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Subject: **Final Report for Failure Analysis of High-Power Piezoelectric Transducers**
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GOALS

Low-frequency projectors for underwater sound are often driven near stress limits because of the conflicting requirements of high power and small size. One common failure mode is ceramic cracking and the associated arcing between high-voltage electrodes. While there are a number of manufacturing defects that can cause premature electric breakdown or premature cracking, a fundamental problem results from the coupling between the electric field and stress in a piezoelectric material. For a transducer operated near resonance, there will be “hot spots” or regions of locally intense stress and electric field that precipitate premature failure. The long-term goals of this project are: (1) to develop a capability to describe such failure modes, (2) to understand the factors that precede failure, and (3) to develop guidelines for failure mitigation.

EXECUTIVE SUMMARY

In analyzing failure of high-power transducers it is essential to distinguish between fundamental limits and limits introduced by design departures from ideal conditions. The results of an examination of piezoelectric survivability under near ideal conditions show that the material can withstand considerably higher stress (both electrical and mechanical) than the usual guidelines for design suggest. In practice, failure often results from “edge effects,” that is, effects that result from joints between materials or abrupt termination (edges) of materials. Discontinuities in physical properties produce concentrations in stress that can be well beyond the averaged maximum stresses assumed for a particular structure. These concentrations in mechanical stress can result in concentrations in electric field so that a mechanical stress concentration can actually lead to an electrical-field failure. If the problem is diagnosed as a simple electric-field induced failure, then incorrect action may be taken to “correct” the problem.

Several of the important points exposed by this study are:

- Stress concentrations should be addressed and minimized in high-power transducer designs

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13. ABSTRACT (Maximum 200 words) Low-frequency projectors for underwater sound are often driven near stress limits because of the conflicting requirements of high power and small size. One common failure mode is ceramic cracking and the associated arcing between high-voltage electrodes. While there are a number of manufacturing defects that can cause premature electric breakdown or premature cracking, a fundamental problem results from the coupling between the electric field and stress in a piezoelectric material. For a transducer operated near resonance, there will be "hot spots" or regions of locally intense stress and electric field that precipitate premature failure. The long-term goals of this project are: (1) to develop a capability to describe such failure modes, (2) to understand the factors that precede failure, and (3) to develop guidelines for failure mitigation.				
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- Intrinsic material limits are rarely achieved with current transducer designs
- Measurements of failure must be made under conditions representative of operation with regard to electrical, mechanical, and thermal stressing
- Thermal runaway in soft ceramics may be preventable by using fully biased drive but the bias can prevent reaching the same AC drive amplitude in field-limited transducers
- Failure along the bond line must also be considered in transducers for which a ceramic element is bonded to a substrate to produce a flexural structure
- Polishing edges of ceramic seems to inhibit mechanical failure
- Fully biased drive may have advantages in some cases but the implementation with regard to efficiency and cost must be addressed
- If the dominant failure mode is voltage-controlled, the actual peak voltage of the waveform must be considered. For waveforms other than simple sinusoids and sinusoidal pulses, the peak voltage can be much more than $\sqrt{2}$ higher than the *rms* voltage.
- The *rms* voltage is only useful as a failure criterion when the failure is thermal.

There is surprising little work that addresses potential improvements in, for example, mechanical design to lessen stress concentrations in transducers in which a piezoelectric ceramic is bonded to a metal or carbon-fiber substrate. This is one area in which significant improvements in high-power transducers can be expected but progress depends on recognition of the importance of "edge effects" in transducer failure and on creative mechanical design of ceramic/substrate assemblies.

A high priority should be put on mechanical design techniques to reduce stress concentrations in high-power piezoelectric transducers.

Future Directions

- Study and develop mechanical designs for flexural transducers specifically to reduce mechanical, electrical, and thermal stress concentrations
- Develop an automated controlled-Q test apparatus to facilitate evaluating materials
- Develop economical and efficient DC biasing schemes

OBJECTIVES

The overall objective of this effort is to develop design and analysis tools for prediction of failure in high-power piezoelectric transducers. Emphasis will be placed on practical transducer configurations and on design solutions to avoid premature failure.

There are three major objectives within the scope of this investigation. The first of these objectives is to produce failures in a controlled and repeatable manner in ceramics under stress fields and electric fields representative of those encountered in transducers in which the ceramic is in flexure. The second is to model the fundamental coupled systems of equations that relate stress, strain, electric field, and polarization. The third is to model, at least empirically, edge effects, stress concentrations, and charge concentrations. In this context, the "model" is used to indicate either numerical calculation or synthesis from controlled measurements.

APPROACH

The need for a detailed understanding of failure is acute as more power is required from smaller sources and the trend continues. It is surprising that so little effort is expended in the direction of applications-oriented failure studies in high-power piezoelectric materials. Most controlled experiments regarding failure are made under conditions so far from typical operating conditions that the results are not instructive.

Consequently, an attempt was made in this project to develop tests that were representative of the modes in which the material would be used in operational transducers. In one case, an apparatus was developed to replicate the normal operational range of quality factor while stressing the material to failure. In another case, the electrical impedance was tracked simultaneously with the acoustic output and device temperature of a flexural-disk transducer.

