibration modes.

Prof. Jay Maynard, Distinguished Professor of Physics at PSU, and one of the pioneers of the RUS technique assisted with the evaluation of samples of Conathane EN9 polyurethane. Loading the samples with specific customized secondary masses effectively separated the modes in the models. Two opposing round glass plate mirrors were applied to the samples (Figure 14). These mirrors provided mass loading, while also allowing for measurement of the displacements of the polyurethane faces. The LASER passed through the glass and reflected off of the mirrored surface against the urethane surface; the LDV could analyze the motions of the urethane surface directly. The grit-blasting the mirrors provided a roughened surface for urethane bonding as well as scattering surfaces for the LASER beam. (Smooth mirrors reflected the LASER beam too directly, with little or no scattered return signal, and their smoothness led to occasional de-bonding of the urethane.)

To impose the vibration, small neodymium magnets were bonded to the samples. Varnished copper transformer wire was wound onto balsa cores to produce AC induction drivers. When situated near to the magnets these drive/pick-up coils provided non-contact vibration driving and sensing. Environmental vibrations were damped by mounting the transducers in lead bricks and suspending the samples by thin balsa strips or fine wires. The sample hanger was suspended from an NRC Newport Corp. motorized positioner for final fine tuning of the spacings between the magnets and the coils Figure 15).

Figure 14 "Mirror Sandwich" of 4-inch mirrored glass plates and urethane

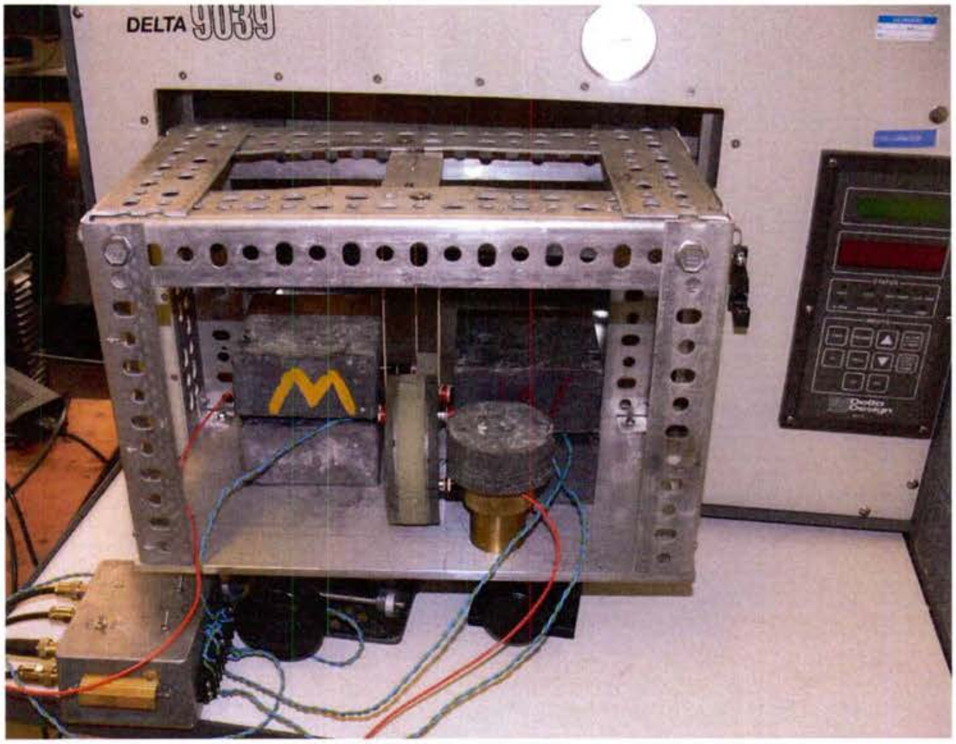


Figure 15 "Sandwich" suspended in the testing frame prior to insertion in the environmental chamber

Examples of modeled mode shapes are shown in Figure 16.

