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# Mechanical Pre-Stressing a Transducer through a Negative DC Biasing Field

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This report provides a qualitative study with regards to the feasibility of using a negative DC biasing approach to apply a mechanical compressive stress to a transducer's piezoelectric ceramic stack instead of using a stress bolt. A typical underwater Tonpilz longitudinal-type transducer is made up of four major parts: a piezoelectric ceramic drive element that is sandwiched between two masses, a tail mass, a radiating head mass, and a stress bolt. The stress bolt that passes through the ceramic stack (and connects the head mass to the tail mass) keeps the transducer parts together and keeps the ceramic element under a constant compressional stress. The compressive stress prevents the ceramic from going into tension and fracturing when driven under high AC drive conditions that exceed its low tensile strength. The typical compressive stresses applied by the stress bolt are 3000 to 6000 psi. When the transducer element lateral dimensions are small, compared with acoustic wavelength, there is little or no room for a stress bolt. An alternative method of applying a compressive preload without the stress bolt is achieved by applying a negative DC electric field across the piezoelectric ceramic stack, which in turn causes the piezoelectric ceramic element to contract and results in an internal compressive stress. The plausibility of this method will be discussed.

**15. SUBJECT TERMS**

sonar, transducer, Tonpilz, PZT, negative DC biasing, piezoelectric, stress rod, underwater acoustics

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## LIST OF ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| AC | Alternating Current |
| DC | Direct Currant |
| FEA | Finite Element Analysis |
| NUWC | Naval Undersea Warfare Center |
| ONR | Office of Naval Research |
| PMN-PT | Lead Magnesium Niobate-Lead Titanate |
| PZT | Lead Zirconate Titanate |

**MECHANICAL PRE-STRESSING A TRANSDUCER THROUGH A NEGATIVE DC BIASING FIELD**

## 1. INTRODUCTION

A Tonpilz longitudinal-type transducer is generally made up of three major parts: (1) a ceramic drive element (which is sandwiched between two masses), (2) the tail mass, and (3) the head mass. The ceramic drive element is typically composed of many piezoelectric ceramic rings that are epoxied mechanically in series and electrically connected in parallel. When an electrical signal is applied to this ceramic stack, the stack will expand and contract longitudinally, depending on the polarity of the electrical signal. The tail mass is usually made of a heavy material (such as steel, brass, or tungsten) and the head mass is usually made of light stiff material (such as aluminum or magnesium). With the ceramic stack sandwiched between the two masses, a two degree-of-freedom system is developed, with the ceramic stack acting as the system's spring driving both masses back and forth. The displacement of the lighter head mass is greater since the tail mass acts as a high initial mass to the system.

When a sinusoidal voltage is applied to the ceramic, the front face (piston) part of the head mass creates sound waves by compressing the water in front of the piston. A stress bolt or tie rod that passes through the ceramic stack and connects the head mass to the tail mass keeps the transducer's parts together and keeps the ceramic element under constant compressional stress, thus preventing the ceramic from going into tension (fracture) under high drive conditions due to its low tensile strength. Typical compressive preloads are 3000 to 6000 psi. The typical dimensions for a Tonpilz-type transducer element are a wavelength long and its front radiating face of the head mass is typically a half-wavelength across. These dimensions will leave a significant amount volume under the head mass for the ceramic stack and tie bolt (figure 1).