WORK COMPLETED – Third Performance Period

An apparatus (Figs. 1 and 2) was developed in which the piezoelectric ceramic element could be stressed to failure: (a) with the neutral plane outside the ceramic element, (b) with the structure driven at resonance, and (c) with a variable ratio between electrical stress and mechanical stress (through a variable quality factor, Q).

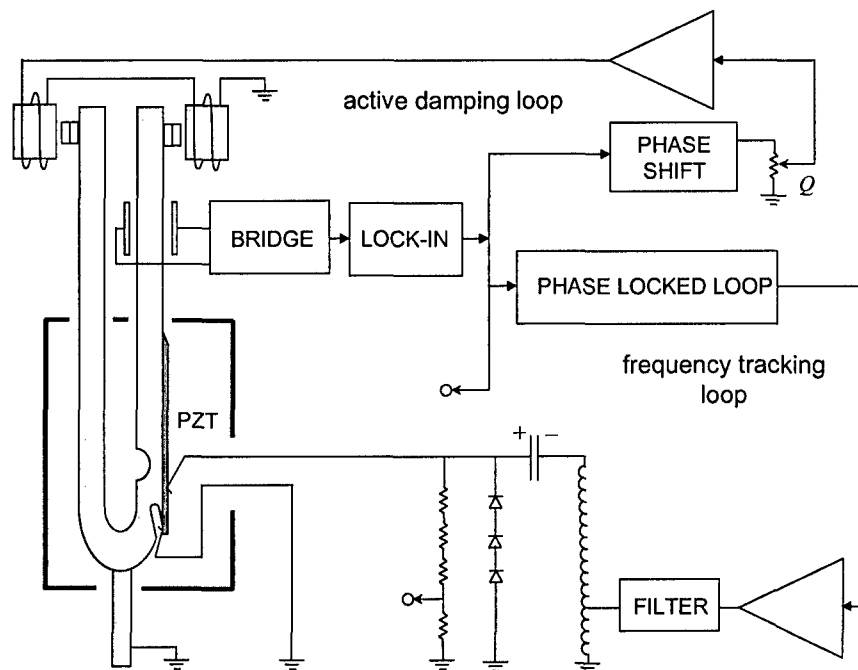


Figure 1. Block diagram of the improved controlled-Q failure test apparatus. In normal operation, the resonator with attached piezoelectric sample is driven by a voltage applied to the piezoelectric element. The resonator displacement is sensed by a differential-capacitance probe and this signal drives two feedback loops. One loop maintains the drive frequency at resonance; the other loop applies a controlled amount of damping through the moving-magnet driver.

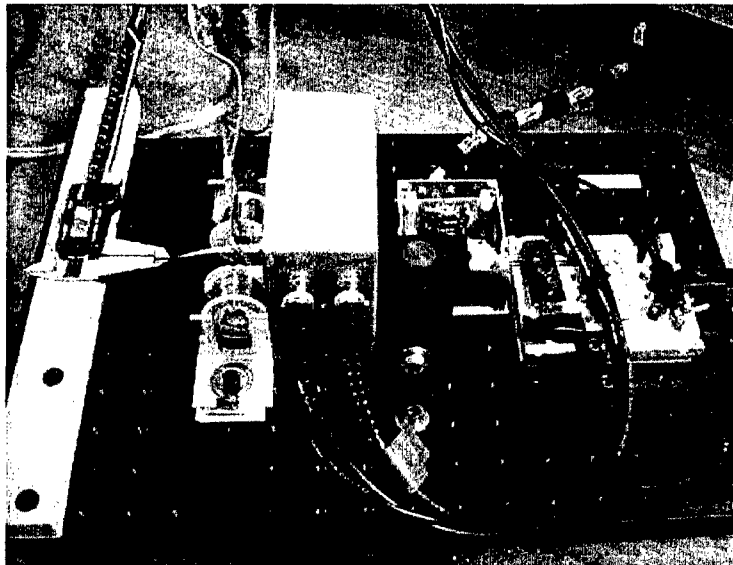


Figure 2. Photograph of the core of the controlled-Q test apparatus. The electromagnetic drive coils that adjust the damping are visible just to the left of the large aluminum box. The capacitive displacement sensor elements are inside that box and the drive monitor circuitry for the high-power drive signal to the piezoelectric element is in the smaller open box just to the right of the displacement-sensor box.

Another apparatus was developed to monitor gradual degradation. In this apparatus, the material was driven with a large-amplitude AC voltage (with the option of including a DC bias voltage) and a small-amplitude probe voltage at another frequency. The complex ratio of drive voltage to drive current (the impedance) was monitored by synchronous detection at the high-amplitude drive frequency. The probe signal was detected (again, synchronously) by an acoustic pressure sensor in order to monitor the acoustic output. The temperature in a small closed cavity directly behind the flexural element was measured also: this is not the temperature of the element itself but it is proportional to the element temperature.

