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SINGLE CRYSTAL PZN/PT AS A HIGH-POWER TRANSDUCTION MATERIAL

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14. ABSTRACT

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ABSTRACT

The performance of two hypothetical, 20-kHz, 10-inch-diameter projector arrays of PZN/PT and PZT-8 tonpilz-like transducer elements, respectively, is computed. The specific PZN/PT piezoceramic material is monocrystalline $[Pb(Zn_{1/3}Nb_{2/3})O_3]_{0.955}$-$[PbTiO_3]_{0.0455}$ (0.955 PZN-0.045 PT). The PZN/PT material coupling factor $k_{33} = 0.93$ allows the usable bandwidth to be greatly expanded from 11.7 kHz for PZT-8 to 40.4 kHz for PZN/PT. The source level is also increased, but not as much as the 12.7 dB increase in energy density would suggest because the mechanical quality factor and the volume of the PZN/PT are smaller than those of the PZT-8. Still higher drive levels than the conservative ones of this study may be feasible, however. Biased operation of PZT-8 is also considered as an alternative method for achieving higher power. Although biasing PZT-8 provides no increase in bandwidth, substantial increases (7.4 dB in this example) in source level can be achieved. Suggestions are made for future work with PZN/PT.

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1. INTRODUCTION

Single crystal lead zinc niobate (PZN) shows promise as a high-power transduction material[1] for use in underwater sound projector arrays. Preliminary measurements[1,2] of the material properties indicate electromechanical coupling factors in excess of 0.9 and electromechanical energy densities as high as 10 kJ/m^3. In comparison, the most commonly used lead zirconate titanate (PZT) material, PZT-8, has a coupling factor of 0.65 and an electromechanical energy density of 0.57 kJ/m^3. In this note, we attempt to estimate the performance of a PZN projector array and compare it with that of a conventionally designed PZT-8 projector.

In operation, PZN will require the application of a dc-bias voltage to prevent depolarization during the reversed field portion of the ac excitation cycle. PZT-8 does not require biasing when driven in the conventional manner. However, because PZN requires a bias field, it makes sense to consider biased operation of the PZT-8 piezoceramic as a method of enhancing its performance. Biasing does not change the coupling factor, but it will permit higher source levels.[3]

It should be emphasized that the PZN single crystal materials are still undergoing development and are only available in small sizes and quantities. They have not been measured under the prestress conditions that would be necessary in a practical transducer. The calculations presented below should only be taken as an indication of the need for further investigation of this promising material.

2. THEORY AND CALCULATIONS

The field-limited power radiated by a transducer at resonance is

$$P_f = 2\pi\eta_{ma} f_0 \, Q_m \, k_{eff}^2 \, U_f, \tag{1}$$

where η_{ma} is the mechanoacoustic efficiency, f_0 is the resonance frequency, Q_m the mechanical quality factor, k_{eff} the effective electromechanical coupling factor, and U_f the input electrical energy. The bandwidth over which the tuned transducer presents a suitable impedance to the power amplifier is

$$\Delta f = f_0 \, k_{eff} / (1 - k_{eff}^2)^{1/2} \, . \tag{2}$$

Provided the transduction material is not excessively lossy (in which case it would not be a suitable high-power material), the only material-dependent quantities in equations (1) and (2) are the effective coupling factor k_{eff} and the electrical energy U_f. The transducer effective coupling factor k_{eff} influences both the source level and the bandwidth. For the 33-mode of operation it will be related to the material coupling factor

$$k_{33} = d_{33} \, / \, (s_{33}^E \, \varepsilon_{33}^T)^{1/2} \, , \tag{3}$$

where d_{33} is the piezoelectric strain coefficient, s_{33}^E is the free compliance coefficient (reciprocal of Young's modulus), and ε_{33}^T is the free permittivity. For a tonpilz transducer, k_{eff} is typically 80 percent of k_{33}.

The input electrical energy is

$$U_f = \varepsilon_{33}^{\mathrm{T}} E_{rms}^{2} V, \tag{4}$$

where E_{rms} is the root-mean-square electric field drive amplitude and V is the volume of the active transduction material. High-power materials must possess large values of the electromechanical energy density,

$$k_{33}^{2} U_f / V = k_{33}^{2} \varepsilon_{33}^{T} E_{rms}^{2} \,. \tag{5}$$

In table 1 we list of the 33-mode properties of piezoceramic, polycrystalliine PZT-8 (Navy Type III) lead zirconate titanate and single crystal 0.955 PZN-0.045 PT, a formulation of 95.5-percent lead zinc niobate and 4.5 percent lead titanate. The unbiased PZT-8 values are taken from reference 4. Biasing this material is expected to have little effect on the piezoelectric coefficients, but it will allow the drive field to be substantially increased. The properties of PZN/PT are based on stress-free measurements reported by Shrout[2] and reprinted herein as figure 1, where the slopes of the straight lines drawn through the polarization and strain data points are taken as the permittivity ε_{33}^{T}, and the piezoelectric coefficient d_{33}, respectively. They should be treated only as rough estimates of the values to be expected when quality-controlled samples become available for testing under prestress conditions. They suggest, however, that significant improvements in source level and in bandwidth might be achievable with the monocrystalline PZN/PT.