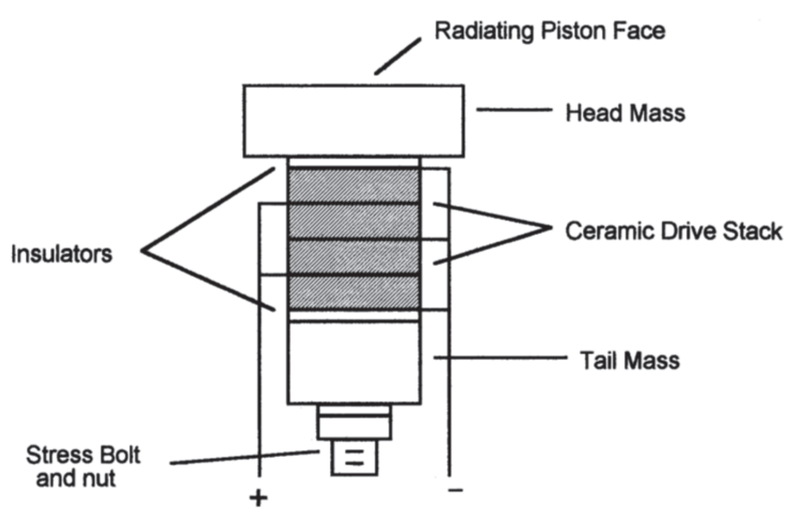



*Figure 1. Tonpilz-Type Transducer*

When an element head mass is on the order of 1/8 of a wavelength across, this leaves little or no room for a stress bolt. Putting a hole through the lead zirconate titanate (PZT) stack to handle a stress bolt would reduce the active area, thus reducing the elements maximum acoustic output (see figure 2). One method to keep the element from fracturing is to drive the element so that it is in slight tension, but driven low enough that the ceramic and epoxy joints' dynamic peak AC tensile strengths are not exceeded. Another method to prevent a fracture is to apply a preload (via hydrostatic water pressure) to the surface of the element's head mass; this method would only work on tail-mass-mounted elements and not on head-mass-mounted elements. An example of a fractured transducer element being driven at resonance into tension is shown in figure 3; it was estimated from finite element analysis (FEA) that the tensional stresses exceeded 2000 psi.

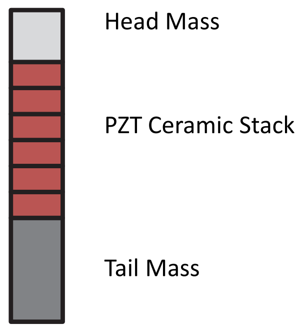



***Figure 2. Thin Transducer***

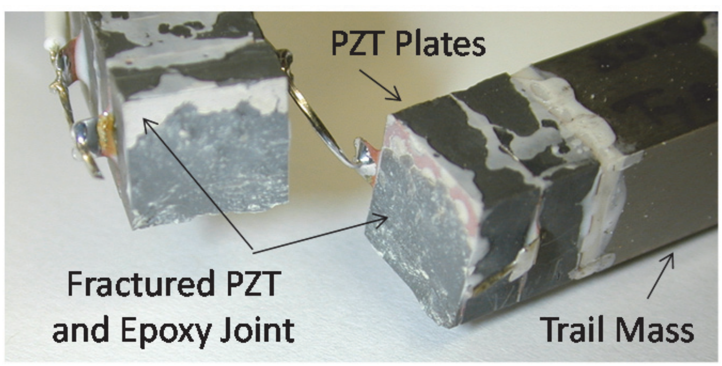



***Figure 3. Fractured Transducer Element***

Another interesting method proposed (as a question) by Dr. David Drumheller (ONR-333) at a recent meeting is the possibility of applying compressional pre-stress by placing a negative DC electric field on the element's piezoelectric ceramic stack instead of using a stress bolt. This particular method is discussed in more detail in the following sections of this report to determine whether this is a possible or even a plausible method.

## 2. PZT POLARIZATION

Unlike quartz, which exhibits natural piezoelectric effects, synthetic piezoceramic materials such as PZT (used in 90% of all Navy sonar transducers) need a large electric field to align their crystal domains to become piezoelectric; this process is called poling and is illustrated in figure 4. The dipole moments in PZT are randomly distributed in ceramic grains (figure 4a), where no piezoelectric effect is exhibited. The ceramic element is made piezoelectric by applying a strong electric field to greater than the coercive field $E_c$ up to the saturation polarization field $E_{sat}$ (approximately 60 kV/in or 60V/mil for hard PZT) across its electrode surfaces under elevated temperatures (120°C) in an oil bath, as shown in the hysteresis curve for polarization (figure 5a).

Under the action of this field, the domains will align with the electric field and the ceramic lengthens in the direction of the field (figure 4b). When the electric field is removed, the dipoles remain locked in approximate alignment (figure 4c), giving the ceramic material a remanent permanent polarization $P_r$ and permanent elongation (figure 5a). The material is now piezoelectric and will operate in a linear fashion producing strain (displacement) for an applied electric field.