RESULTS – Third Performance Period

Two representative results are presented here. The first is the failure envelope for a hard lead-zirconate-titanate (PZT) from the controlled-Q apparatus (see Fig. 3). This failure envelope suggests that, for typical high-power, wide-bandwidth ("low" Q) transducers, basic material failure is controlled by the magnitude of the electric field. Furthermore, from these measurements, it would appear that 1 kV/mm (25 volts per mil) would be a safe drive level. However, this would not be a safe drive level for actual transducers because the stress concentrations and edge effects in the test apparatus are much smaller than they would be in most flexural transducers.

The second result presented here (of the many experiments and tests performed) is a comparison of the behavior of the loss tangent under high drive for a soft PZT (Figs. 4 and 5). The intent was to consider the impact of fully biased drive (unipolar drive) on the self-heating of such materials. With no bias, the self heating is substantial (although the indicated temperature is not the bulk temperature of the ceramic) and the impedance at high drive levels is primarily dissipative. Because these particular flexural disk elements evidenced electrical breakdown at the higher bias levels (where the DC bias plus the peak AC level exceeded the breakdown threshold), comparable AC drive levels were not possible for the case of fully biased material so the results are equivocal. The results do point the way toward better characterization and raise an important practical issue with respect to biased operation: in an electric-field limited transducer, the DC bias may limit the usable AC amplitude in the drive signal.

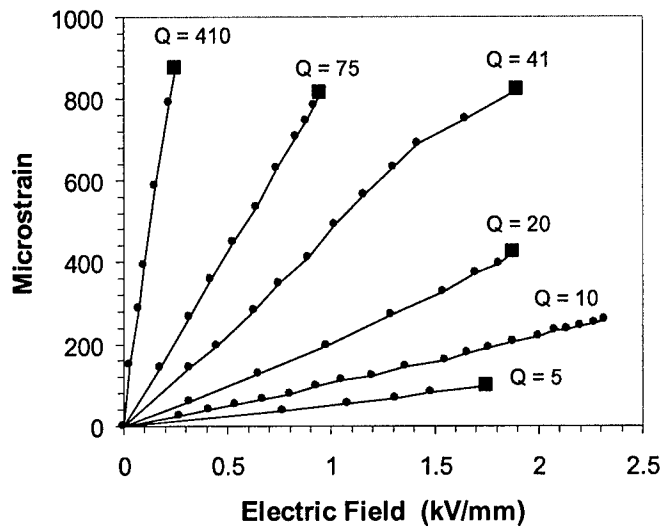


Figure 3. Paths to failure for PZT8 under unipolar electric-field drive with controlled quality factor. For high Q , the failure correlates strongly with maximum strain; for low Q , the failure correlates strongly with maximum electric field. For values of Q less than 40, the maximum electric field defines the onset of failure. (One kV/mm is approximately 25 volts per mil.)

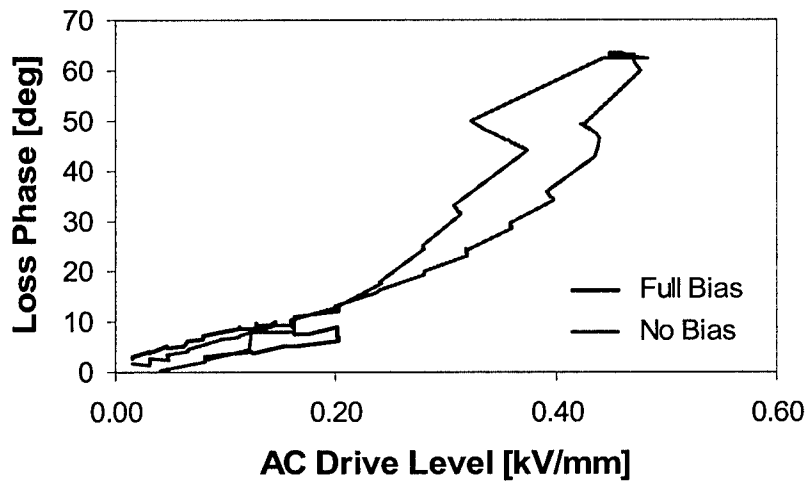


Figure 4. Loss tangent (shown as phase in degrees) as a function of AC drive level for a soft PZT flexural element under high drive. The red curve is for drive with no DC bias and the black curve is for drive with full DC bias. The no-bias case reaches a loss phase of over 60 degrees, which indicates that the drive impedance is primarily resistive rather than capacitive. The irregular steps in the no-bias curve result from the stepwise changes in drive and the lag between the drive changes and the element temperature. The full-bias case does not extend as high in drive level because the element is limited by the total electric field (AC plus bias).

