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STRESS ISOLATION PZT-AIR COMPOSITES

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We describe a new piezoelectric hydrophone material, a 1-3 type Lead Zirconate Titanate (PZT)-Air composite, which is constructed in such a way that the PZT rods are isolated from stresses in the 1 and 2 directions. The theory for these new composites predicts a hydrophone figure of merit that is substantially greater than that of PZT. Measurements on the composites give values of the hydrostatic voltage coefficient of up to 235×10^{-3} Vm/N and figures of merit of the order of $41{,}000 \times 10^{-15}$ m^2/N at 2 MPa. However the hydrostatic coefficients show a substantial pressure dependence and hysteresis which is attributed to stress amplification in the PZT rods. The composites are easy to manufacture and show no signs of mechanical breakdown up to pressures of 14 MPa.

INTRODUCTION

Piezoelectric composites have been the subject of much recent study because of their possible advantages over single phase piezoelectric materials for hydrophone applications. The connectivities of the phases in the composites are important in determining the final properties of the composites.[1,2] One promising geometry studied by Klicker *et al.*[3] consisted of thin lead zirconate titanate (PZT) rods aligned perpendicular to the electrode surface and surrounded by a thermosetting polymer (epoxy); these materials are designated as 1-3 composites in the notation adopted by Newnham *et al.*[4] The theory of 1-3 composites[5–9] suggests that such composites would have a much higher hydrostatic figure of merit, $g_h d_h$, than PZT itself. Experimental results[3] showed that there was indeed a substantial improvement in the figure of merit but that the improvement was not as great as predicted by theory; besides, the figure of merit depended on the sample thickness and the cross-sectional area of the PZT rods.

The failure to obtain the theoretically predicted figure of merit is probably due to stress transfer in the polymer. When a hydrostatic stress is applied to the composite with flexible electrodes, the polymer deforms in the thickness direction rather more than the PZT rods and correspondingly applies a stress on the PZT rods in the 1 and 2 directions. Shorrocks *et al.*[10] used stiff electrodes, which ensure conditions of constant strain at the electrode boundaries, and found that the hydrostatic figure of merit increased by a factor of about 2. Recently, Xu *et al.*[11] have developed a "double-moonie" transducer with shallow cavities under thick metallic electrodes which help redirect stress from the 3 direction to the 2 and 1 directions and this results in a figure of merit which is of the order of 250 times that of PZT.

In this paper we report on the development of a new type of composite in which the PZT rods are isolated from stresses in the 1 and 2 directions and which uses stiff electrodes. As shown in Figure 1, the PZT rods are separated by air and a structural ring around the composite supports the hydrostatic stress in the 1 and 2 directions. These composites may be described as Stress Isolation PZT-Air Composites or SIPACs.

THEORY

In constructing a theory for the SIPAC we assume that the composite undergoes a constant strain in the 3 direction and that the epoxy and structural ring isolate the PZT rods from any strain in the 1 or 2 directions. The effects of possible shearing forces on the rods are ignored. In the presence of an hydrostatic pressure, P, the thick electrodes compress the PZT rods and the epoxy equally.

We consider the general case of a SIPAC with n PZT rods of total cross-sectional area $A_p = n\pi a_p^2$ where a_p is the radius of the PZT rods and l is the length of the rods and hence the separation between the electrodes. The rods are surrounded by a structural ring and epoxy of cross-sectional area $A_i = \pi(a^2 - a_i^2)$ where a is the outer radius of the ring-epoxy structure which is the radius of the composite and a_i is the inner radius of the ring-epoxy structure. If the total thickness of the epoxy between the electrodes is t_e, the application of a hydrostatic pressure, P, will produce a compression in the 3 direction which is given by