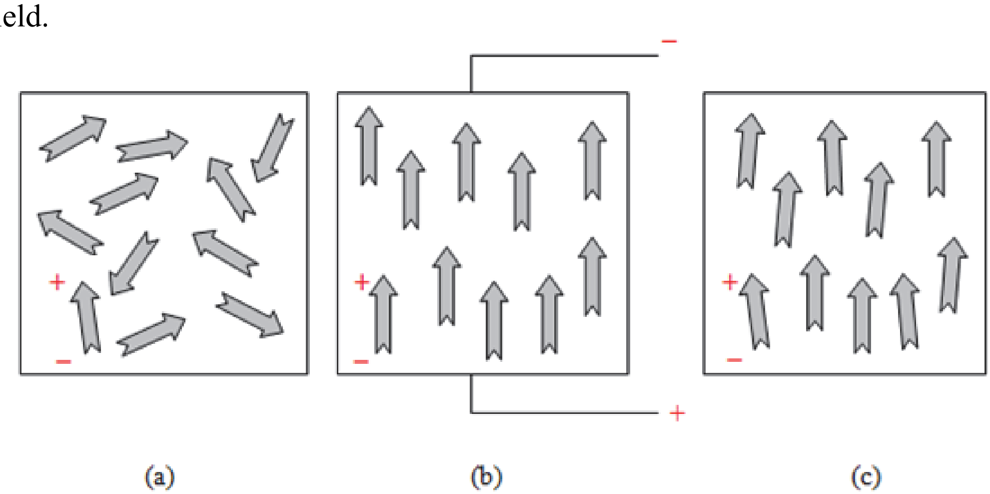



***Figure 4. Polarizing (Poling) a Piezoelectric Ceramic, (a) Random Orientation of Polar Domains Prior to Polarization, (b) Polarization in a DC Electric Field, and (c) Remanent Polarization after the Electric Field is Removed***

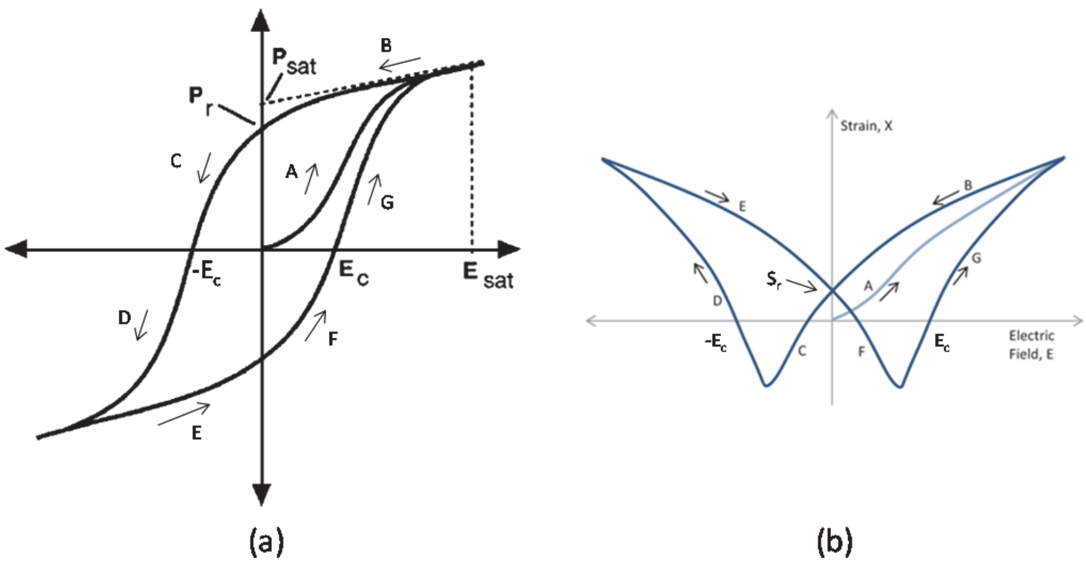



***Figure 5. (a) Hysteresis Polarization Curve and (b) Strain versus Electric Field "Butterfly" Curve for a PZT***

A typical strain versus electric field "butterfly" curve for a PZT material driven to its saturation limits is shown in figure 5b, and follows the same path as the hysteresis polarization curve in figure 5a. Curve A shows the initial strain increase with the electric field until saturation where the dipoles are all aligned. When the electric field is removed, the curve follows Path B to remanent strain point $S_r$, where the dipoles remain locked and the ceramic has a permanent length change or elongation. For linear piezoelectric operation, the material is operated along Path B-C curve (figure 6), staying away from the saturation and coercive field limits $E_c$. As shown in figure 6, Path B strain can produce a larger positive strain than Path C negative strain.