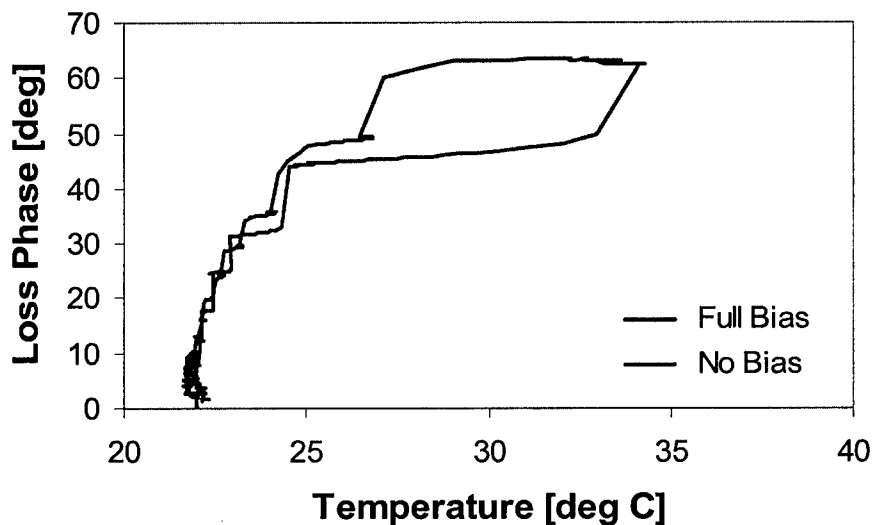


Figure 5. Loss tangent (shown as phase) as a function of element cavity temperature for a soft PZT flexural element under high drive. These curves are for the same test as shown in Fig. 4. The no-bias case shows a significant temperature rise, which contributes directly to the highly resistive (lossy) impedance at those levels. The apparent hysteresis is largely the result of thermal lag in the temperature measurement since the thermistor is weakly coupled to the element. The full-bias case shows no significant temperature rise although, as in Fig. 4, the AC component of the drive is limited to lower values.

One of the principal conclusions from this study is that *issues associated with practical construction details of a transducer probably have more impact on its failure envelope than the fundamental properties of the piezoelectric material*. This is almost certainly the case for arcing or fracture failure; it may be less so for the gradual degradation from, for example, stress- or field-induced depoling.

From measurements made under operating conditions representative of high-power transducers (high drive with quality factors of 5 to 10), a hard PZT like PZT-8 fails at much higher drive levels than are typical "safe" levels for actual transducers. However, these measurements were made specifically to minimize stress concentrations in the ceramic. The ceramic and the electrodes were both designed so that the edges were in low-stress regions of the flexing apparatus (Fig. 1). In operational transducers, there is typically little concern for stress concentrations in laminated ceramic-substrate designs. For example, in typical flexural-disk transducers, the edges of the ceramic are at moderate to high stress regions of the flexural assembly. Because the edges are step changes in properties and thickness, high stress concentrations can be expected in these regions. To compound the problem, electrodes are often not extended over the entire surface of the ceramic element and this creates high gradients in electric field, which, in turn, produce additional concentrations of mechanical stresses.

Even if the bulk of the ceramic is protected against tensile stress, failure levels of shear and tension can be produced in the edge regions and a failure that starts at the edge can easily propagate into the body of the element. It is likely that, with some thought, these edge stress concentrations can be reduced in practical designs but designers must recognize the coupled nature of the fields in such elements. The failure may be the result of a combination of electric-field induced stress concentrations and purely mechanically induced stress concentrations (and aggravated in some cases by electrical breakdown). Focusing on a single problem is unlikely to lead to an effective practical solution.

Furthermore, thermal issues need to be considered more carefully. Many studies of the properties of PZT at elevated temperatures have been made but typically these studies are done under conditions far different from those encountered in high-power transducers. The thermal expansion coefficients and thermal conductivities of ceramics and typical substrate materials are often significantly different and this can lead to mechanical stress and stress concentrates in excess of those predicted by isothermal analyses. In addition, the oscillating stress produces temperature oscillations and the disparity between the thermal penetration depth in ceramic and that in a metallic substrate leads to thermal relaxation losses that are not normally considered in transducer design. Such thermal losses (and bond layer losses) can result in higher internal losses (and lower efficiency and higher self heating) than predicted by simpler models.

Soft PZT's are sometimes considered for high-power applications (for example, in piezoelectric composites) but their much higher rate of increase of loss tangent with temperature means that thermal runaway is a distinct possibility. It is possible that runaway can be forestalled or prevented by using a fully biased drive but only if the transducer can tolerate the peak total field (peak AC plus DC) without electrical breakdown. This is another area in which further research would be valuable.

WORK COMPLETED – Second Performance Period

Work for this period focused on: (1) construction of an apparatus for evaluating loss tangent, temperature rise, and acoustic output for flexural transducer elements under high drive levels, and (2) evaluation of flexural power elements with and without bias fields.

The apparatus developed in this third performance period permits high-level biased or unbiased drive of a flexural-disk transducer element. Simultaneous with this high-drive signal, a low-amplitude probe signal is also applied and synchronously detected in order to track degradation in acoustic output. In these most recent experiments, the ceramic elements were not driven to catastrophic failure so monitoring gradual degradation was necessary. In addition to monitoring the acoustic output, the driving point impedance and the element temperature were monitored continuously throughout each test. The loss-tangent and impedance measurements were calibrated with a low-loss polyester film capacitor (to establish the zero loss-phase point) and with a low-loss capacitor in parallel with a metal-film resistor (to produce a known loss phase).