Table 1. Properties of PZT-8 and PZN/PT

	Unbiased PZT-8	Biased PZT-8	0.955 PCN-0.0445 PT
Density (kg/m^3)	7600		8300
s_{33}^{E} (pm^2/N)	13.5		150
$\varepsilon_{33}^{T}/\varepsilon_0$	1000		2800
d_{33} (pm/V)	225		1800
k_{33}	0.65		0.93
E_{dc} (MV/m)	0	0.72	1
E_{rms} (MV/m)	0.39	0.91	0.7
$k_{33}^{2}\varepsilon_{33}^{T}E_{rms}^{2}$(kJ/m^3)	0.57	3.1	10.5
relative dB	0.0	7.4	12.7

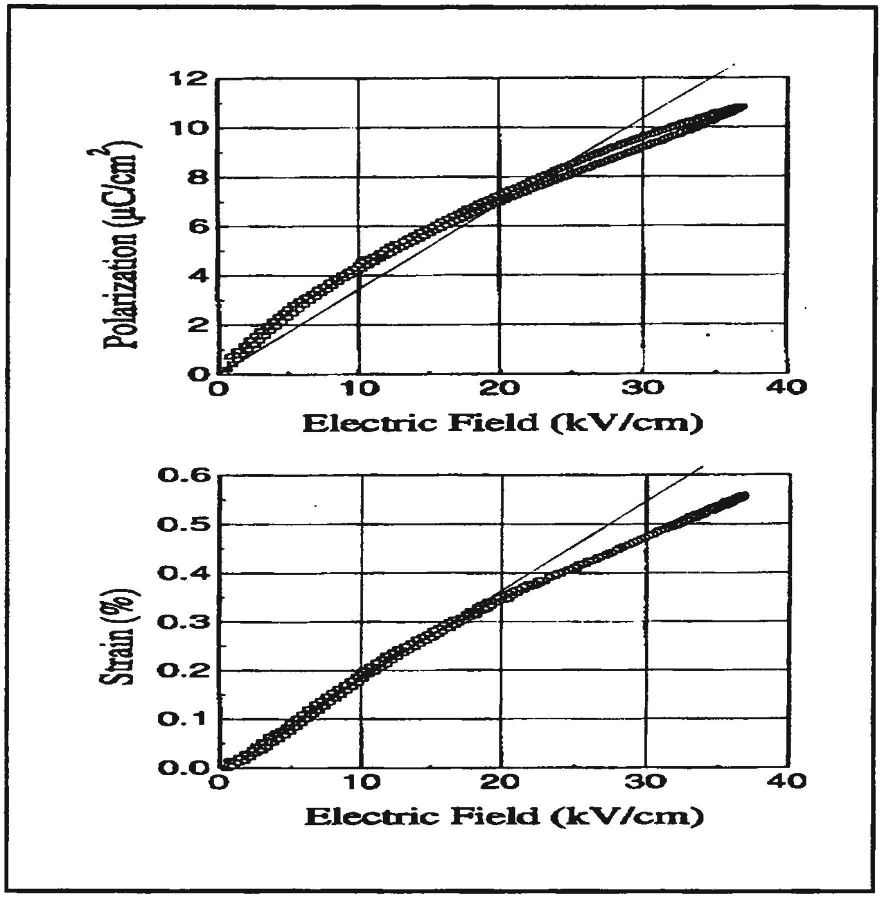

Figure 1. Polarization and Strain as a Function of Applied Electric Field for 0.955PZN-0.045 PT[2]

For the unbiased PZT-8, the drive level listed in table 1 is the generally accepted maximum field limit, 0.39 MV/m rms (10 V/mil rms). The drive levels for the biased materials in table 1 correspond to a peak electric field strength of 2 MV/m (51 V/mil). These levels are conservative in the sense that we have routinely been able to apply fields with this peak strength to oil-immersed, 10-mm samples in the laboratory. It can be seen from figure 1 (where the maximum field is about 3.7 MV/m) that higher fields are possible with PZN/PT. Fields as high as 6 MV/m (152 V/mil) have been reported,[1] accompanied by strains exceeding 0.01 (with no prestress applied, however). The corresponding bias field, E_{dc}, and ac drive field E_{rms} would be approximately 3 MV/m (76 V/mil) and 2.1 MV/m (54 V/mil), respectively, or 9.5 dB greater than the drive levels of table 1, so that, instead of a 12.7-dB increase in power level relative to unbiased PZT-8, the increase would be about 22 dB. (However, one should not expect that the piezoelectric "constants" will retain the values given in table 1 for such high drive levels.)