It is generally recommended that AC electric drive fields not exceed 12.7Vpk/mil (9 Vrms/mil) in the negative field direction or partial-to-full depoling will result for hard type PZT-4 material. As the material is strained it is also stressed: the material is in tension during the positive AC electric drive field, and the material is in compression during the negative AC electric drive field. The compressive stress of hard PZTs are very high (greater than 6000 psi) and the peak dynamic tensile strength limit of hard PZT's is approximately 3500 psi for simple shapes.

The transducers outlined in figures 1 and 2 are bonded together with rigid structural epoxies such as Armstrong A2/E epoxy, which has a static bond strength of approximately 4500 psi and a shear bond strength of 2500 psi. Transducers with tie bolts are typically pre-stressed to 3000 to 4000 psi so that the stack will never go into tension. The rule of thumb is to keep the tensile stresses less than 2000 to 3000 psi; otherwise, ceramic/epoxy will fracture under real conditions.

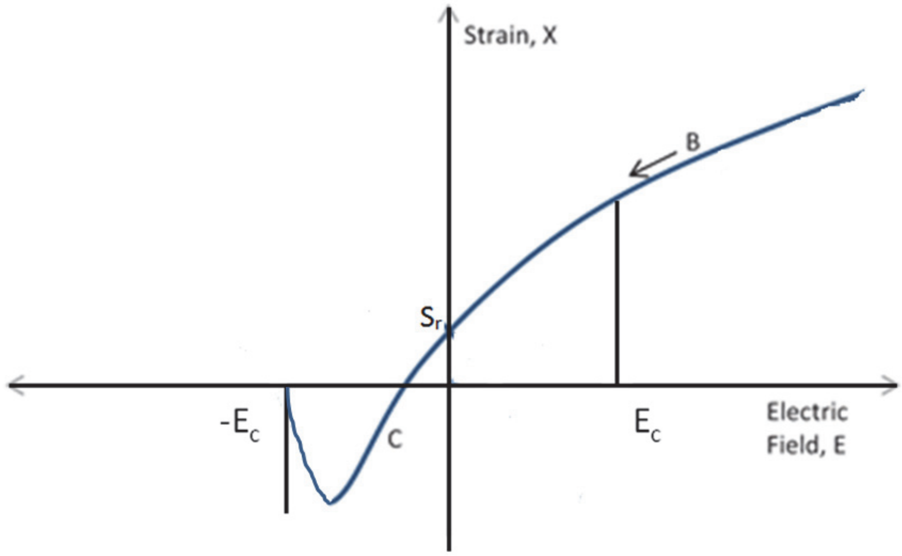



***Figure 6. Operating Strain versus Field Curve after being Poled***

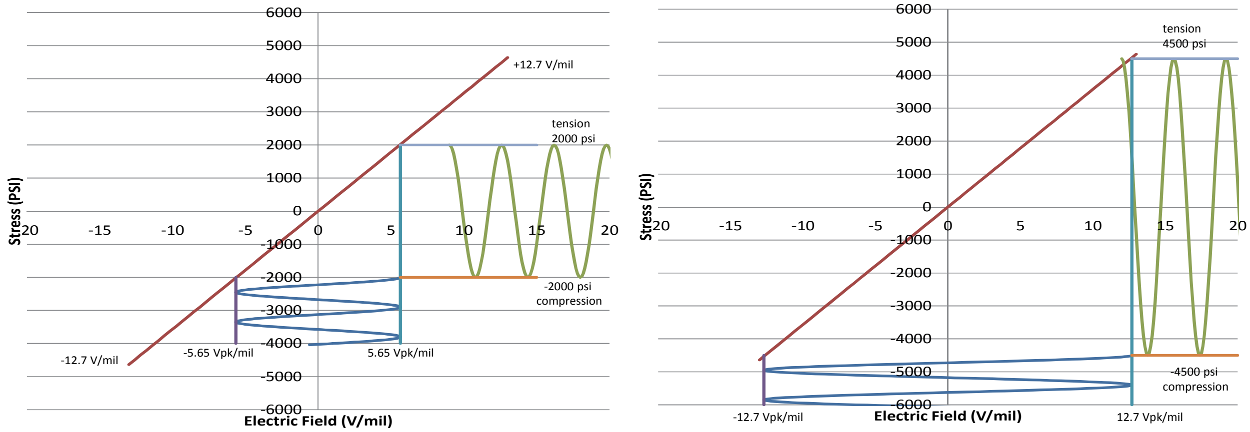
## 3. NEGATIVE DC BIAS

The thin transducer in figure 2 has a maximum drive level of 500 Vrms or 4 Vrms/mil (5.65 Vpk/mil) to meet source level requirements while keeping the stress levels below 2000 psi. An idealized stress-versus-electric-field