RESULTS – Second Performance Period

The most significant result from the previous performance period was a definition of the envelope of failure for axes of mechanical stress and unipolar electric field. An apparatus has been described previously in which the resonator quality factor (Q) can be controlled and the sample can be tested with stable ratios of maximum electric field to maximum stress. This permitted development of a maximum combined stress envelope for hard ceramics like PZT-8. The failure envelope for samples of PZT-8 is roughly rectangular. For Q 's greater than about 40, the material fails at about 800 microstrain with little dependence on electric field. For Q 's less than 40 (more typical for low-frequency transducers), the material fails at about 1.7 kV/mm (about 45 V/mil) with little dependence on strain. These results are particularly significant with regard to transducer operation at low Q . Low Q is desirable because a low Q results in larger signal bandwidth. However, from the standpoint of

failure under unipolar drive, the higher strains (or stresses) cannot be achieved at the lower Q 's because of the coupling between mechanical stress and electrical stress.

The results from this performance period address gradual degradation in performance of flexural disk elements. The test elements were three layer (ceramic/brass/ceramic) disk structures made of soft ceramic (PZT-5H) to accentuate depoling and thermal effects. Many samples were tested, most to failure. Two representative test samples are reported here. In each case, the electric field was increased in steps while recording the acoustic output, the loss-tangent phase (through the electrical impedance), and the element temperature. In most cases, the electric field was then decreased in steps to differentiate between permanent changes in properties and "recovery" of properties.

For example, consider Fig. 6. Sample 009 was driven with an AC field superimposed on a DC bias so that the field never reversed direction in either ceramic layer. The left-hand vertical axis relates to the AC component only. The right-hand vertical axis is a linear scale in acoustic output, the absolute value of which is immaterial. For Sample 009, the acoustic output is stable until the electric field is fairly high; then the degradation is rapid. As soon as the field is reduced, the acoustic output becomes stable again but at a lower level indicating permanent damage. Sample 010 was driven with an AC field only so that the field reversed direction twice each cycle. In this test, the percentage degradation in acoustic output is much larger than for Sample 009 but there is some recovery after the field is reduced. This recovery is probably associated with the drop in sample temperature as the field is reduced.

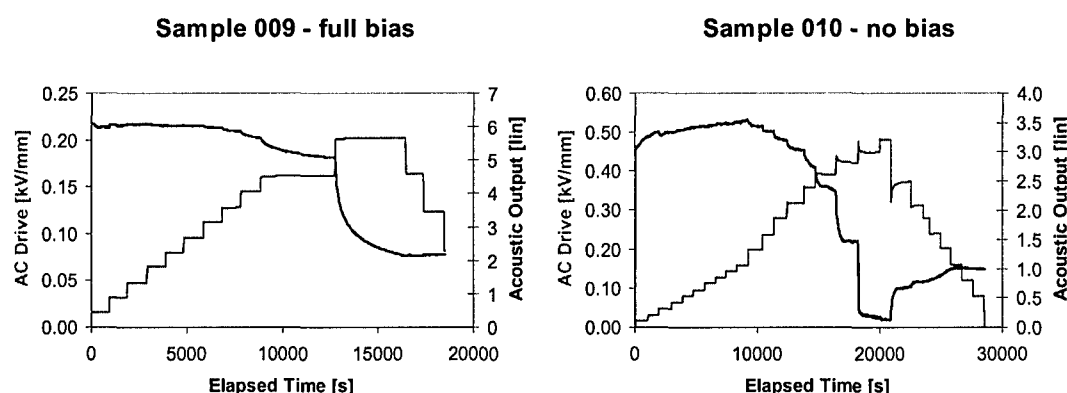


Figure 6. Degradation in acoustic output of flexural element under high drive. The red curve shows the increase in drive field with time; the black curve shows the measured acoustic output. The sample on the left is driven unipolar while the sample on the right is driven with no bias.

Figure 7 shows the behavior of the loss phase for the same two samples. The loss phase is the deviation in phase from zero between the drive current and drive voltage. For both plots, the loss phase is on the right-hand vertical axis but notice the difference in the axis range between the two plots. The loss phase increases far more for Sample 010, driven without DC bias, compared to Sample 009, driven with full bias. In both cases, the loss phase returns to its small-drive value after the drive is reduced so there appears to be no permanent effect of the "failure" on the loss tangent. However, the peak loss phase reached in the unbiased sample is more than 60 degrees (compared to a peak of less than 10 degrees in the biased sample); the unbiased sample is more resistive than reactive at the higher drive levels. Consequently, the unbiased sample should also produce a larger temperature rise.

The larger temperature rise is in fact dramatic as seen in Fig. 8. In that figure, the element temperature is indicated on the right-hand vertical axes of both plots. (The measuring thermocouple is not in direct contact with the ceramic; it is in a very small cavity adjacent to one side.) The fully biased sample (009) shows very little temperature change throughout the test while the unbiased sample (010) shows a sharp temperature rise at the higher drive levels. Beyond the magnitude of the temperature rise, it is also notable that the drive voltage does not increase in right-angle steps during the high-drive step changes. This is because the drive amplifier is not sufficiently low in output impedance to handle the relatively low, resistive impedance of the unbiased element at the higher temperatures. The temperature changes (and the related loss phase changes) would be considerably smaller in a hard ceramic (PZT-4 or -8) and the depoling would take a considerably longer time but the trends would be similar. The difference in effects between biased and unbiased soft ceramic is so dramatic that biased drive should be considered for any high-power application of soft ceramic.