$$\delta l = \frac{P\pi a^2}{[c_{33}^{p} A_p/l + c_{33}^{e} A_i/t_e]} \tag{1}$$

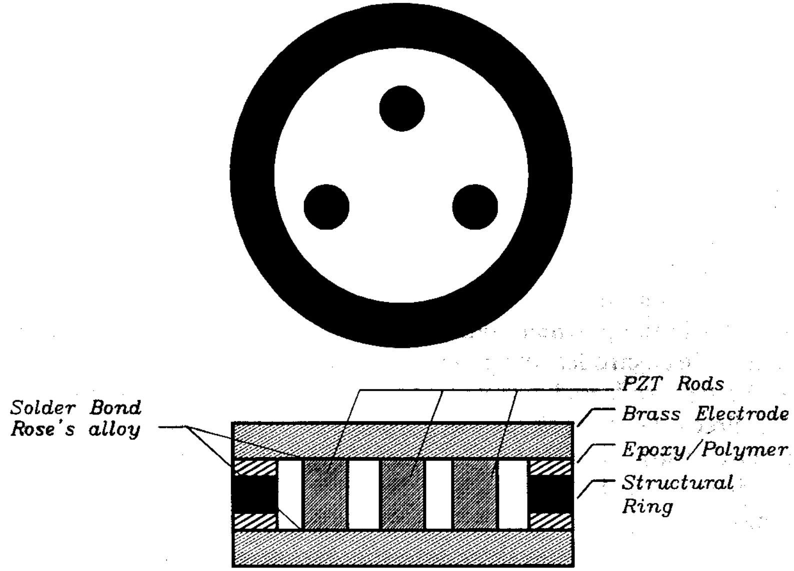

FIGURE 1 Schematic of a SIPAC with three rods.

where c_{33}^{p} and c_{33}^{e} are the coefficients of elastic stiffness in the 3 direction of the PZT and the epoxy respectively. The stress on the PZT rods is then given by

$$T = c_{33}^{p}\delta l/l \tag{2}$$

and consequently the charge generated in the rods is

$$Q = d_{33}TA_p \tag{3}$$

where d_{33} is the piezoelectric charge coefficient in the 3 direction. The capacitance of the sample is the sum of the capacitances of the PZT rods, the epoxy ring structure and the air which are all in parallel. Since the capacitance of the air is much smaller than that of the PZT rods and the epoxy-ring structure, it may be neglected and the capacitance of the composite may be written as

$$C = \varepsilon_{33}^{p}A_p/l + \varepsilon_{33}^{e}A_i/l \tag{4}$$

where ε_{33}^{p} and ε_{33}^{e} are the permittivities of the PZT and of the epoxy ring structure respectively. An effective permittivity for the composite can then be defined by

$$\varepsilon = Cl/\pi a^2 \tag{5}$$

The voltage generated by the charge Q on the composite is $V = Q/C$ and it follows that the hydrostatic voltage coefficient is given by

$$g_h = V/Pl = \frac{d_{33}c_{33}^{p}A_p}{\varepsilon l[c_{33}^{p}A_p/l + c_{33}^{e}A_i/t_e]} \tag{6}$$

The hydrostatic charge coefficient of the composite is then obtained from the expression

$$d_h = g_h\varepsilon = \frac{d_{33}c_{33}^{p}A_p}{l[c_{33}^{p}A_p/l + c_{33}^{e}A_i/t_e]} = \frac{d_{33}}{1 + \dfrac{c_{33}^{e}}{c_{33}^{p}}\cdot\dfrac{A_i}{A_p}\cdot\dfrac{1}{t_e}} \tag{7}$$

The usual figure of merit for hydrophone materials is taken to be $M = g_hd_h = d_h^2/\varepsilon$. Expression (7) shows that as the stiffness or the area of the epoxy is reduced, d_h tends to the limiting value of d_{33}; the presence of the epoxy causes the value of d_h to be somewhat smaller than d_{33}, but the function is a slowly varying one. On the other hand, since the permittivity of the epoxy as well as that of air is much smaller than that of PZT, it is clear from expressions (4) and (5) that the effective permittivity of the SIPAC can be very much smaller than that of bulk PZT. Thus the SIPAC can be expected to have a much better figure of merit than bulk PZT.