3. TRANSDUCER DESIGN

To get a more quantitative idea of the performance improvements to be expected from the new material, we use a mathematical model of two hypothetical, 10-inch-diameter, transducer arrays of tonpilz-like elements with rod drivers. One of the arrays utilizes PZN/PT, while the other uses PZT-8 rods. The model, depicted in figure 2, is relatively simple. There are four rod drivers per transducer element. The rod length (L) is 0.445 inch for the PZN/PT and 1.57 inches for the PZT-8 material, resulting in a (short-circuit) resonance frequency of 20 kHz in each case.

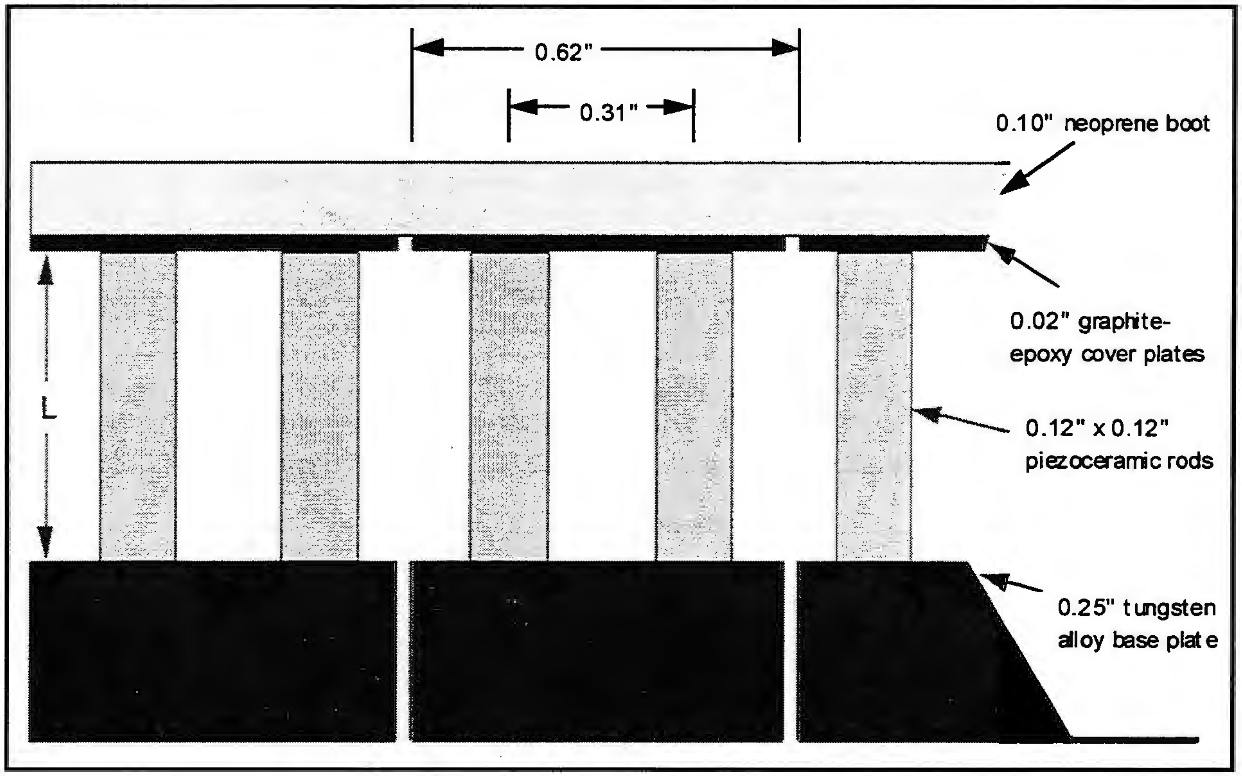

Figure 2. Schematic Drawing of Tonpilz-Like Transducer Array

In practice, one would use stacks of plates or rings, rather than rods or bars, for the piezoelectric drivers, to keep the drive voltages at reasonable levels while providing the high fields that will be required. For the purposes of this study, however, it is more convenient to compare the performance of rod drivers. (The short-circuit resonance frequency of a rigidly backed rod differs only slightly from that of a rigidly backed stack of the same length.)

The large coupling factor of PZN/PT makes possible the attainment of a wide bandwidth,[5] but it also reduces the optimum value of the mechanical quality factor, Q_m. To attain this lower Q_m, we use a lightweight, stiff-head material, graphite-epoxy composite, with a thickness, 0.02 inch that is sufficient to ensure that flexural-mode resonance frequencies be well above the frequency band of interest. The mechanical quality factor is approximately proportional to the ratio of the rod cross-sectional area A to the radiating head area, A_0. For the present purposes, we have chosen an area ratio, A/A_0, of 0.15 for both transducer materials.