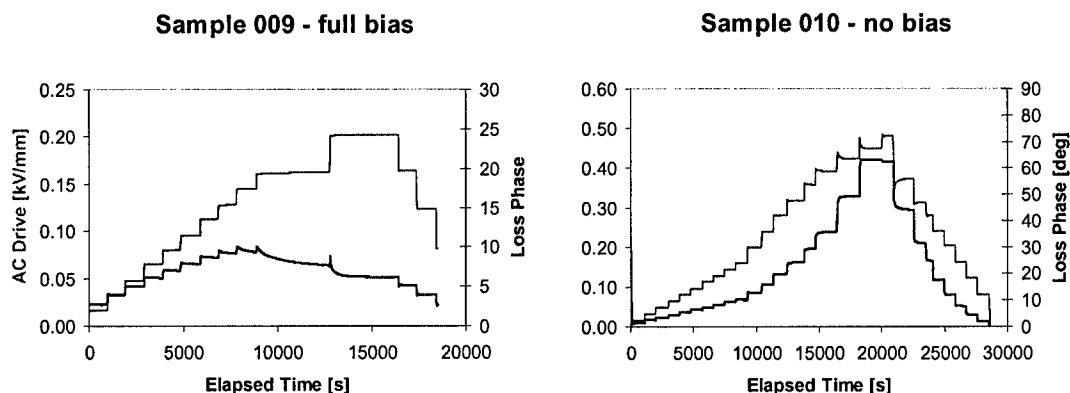


Figure 7. Variation in loss tangent (shown as phase) of flexural element under high drive. The red curve shows the increase in drive field with time; the black curve shows the measured loss phase. The sample on the left is driven unipolar while the sample on the right is driven with no bias.

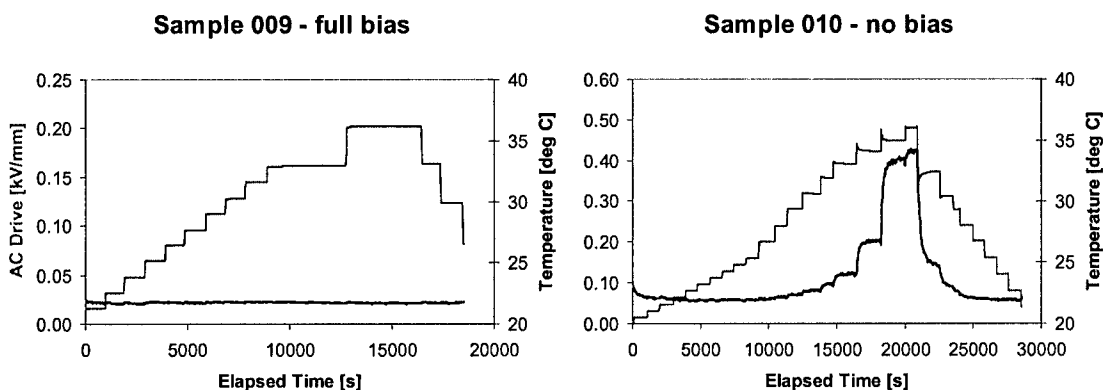


Figure 8. Temperature rise of flexural element under high drive. The red curve shows the increase in drive field with time; the black curve shows the measured element temperature. The sample on the left is driven unipolar while the sample on the right is driven with no bias.

The central conclusions from this project are listed below:

Fundamental Issues

- To first order, a performance specification sets a requirement on stored strain energy
- The transducer design should make distribution of strain energy density as uniform as possible
- Electric field concentrations produce additional mechanical stress
- For practical transducer bandwidths, ultimate failure is electric-field limited but the elements still fail mechanically, too
- Thermal runaway in soft ceramics may be preventable by using fully biased drive

Practical Issues

Documented transducer failures are well inside the failure envelope obtained in well-controlled flexure experiments. The ultimate potential of the material is not usually achieved in flexure-based transducers.

Practical issues may overwhelm fundamental failure limits:

- Stress concentrations (unavoidable in constant-thickness flexural disk elements; worse in center-supported compared to edge-supported disk structures)
- Concentration of shear stress running through bond line: worst in two-layer ceramic elements with no substrate
- Polishing edges of ceramic seems to inhibit mechanical failure
- Implementation issues for fully biased drives need to be addressed; there is significant room for improvement here.

WORK COMPLETED – First Performance Period

Work for this performance period focused on: (1) design and refinement of the test apparatus, (2) preliminary exploration of the strain/field failure space, and (3) investigation of the influence of stress concentration and electrode discontinuity on total failure stress.