curve for our thin transducer is shown in figure 7. Appling an AC electric field of ±5.65 Vpk/mil produces a tensile stress of 2000 psi and compressive stress of −2000 psi below the PZT and epoxy stress limits. Driving the transducer at its maximum field limit of ±12.7 Vpk/mil will produce a tensile stress of 4500 psi and compressive stress of −4500 psi (figure 7b). Driving at these high electric fields would result in the fracturing of the ceramic and epoxy bond joints and a tie bolt would be required.

Applying a negative DC bias creates a new compressive stress in the material. For the case presented in figure 7a, applying a bias field of −5.65 Vdc/mil would generate a −2000 psi compressive stress offset. Comparatively, driving the element with an AC 4Vrms/mil electric field input signal does not produce an output stress level that puts the material into tension, and the peak compressive stress is now −4000 psi (i.e. below compressive stress limit of hard PZTs), as shown in figure 8a.

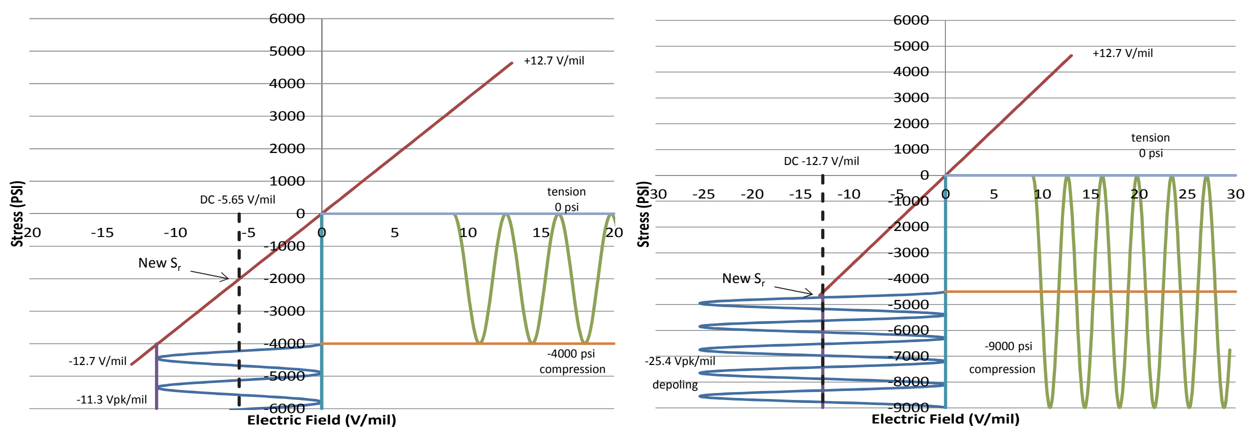
To drive at full levels of 9 Vrms/mil, the DC bias would need to be −12.7 Vdc/mil, knowing that during the positive drive swing there is zero tensile stress but during the negative drive swing the electric field is far greater (−25.4 Vpk/mil) than the electric field limit of −12.7 Vpk/mil. At these high electric field values, depoling of the material will result and arcing (or electrical breakdown) may occur.