THE SPECIMENS

Our SIPACs were made using electroded and poled Navy V type PZT rods which were supplied by B. M. Hi-Tech Inc. of Collingwood, Ontario (their PZT # BM 532) and whose nominal geometries and properties are given in Table I. The electrodes were brass discs 2.54 cm in diameter and 0.3 cm thick. The rods were soldered to the brass discs using Rose's alloy, a low temperature (53°C) solder supplied by Allied Chemical and Dye Corporation; the solder was applied with a

TABLE I
Properties of Navy V PZT rods

D=2a (m)	l (m)	d_{33} (pC/N)	$\varepsilon^T_{33}/\varepsilon_o$ (#)	c^D_{33} (N/m^2)
.00325	0.00315	580	3200	8.5×10^{10}

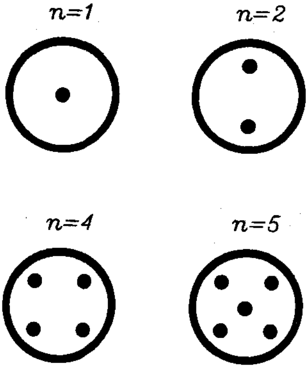

FIGURE 2 Schematic showing the positioning of the rods for our SIPAC specimens.

heat gun and a Wood's metal flux. The epoxy used was Cole-Parmer's 8778 extra fast setting epoxy. The epoxy was applied by mounting the sample on a jeweler's lathe and pushing the epoxy into the space between the stiff electrodes and the structural ring. The structural isolation ring for these samples consisted of two vulcanized fiber washers (1 in. × 0.75 in. × 1/32 in.) manufactured by Spae-Naur. The number of rods, n, ranged from 1 to 5 and the positioning of the rods is shown in Figure 2. Samples were left to cure at room temperature for 1 week prior to measurements. The photograph in Figure 3 shows a finished SIPAC in the background while the foreground shows the two brass electrodes, two PZT rods and two vulcanised fiber washers.

RESULTS

The capacitance, C, and the piezoelectric charge coefficient, d_{33}, of each SIPAC were measured both before and after the epoxy was applied and Figures 4 and 5 show the measured values plotted as a function of the number of rods in each SIPAC. The capacitance increases linearly with the number of rods and there is a slight increase in the capacitance after application of the epoxy. Figure 5 shows that prior to the application of the epoxy d_{33} is more or less independent of the number of rods. However, the application of the epoxy reduces d_{33} and the decrease depends on the number of rods in the SIPAC. The decrease is caused by the epoxy supporting a part of the stress in the 3 direction; as the number of rods is increased, a larger fraction of the stress is supported by the PZT rods and hence the reduction in d_{33} becomes smaller.

The admittance of each SIPAC has been measured as a function of frequency.

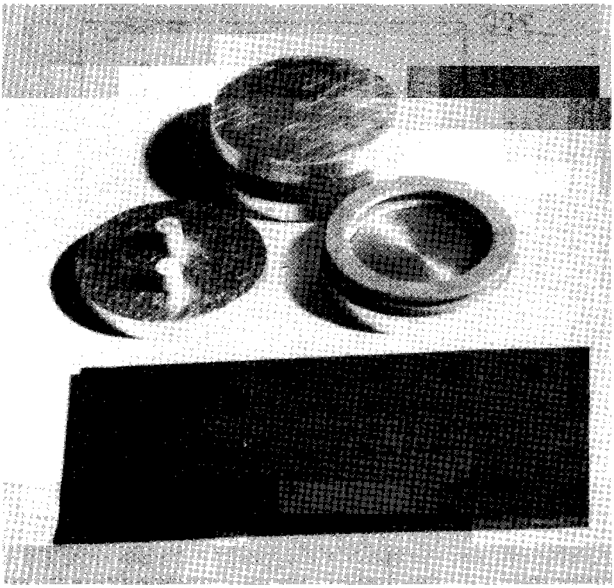

FIGURE 3 Photograph of a SIPAC: the constituent parts are shown in the foreground and a finished SIPAC is shown in the background.