A piezoelectric material is fundamentally represented by a set of coupled equations, for example,

$$\begin{aligned} S &= s^E T + d^T E \\ D &= d T + \epsilon^T E \end{aligned}$$

where S , D , T , and E are the strain, electric displacement, stress, and electric field vectors respectively; s^E is the elastic compliance matrix at constant electric field, d is one of the piezoelectric coefficient matrices, and ϵ^T is the electric permittivity at constant stress. For a flexural disk transducer and axially symmetric deflection the two in-plane normal stresses are related to the electric field as follows

$$T_1 = T_2 = \frac{-d_{31}}{s_{11}^E + s_{12}^E} E_3 = (15 \text{ Pa} \cdot \text{m/V}) \cdot E_3$$

where the numerical value applies to PZT8 and the shear stress is related to the electric field as follows

$$T_5 = \frac{-d_{15}^E}{s_{44}^E} E_1 = (-13 \text{ Pa} \cdot \text{m/V}) \cdot E_1$$

If the electrodes covered both faces of the ceramic disk completely, the in-plane electric field would be very small; however, it is common practice to stop the electrode short of the edge of the disk. In the case of a center-supported disk, this produces a significant E_1 (perhaps about three times E_3) at a point near a mechanical stress concentration (see Fig. 9). Consequently, the total stress is considerably higher than would be predicted by the full-electrode model.

A block diagram of the improved apparatus is shown in Fig. 10. The piezoelectric sample is attached to one leg of a tuning fork resonator in a position to straddle the peak stress point. The sample is driven and a capacitive sensor measures the resonator displacement. The displacement measurement is used in one feedback loop to maintain the drive at the resonance and it is used in another feedback loop to add damping to the resonator through a moving-magnet actuator. In this way, the resonator Q can be controlled and the sample can be tested with stable ratios of maximum electric field to maximum stress.

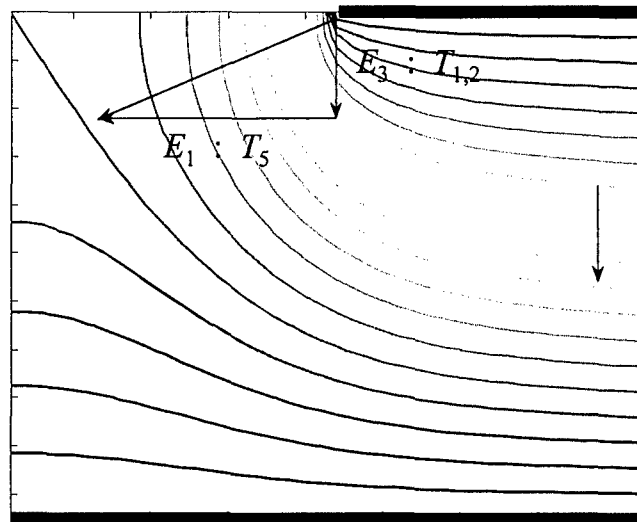


Figure 9. Contour plot of the electric potential near the inner edge of a circular disk with an upper electrode that is not extended to the edge. A large, in-plane field component is produced as an edge effect. This, in turn, produces a shear stress in addition to the normal stress concentration associated with the center hole in the disk (at the left edge).

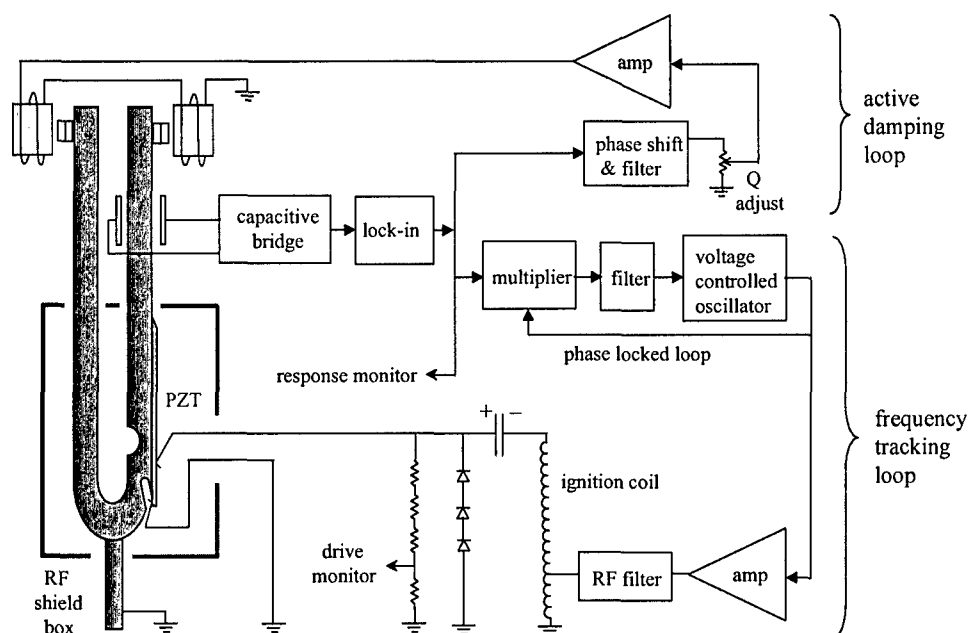


Figure 10. Block diagram of prototype failure test apparatus. In normal operation, the resonator with attached piezoelectric sample is driven by a voltage applied to the piezoelectric element. The resonator displacement is sensed by a differential-capacitance probe and this signal is split to two feedback loops. One loop maintains the drive frequency at resonance; the other loop applies a controlled amount of damping through the moving-magnet driver.