A greater drive field would be possible if some tension is allowed in the PZT material. If the transducer was allowed to go into a slight tension of 1000 psi with a bias field of −5 Vdc/mil, then a 7.7 Vrms/mil drive signal could be realized without exceeding electric field limit of −12.7 Vpk/mil (figure 9). In practice, however, the actual stress-versus-field response is similar to figure 6, in which there is a dynamic response due to the influence of the applied electric field on the material domain structure. The piezoelectric strain coefficient $d_{33}$ increases with rising positive electric drive, while a negative electric drive acts to lower the piezoelectric coefficient. This results in reduced strain on the negative swing of the bipolar AC drive field. This is important to note as the resultant strain achieved for a given drive field will be reduced in the presence of a negative DC bias field and would require further investigation to be able to provide more than an idealized, qualitative analysis.




(a) (b)

***Figure 7. Transducer Stress versus Field with no DC Bias for an Applied Electric Field of (a) 4 Vrms/mil and (b) 9 Vrms/mil***




(a) (b)

***Figure 8. Transducer Stress versus Field with Negative DC Bias for an Applied Electric Field of (a) 4 Vrms/mil at −5.65Vdc/mil Bias and (b) 9 Vrms/mil at −12.7Vdc/mil Bias***

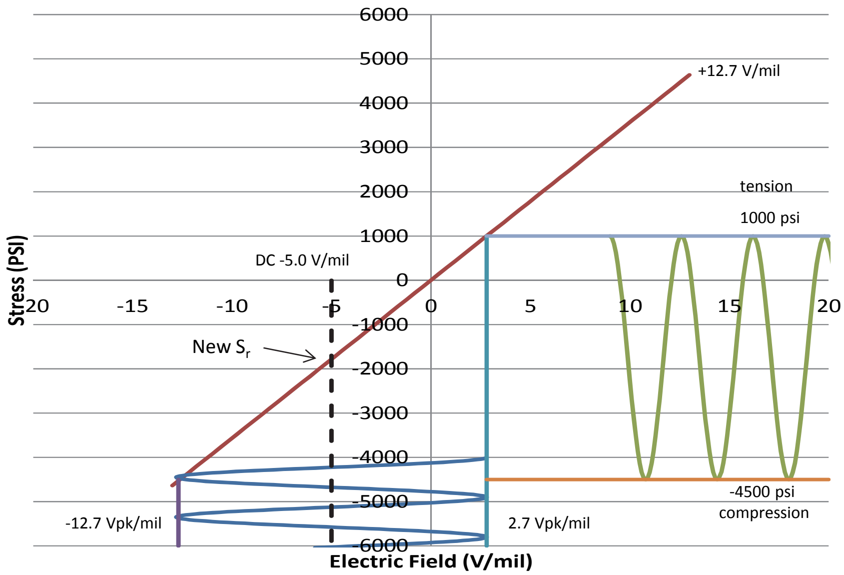



***Figure 9. Transducer Stress versus Field with Negative DC Bias for an Applied Electric Field of 5 Vrms/mil at −5Vdc/mil Bias with Element in Slight Tension 1000 psi***

## 4. EPOXY

The piezoelectric drive stack is composed of multilayers of PZT plates, with each plate bonded to one another with a rigid structural epoxy. An electrical connection is produced via a thin (0.003 inches) foil electrode of copper or brass between each plate. Figure 10a shows a ceramic stack (PZT plate-epoxy-PZT plate) static case with no negative DC bias and where the epoxy joint is not under tension. Figure 10b shows the same stack, but with the application of a negative DC bias to a degree that the ceramic deforms and puts the epoxy joint under tension. The conditions in figure 10b may be a problem at the high drive levels where compressive stress and lateral strains are high, resulting in tensile and shear stresses in the bond joint that are greater than that of the epoxy.

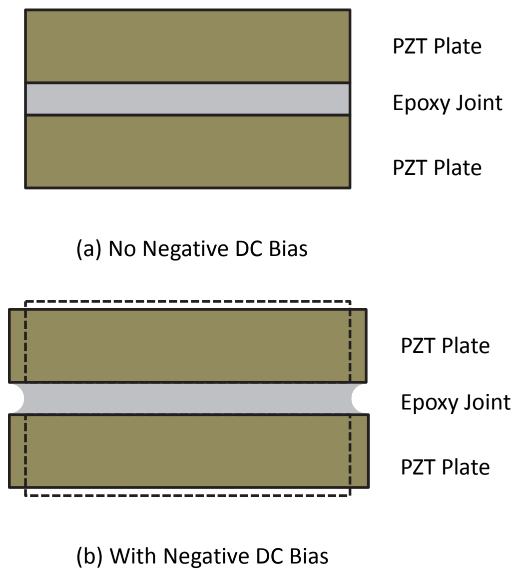



***Figure 10. Ceramic Stack of PZT Plate-Epoxy-PZT Plate: (a) with no Negative DC Bias where the Epoxy Joint is not Under Tension, and (b) with Negative DC Bias where the Epoxy Joint is Under Tension***