The tail masses shown in figure 2 are made of a tungsten alloy, but because their masses are about 130 times greater than the head masses, we can safely assume rigid backing conditions for the driver rods. We use a Mason equivalent circuit,[6] which accounts for the distributed nature of the rod mechanical impedance. The head mass, because it is so thin, is treated as a lumped element, with a mass of 0.2 g. The neoprene boot is assumed to have the acoustic properties of sea water and, therefore, provides a resistive radiation resistance equal to $\rho_0 \, c \, A_0$, where ρ_0 is the density and c is the sound speed in sea water.

We have chosen the head size of the transducer elements, 0.62 inch x 0.62 inch, to correspond to one-half wavelength in sea water at 48 kHz, because the increased coupling factor of PZN/PT allows operation to well beyond the 20-kHz resonance. This head size (and element spacing) prevents the formation of grating lobes and loss of signal at the upper end of the frequency band. However, because the elements are less than one-quarter wavelength apart when operating at the resonance frequency, element-to-element interactions could cause detrimental loading effects. This consequence of increasing the bandwidth should be carefully examined if PZN is to be used for bandwidth enhancement.

In the simple transducer models used here, stress bolt properties are not included, nor are those of the transducer mounting suspension system. Coupling losses are small and due solely to the distributed nature of the rod motion (only part of the rod behaves as a spring). Frictional and dielectric losses are not included. In other words, these transducers are 100 percent efficient.

4. TRANSDUCER ARRAY PERFORMANCE

The two transducer arrays were designed to have the same resonance frequency, 20 kHz, which we define as the frequency of maximum conductance. Figure 3 plots the conductances (for all elements wired in parallel) normalized with respect to their maximum values, 133 μS for the PZT-8 array and 857 μS for the PZN/PT array. For constant voltage drive (i. e., with a low-impedance power amplifier), the power input to the transducer is proportional to the conductance. In the lossless case we are considering, the radiated power is also proportional to the conductance. Thus the plots of figure 3 may be taken as the frequency dependence of the radiated power. From the half-power points of the plots of figure 3, we determine the mechanical quality factor Q_m to be 1.7 for the PZT-8 array and 0.52 for the PZN/PT array. The lower Q_m of the PZN arises from the higher compliance coefficient s_{33}^E of that material (see table 1).

To minimize the reactive load presented to the power amplifier, it is customary to tune projector transducers with inductors wired in parallel with the transducer input. We used inductance values of 65.1 mH and 29.5 mH, respectively, for the PZT-8 transducer array and the PZN/PT array, to tune the arrays to 20 kHz. The phase angles of the admittances are plotted in figure 4, where it can be seen that the phases vanish at 20 kHz. The magnitudes of the tuned admittances are shown in figure 5.

In figure 6, the tuned admittance for the PZT-8 transducer array is plotted in the complex admittance plane, as an admittance loop. Also plotted in figure 6, as the dashed-line segments and circular arcs, is the boundary of the preferred zone of operation where the admittance presented to the power amplifier is within acceptable limits. These acceptable limits are, to some extent, a matter of engineering judgment, and we have used those suggested by Stansfield.[5] In the complex plane, they correspond to the full- and half-power loci, (the circular arcs for the magnitude of the admittance) and the 80-percent-power-factor loci (the straight lines of slope equal to ± 0.75). In figure 6, as the frequency is increased, the tuned admittance enters the preferred zone at the point indicated by the lower circle plotting symbol and, later, leaves it at the point indicated by the higher circle plotting symbol. The frequencies corresponding to these entry and exit points are 14.5 and 26.2 kHz, respectively, giving us a usable bandwidth of 11.7 kHz.