This apparatus can produce nearly purely mechanical failure (at high Q), nearly purely electric-field failure (at low Q), and combinations in between. At present, the voltage drive applied to the ceramic is unipolar to separate the effects of electric-field failure from depolarization failure. Subsequent experiments will introduce depolarization intentionally.

In addition to the development of the failure test apparatus, a model has been developed to investigate the stress increase that is produced by realistic electrode geometries in the vicinity of existing mechanical stress concentrations.

RESULTS – First Performance Period

The most significant result from this performance period is a preliminary definition of the envelope of failure for axes of mechanical stress and unipolar electric field (see Fig. 11). It is not surprising that there is a clear region in which failure is dominated by mechanical stress and a clear region in which failure is dominated by electric-field strength but the shape of the failure envelope and the behavior through the transition region is important.

In general, failure depends on the history of stress/strain up to the point of failure. The failure apparatus is designed so that the Q remains constant as the drive level is increased. The points of failure are shown as solid squares; intermediate points of drive on the way to failure are shown as smaller, solid circles. Departures of these intermediate points from a straight line indicate small departures from the constant- Q condition. The approach to failure is made slowly – a minimum of three minutes at each intermediate point and several minutes for the slow adjustment from point to point – and the resonance frequency is near 200 Hz.

The failure envelope under these conditions is roughly rectangular. For Q 's greater than about 40, the material fails at about 800 microstrain with little dependence on electric field. For Q 's less than 40, the material fails at about 1.7 kV/mm (about 45 V/mil) with little dependence on strain. (The results are reported in terms of strain because the strain was measured directly with a strain gage on the outer surface of the sample.) The sample run at a Q of 10 did not fail even though it was driven to the voltage limit of the drive amplifier. This sample was polished particularly smoothly along the edges. Since there is strong interest in operation in the range of 5 to 20 for Q , one aspect of further investigation will be the effect of polishing on failure in this region. (It would be premature to draw conclusions from this single polished sample.)

These results are particularly significant with regard to transducer operation at low Q . Low Q is desirable because a low Q results in larger signal bandwidth. However, from the standpoint of failure under unipolar drive, the higher strains (or stresses) cannot be achieved at the lower Q 's.

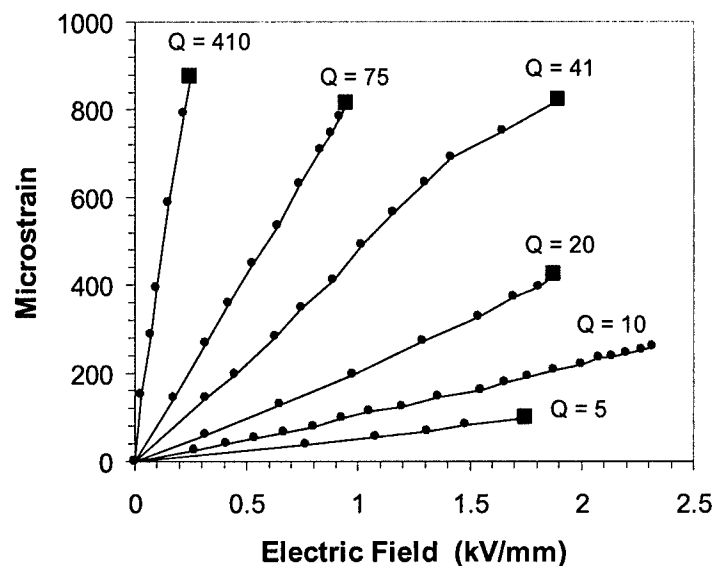


Figure 11. Paths to failure for PZT8 under unipolar electric-field drive with controlled Q . For high Q , the failure correlates strongly with maximum strain; for low Q the failure correlates strongly with maximum electric field. For values of Q less than 40, the maximum electric field defines the onset of failure.

IMPACT/APPLICATIONS

An understanding of failure mechanisms in piezoelectric ceramics is critical to the design of any high-power, underwater transducers that use these materials. The center-supported flexural-disk transducer is being considered as a candidate for use in the projector array for the HPLF coherent-source sonobuoy. Slotted-cylinder transducers and flexural-disk transducers have been considered for the Long Endurance Low Frequency Acoustic Source (LELFAS). These transducer configurations have the potential for enabling these programs but the failure rate for individual elements must be reduced. Understanding stress- and field-induced failure will facilitate construction of more reliable elements

and guide the development of failure mitigation strategies. In particular, deployable sources are normally designed with strict volume limits and such design is difficult unless a realistic assessment of achievable energy and power density is available for the source transducers.

If soft ceramics are considered for power transducers (because, for example, their transduction coefficients are larger), fully biased drive should be given serious consideration. This adds to the complexity of the drive electronics and may affect electrical efficiency but the problem of self-heating and thermal runaway may be markedly reduced. Such an approach may even make the use of 1-3 composites with soft ceramics viable for moderate power applications with modest efficiency requirements.

For any transducer system, resolution of the high-power failure modes would result in shorter, more productive design/test cycles and, ultimately, in increased reliability in high-performance systems.

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