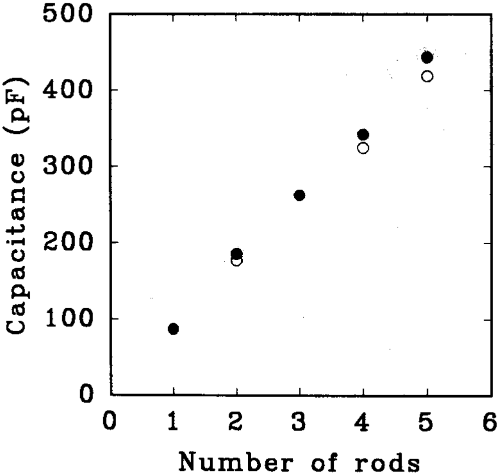

FIGURE 4 The capacitance of the SIPACs as a function of the number of rods. The solid circles (●) represent the capacitance after the epoxy was applied. The open circles (○) represent the capacitance before the epoxy was applied.

The first minor resonances begin to occur at frequencies of around 7 kHz and this value would therefore represent the upper limit of the useful frequency range of the SIPACs when used in non-resonant devices.

Figures 6 and 7 show the variation of the hydrostatic voltage coefficient, g_h, and the figure of merit, g_hd_h, of the SIPACs as a function of the hydrostatic pressure. In calculating these values, the length of the PZT rods has been used as the thickness of the specimen, and therefore the values given represent the upper limits for g_h

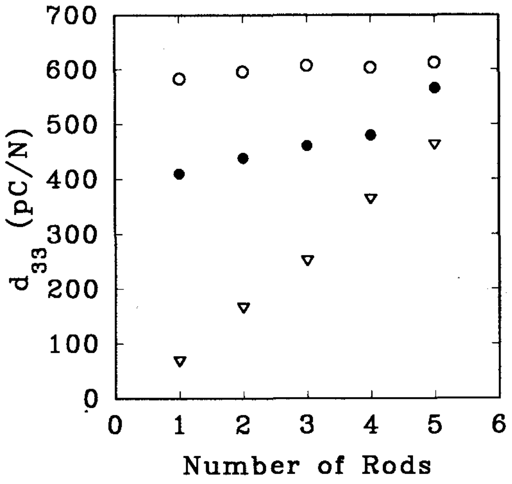

FIGURE 5 The piezoelectric charge coefficient of the SIPACs as a function of the number of rods, showing the influence of the epoxy and of a hydrostatic pressure cycle. The solid circle (●) is the piezoelectric charge coefficient after the epoxy was applied. The open circle (○) is the piezoelectric charge coefficient before the epoxy was applied. The open triangle (▽) is the piezoelectric charge coefficient after the SIPACs had been put through one hydrostatic pressure cycle going up to 14 MPa.

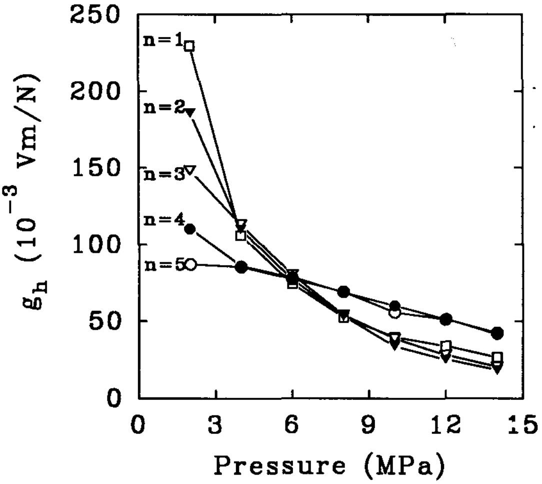

FIGURE 6 The hydrostatic voltage coefficient as a function of the hydrostatic pressure, as the pressure is increasesd. The different curves represent the different number of rods in each SIPAC.

and $g_h d_h$; this is consistent with the practice of other authors who have used stiff electrodes.[10,11] The values of g_h and $g_h d_h$ for the structure as a whole can be obtained by multiplying the given values by l/t_t where l is the length of the rod and t_t is the total thickness of the SIPAC.