## 5. BIAS CIRCUITRY

The DC bias circuitry would add extra complexity to the drive circuity of the transducer and array, though it has been accomplished with single-crystal PMN-PT transducers where a positive DC bias is needed. A simple biasing circuit is shown in figure 11a; an AC power amplifier supplies the AC-gated pulses and a DC power supply provides the negative DC bias. A large-value capacitor (in series with the output of the power amplifier) blocks the DC from shorting through the power amplifier and a large-value resistor keeps the AC current from passing though the DC power supply. The DC power supply could be continually on during the AC pulse train (figure 11b) or gated with each AC pulse (figure 11c). The "gated DC pulse" method may generate spectral overtone because of its rectangle shape. Of course, the depicted circuit in figure 11 is an over simplification of what a real transmit system would require.

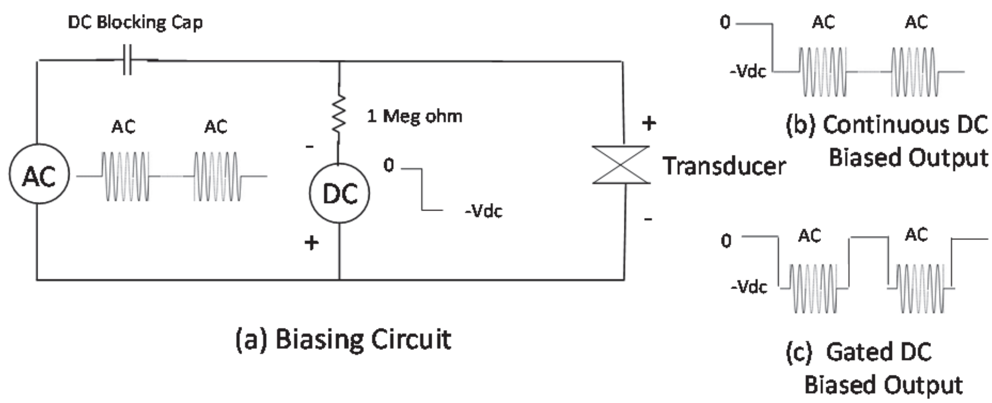



***Figure 11. DC Negative Biasing Circuit***

# 6. CONCLUSIONS

This report provides more of a qualitative study rather than a quantitative analysis with regards to the feasibility of a negative DC biasing approach toward applying a compressive stress to a transducer's ceramic stack. With regards to preventing the stack from going into tension at (a) medium electrical drive fields (4 Vrms/mil) in addition to (b) full AC drive conditions, an effective solution appears to be applying a −2000 psi compressional pre-stress offset. If the ceramic and epoxy joints can handle a 2000 psi swing into tension, then the bias would not be needed in our case.

For electric drive fields greater than medium, the negative drive signal would enter into an electrical depoling area for the PZT material. A good compromise exists where if the transducer were allowed to go into slight tension of 1000 psi, then a larger electrical drive field (7.7 Vrms/mil) could be realized without exceeding electric field limit.

Epoxy issues were discussed, including the potential failure of the epoxy bondline while under the tension caused by PZT going into compression under a negative DC bias. Also discussed is the possibility that the biasing circuity would add extra complexity to the transmit system electronics through the use of a continuous or gated DC bias scheme.

As discussed, the piezoelectric material's properties are also suppressed due to the reduction in the initial polarization in the material. This work would warrant further non-trivial investigation and research, and would make an ideal research or thesis topic.

The results of this study are that electrically pre-stressing PZT (via a negative DC bias) at electrically high-drive levels causes the material to depole as a result of the large values of peak negative voltage (AC + DC) presented to the transducer. Additionally, the epoxy bonding the PZT stack (under negative DC bias) may be stressed beyond its tensile limit. Mechanically pre-stressing via a stress bolt eliminates these conditions; this is an interesting concept but would not work under high-drive conditions.

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