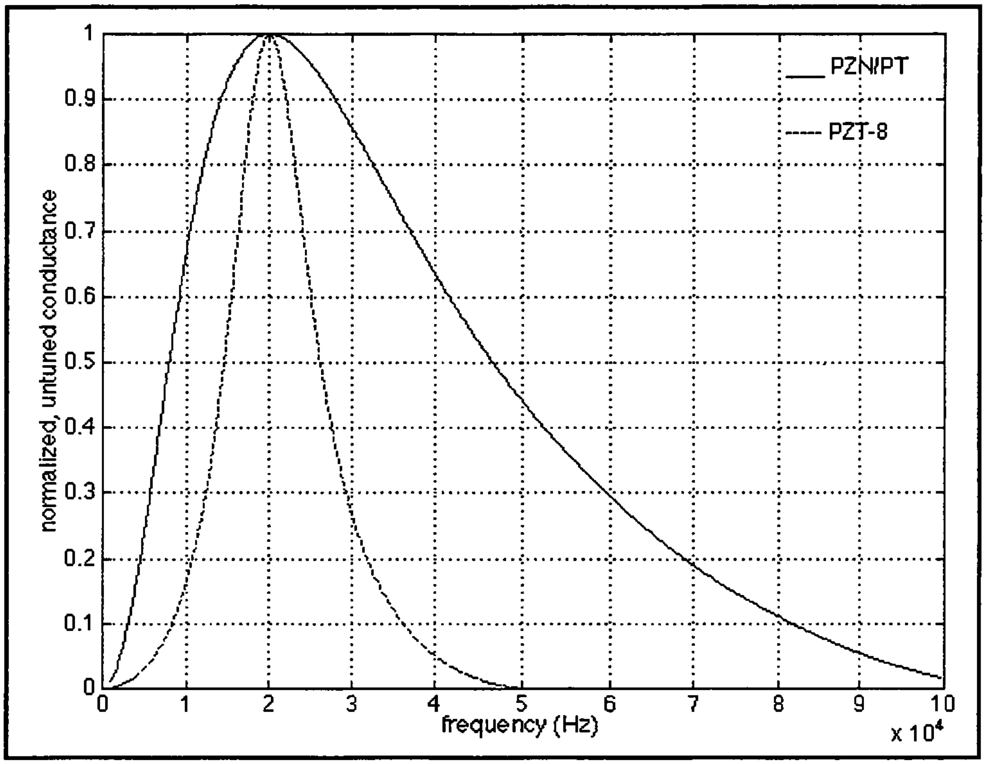

Figure 3. Conductance of 10-Inch Diameter Transducer Arrays, all Elements in Parallel (Solid Curve: 0.955 PZN-0.045 PT Array; Dashed Curve: PZT-8 Array)

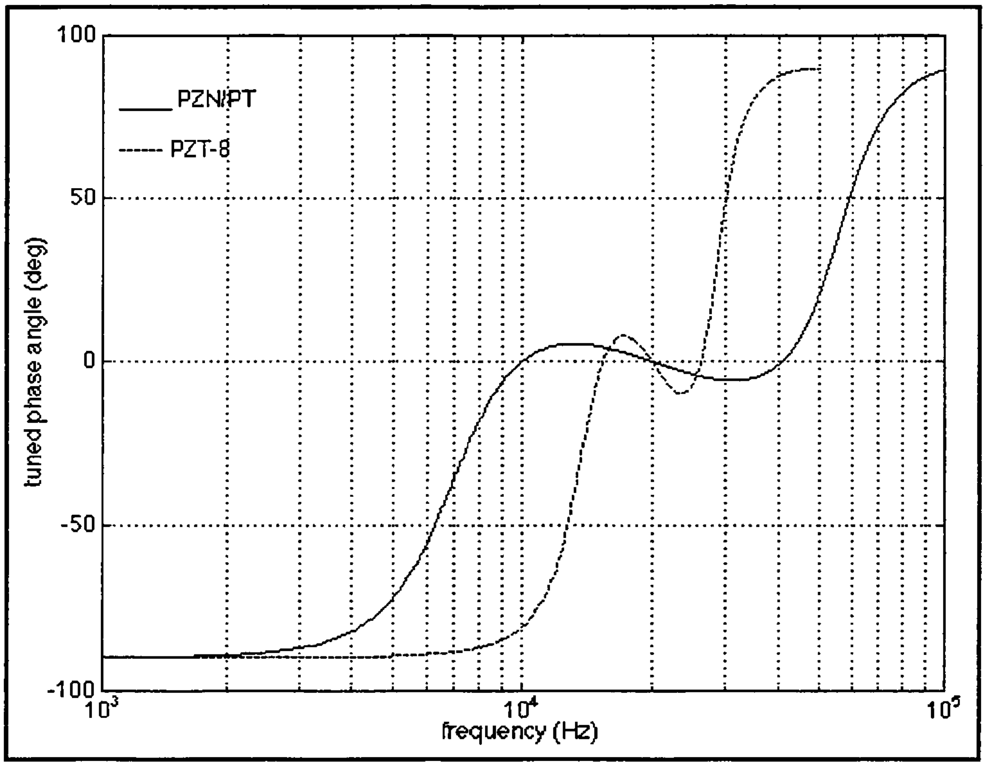

Figure 4. Parallel-Tuned Admittance Phase of 10-Inch Diameter Transducer Arrays (Solid Curve: 0.955 PZN-0.045 PT Array; Dashed Curve: PZT-8 Array)