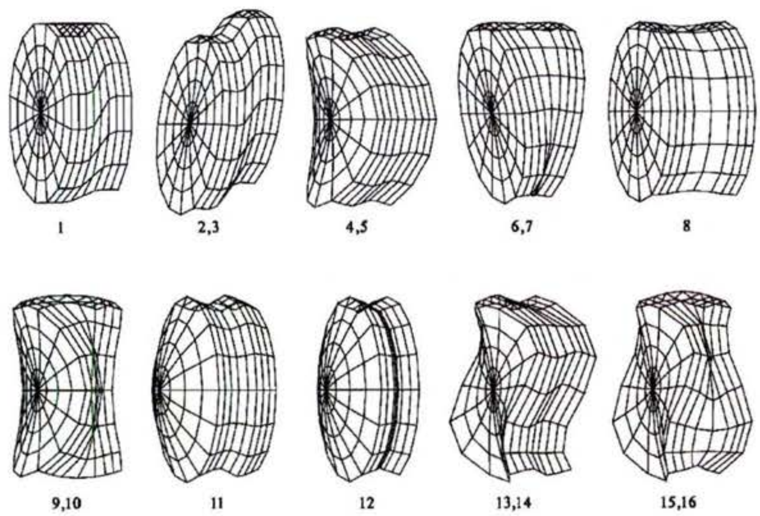


Figure 16 FEA images of displacement mode shapes

Magnets, drivers, and pickups were attached at different nodal points on the samples to preferentially drive or inhibit specific resonances. Examples of some of the actual mode motions measured using the scanning LDV are shown in Figure 17.

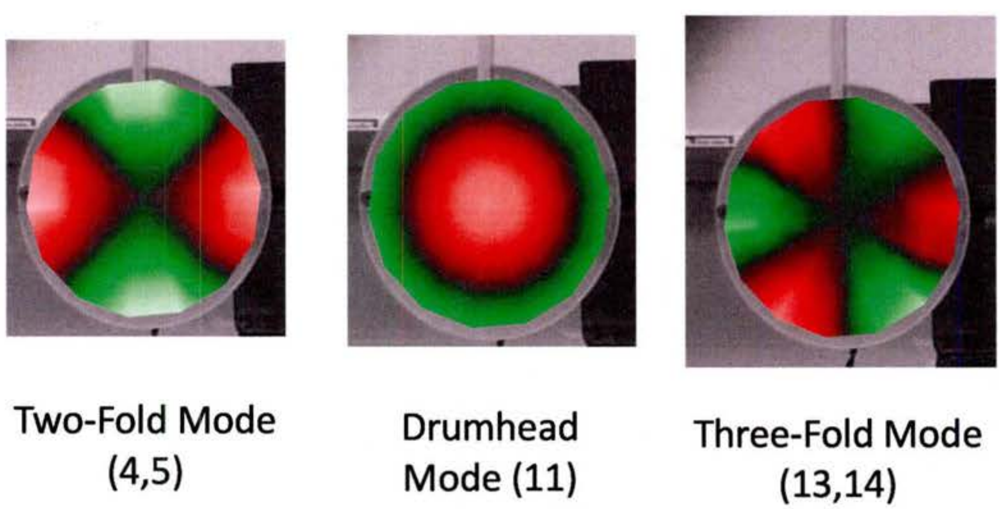


Figure 17 LASER Doppler Vibrometer images of displacements on inner surface of mirrors

Four-inch and 1-inch diameter samples were tested from -10°C to 70°C. Data from these measurements are being processed and will be presented in a refereed publication.

IMPACT/APPLICATIONS

This work is helping to enable the expansion of the functionality of the ATILA ++ finite element software to include considertion of non-linear material properties and device performance. Results from this study where utilized by ISEN as non-linear material property inputs, and to test the outputs of the software relative to the measured device data, and trouble-shoot the code.

Piezoelectric single crystals of Generation 1 - PMNT composition show significantly non-linear material property behavior relative to temperature, dynamisc strain, and preload. The later generation modified crystal are more stable. The High Qm ceramic materials have also been shown to have non-linear behaviors that vary substanitally with each vendors comoposition and should be characterized and modeled for any material being planned for use in a device or environment where these factors are of concern.

PUBLICATIONS

Douglas Markley, Jay Maynard, Richard Meyer, "Elastic properties of Polyurethane measured by modified resonance ultrasound spectroscopy method," In Preparation.