We note from Figure 6 that g_h decreases substantially as the hydrostatic pressure is increased. As the number of rods is increased, the g_h at low pressures decreases but the pressure dependence also decreases. We should also point out that g_h shows hysteresis, although for reasons of clarity the curve showing g_h as the pressure is decreased is not shown in our figure. The hysteresis decreases as the number of

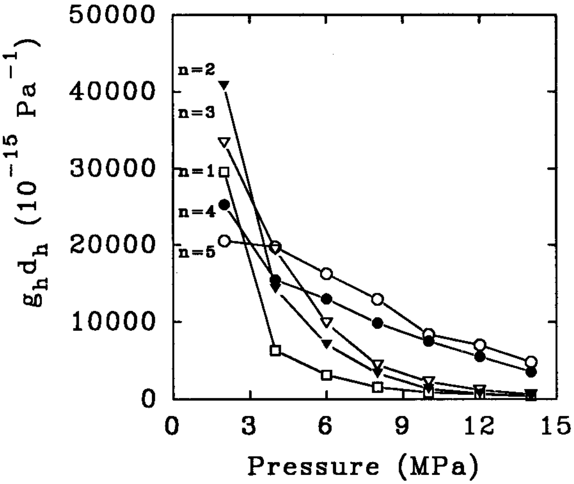

FIGURE 7 The hydrostatic figure of merit as a function of the hydrostatic pressure as the pressure is increased. The different curves represent the different number of rods in each SIPAC.

rods is increased. The d_{33} values of the SIPACs were measured after they had been taken through an hydrostatic pressure cycle and there was a substantial decrease compared to the d_{33} before the application of the hydrostatic pressure, as shown in Figure 5. We therefore conclude that the hysteresis is caused by depoling due to the very high stresses to which the rods are subjected during the application of the hydrostatic pressure on the SIPACs. The hydrostatic pressure on the electrodes is supported by the PZT rods and the epoxy. If the support given by the epoxy is neglected, the stress on the PZT rods themselves can be deduced from expression (2) and is given by

$$T = \frac{Pa^2}{na_p^2} \tag{8}$$

Clearly, the stress on the PZT rods is much greater than the stress on the electrodes and this amplification of the stress is a function of the number of rods. The large mechanical stress on the rods can cause depoling and Equation (8) explains why the depoling and the hysteresis decrease as the number of rods is increased. Indeed a plot of g_h as a function of T reveals a pressure dependence that is similar for all the SIPACs. The stress amplification also suggests that the SIPACs may be destroyed by shock waves.

In Figure 7 it can be seen that the figure of merit, $g_h d_h$, also decreases as the hydrostatic pressure is increased. At low pressures, the highest value of $g_h d_h$ was found to be $41{,}000 \times 10^{-15}$ m^2/N for the SIPAC with 2 rods. Once again the pressure dependence decreases as the number of rods increases and our results suggest that it might be possible to make the figure of merit relatively independent of pressure with a larger number of rods than contained in our SIPACs while maintaining a value of around $10{,}000 \times 10^{-15}$ m^2/N which is still about two orders of magnitude better than the $g_h d_h$ value for PZT.

CONCLUSIONS

We have constructed a new type of piezoelectric composite, a 1-3 type PZT-air composite with stress isolation, and we have found that composites of this type can have very high values of the hydrostatic voltage coefficient (up to 235×10^{-3} Vm/N) and the figure of merit ($g_h d_h$ up to $41{,}000 \times 10^{-15}$ $\mathrm{m^2/N}$). The hydrostatic coefficients of these composites were found to be pressure dependent but this dependence decreased as the number of rods in the composite were increased. The composites were easy to make and they showed no signs of mechanical breakdown up to hydrostatic pressures of 14 MPa.

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