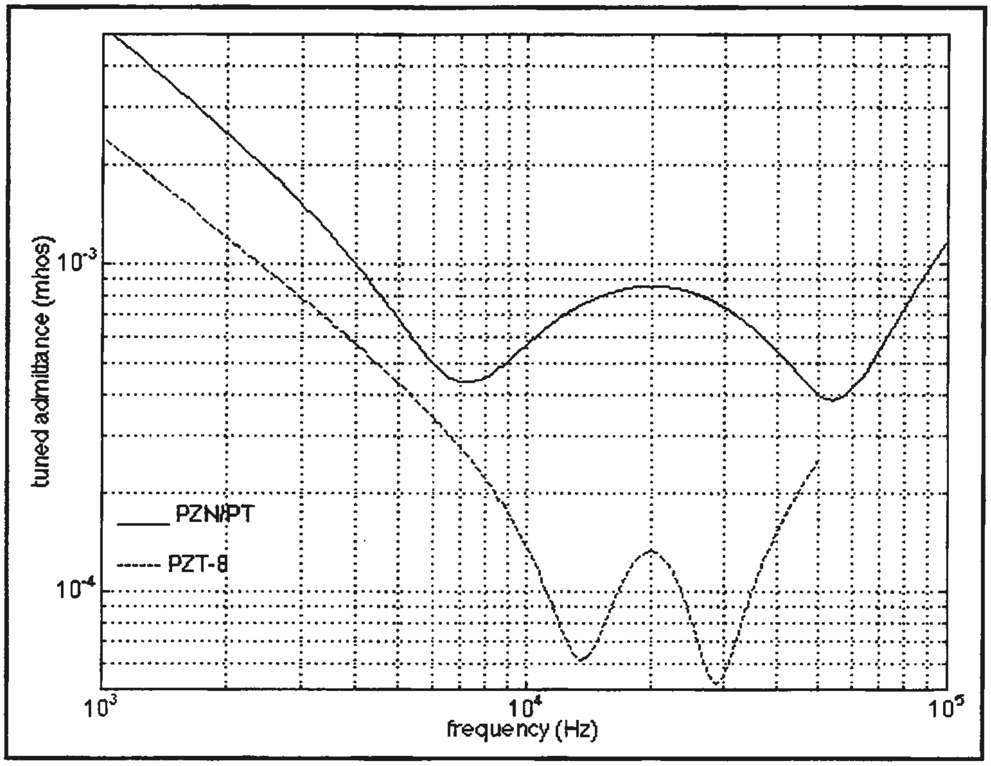

Figure 5. Parallel-Tuned Admittance Magnitude of 10-Inch-Diameter Transducer Arrays (Solid Curve: 0.955 PZN-0.045 PT Array; Dashed Curve: PZT-8 Array)

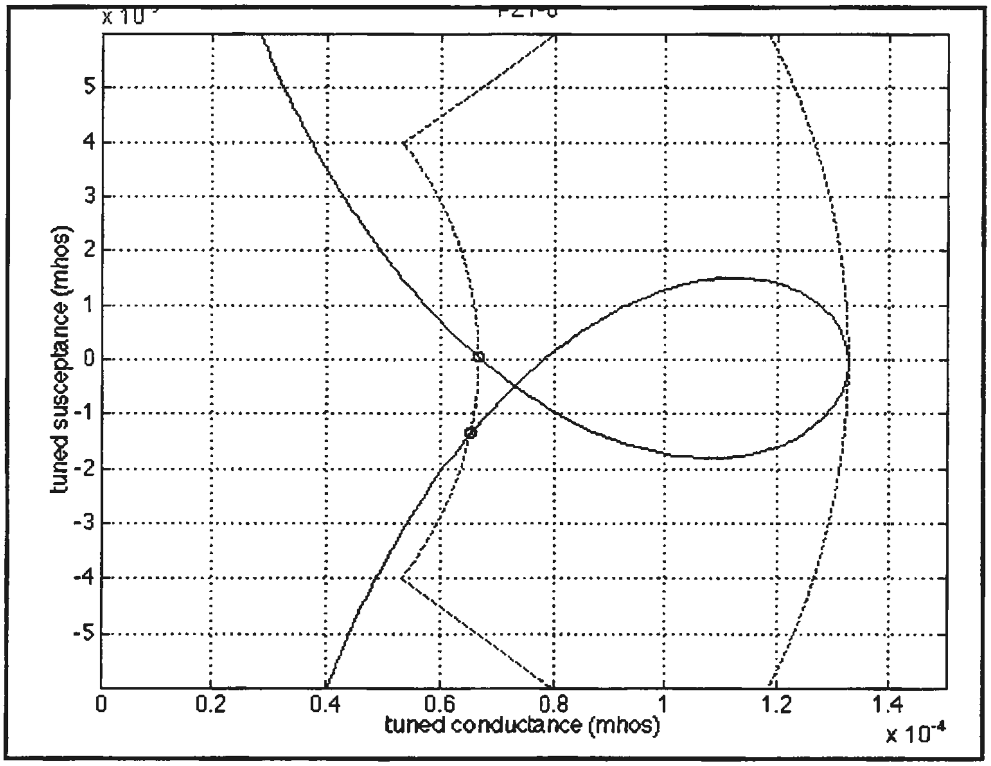

Figure 6. Parallel-Tuned Admittance Loop of 10-Inch Diameter, PZT-8 Transducer Array (Solid Curve) (Dashed Boundary Outlines Zone of Acceptable Admittance Variation)

Figure 7 is the tuned admittance loop for the PZN/PT transducer array. In this case, the entry and exit points to the zone of acceptable admittance variation are at frequencies of 6.9 and 47.3 kHz, respectively, and so the usable bandwidth is 40.4 kHz. This dramatic extension of the bandwidth is because of the higher coupling factor of PZN/PT.

Figure 8 shows the source levels obtainable from the 10-inch-diameter arrays of PZN/PT (solid curve), biased PZT-8 (dotted and dashed curve), and unbiased, i. e., conventionally driven, PZT-8 (dashed curve) elements driven at the electric field strengths listed in table 1. Whereas the conventional transducer array produces a source level of 236.8 dB//*μPa-m* at 21.9 kHz, the PZN/PT array source level is 239.4 dB//*μPa-m* at the same frequency, but reaches a maximum of 243.0 dB//*μPa-m* at 51.8 kHz. It is the directivity of the array that causes the source level to increase with frequency. (As we noted above, the radiated power peaks at 20 kHz in both cases.)

It should be noted that the increase in source level (over that of conventionally driven PZT-8) provided by PZN/PT is not equal to the increase in energy density, 12.7 dB, listed in table 1. There are two other factors that enter into the power level, as indicated in equation (1), and they are the mechanical quality factor, Q_m, and the volume of the piezoceramic material. Both these quantities are smaller for the PZN/PT transducer elements than for the PZT-8 elements. (For example, the larger PZT-8 volume amounts to a 5.5-dB disadvantage for PZN/PT.) The result is that the PZN/PT source level is only 2.6 dB greater than that of the PZT-8 at 21.9 kHz. At all other frequencies, the increase in source level is greater, as can be seen in figure 8.

Another method for achieving higher source levels would be to bias the PZT-8, which in turn would allow us to drive it harder. In this case, as indicated by the dotted and dashed curve of figure 8, the frequency-dependence of the source level would have the same shape as that for the unbiased PZT-8, but the source levels would be 7.4 dB higher, as suggested in table 1 by the increase in energy density.

Still higher source levels would be achieved if we could increase the bias and drive fields to 3 MV/m and 2.1 MV/m, respectively, rather than the conservative values of 1 MV/m and 0.7 MV/m that we have chosen for PZN/PT in this study. With a drive level of 3 MV/m, it is estimated that the PZN/PT source level could be increased about 9 dB above the solid curve shown in figure 8.

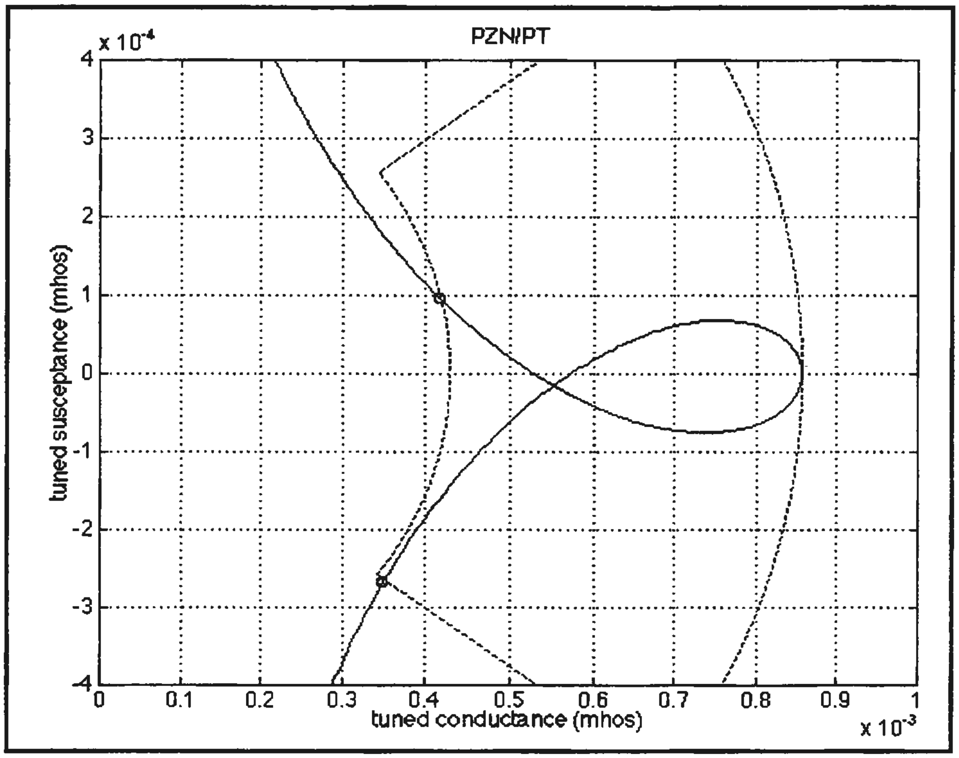

Figure 7. Parallel-Tuned Admittance Loop of 10-Inch-Diameter, 0.955 PZN-0.045 PT Transducer Array (Solid Curve) (Dashed Boundary Outlines Zone of Acceptable Admittance Variation)

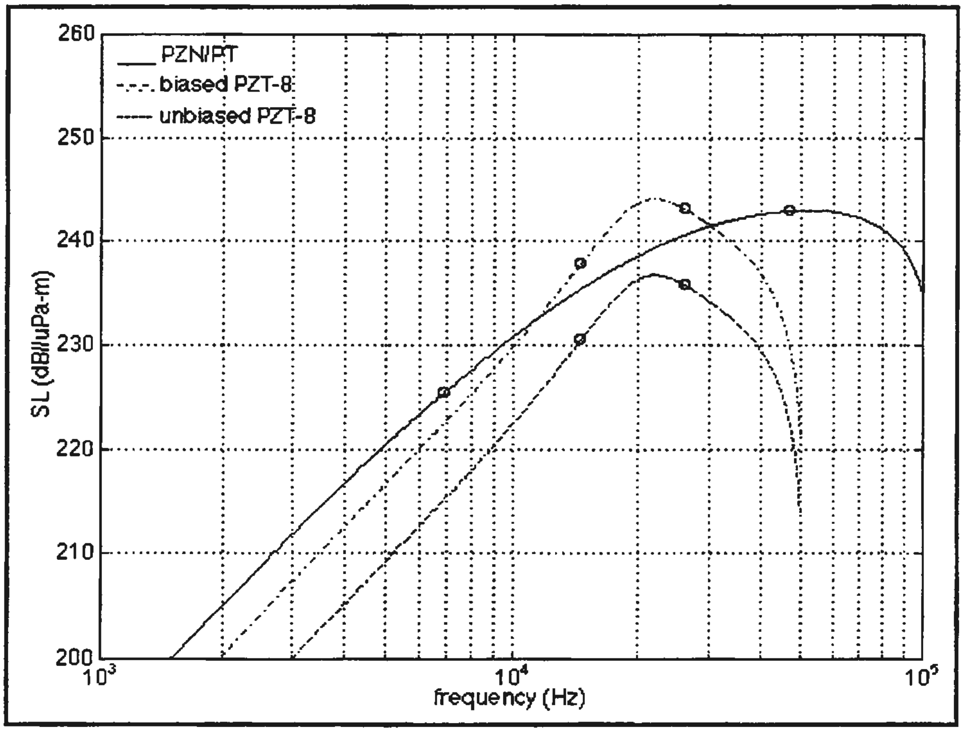

Figure 8. Source Levels of 10-Inch-Diameter Transducer Arrays Driven with the Electric Field Strengths Listed in Table 1 (Solid Curve: 0.955 PZN-0.045 PT Array; Dashed Curve: Unbiased PZT-8 Array; Dotted and Dashed Curve: Biased PZT-8 Array)

5. CONCLUSIONS AND RECOMMENDATIONS

The PZN/PT material shows promise as a high-power transducer material, as indicated by our numerical comparison of two hypothetical, 20-kHz, 10-inch-diameter projector arrays of 0.955 PZN-0.045 PT and PZT-8 tonpilz-like transducer elements, respectively. The k_{33} material coupling factor, 0.93, allows the usable bandwidth to be greatly expanded, from 11.7 kHz for PZT-8 to 40.4 kHz for PZN/PT. The source level is also increased, but not as much as the 12.7-dB increase in energy density would suggest because the mechanical quality factor and the volume of the PZN/PT are smaller than those of the PZT-8. Levels approximately 9-dB higher than the conservative ones of this study may be feasible.

Operation of PZN/PT requires a dc bias field and higher ac drive fields than are conventional, and so we have considered biased operation of PZT-8 as an alternative method for achieving higher power. Although biasing PZT-8 provides no increase in bandwidth, substantial increases (7.4 dB, in this example) in source level can be achieved this way. In future work with PZN/PT, biased operation of PZT-8 should be used as a benchmark for comparison.

There are many areas that need to be investigated before PZN/PT can begin to replace PZT-8 as a transducer piezoceramic material. The piezoelectric constants need to be measured under a variety of prestress and temperature conditions. Because of the high compliance of PZN, the prestress system has to be much more compliant than with PZT. Electric fields will, of course, be higher, and that requires improvements to be made in electrical insulation methods. Power amplifiers will have to be larger. If the greater bandwidth is to be used by extending the upper frequency of operation, the element head size will have to be reduced from that of conventional practice. This reduction in head size could invite deleterious element-to-element interaction effects that require careful study before proceeding further. Stiff, lightweight head materials, such as the graphite-epoxy postulated in this memorandum, need to be investigated.

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