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A DESIGN FOR OPTIMIZING THE HYDROSTATIC PERFORMANCE OF 1-3 PIEZOCOMPOSITES

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ABSTRACT

Improvement in the hydrostatic performance of 1-3 piezocomposites can be obtained through amplification of the axial stress or reduction of the lateral stress in the piezoceramic phase. In the current work, a graded interlayer design is introduced which enables both reduction in lateral stress and axial stress amplification, simultaneously. The interlayer is stiffer at the edges of the rod to enhance load transfer and axial stress amplification and softer along the interior region of the rod to attenuate lateral stresses. The hydrostatic response of a composite with such a graded interlayer is evaluated using the finite-element method. The present graded interlayer design provides improved electromechanical coupling and greater design flexibility.

1. INTRODUCTION

The key principle in designing piezoelectric ceramic-polymer composites is to maximize the electromechanical coupling. Maximum coupling is achieved by building a composite structure that transfers the applied external stresses to the composite's piezoelectric component in a manner that most nearly approximates the piezoceramic's maximally coupled stress patterns[1]. Piezocomposites with 1-3 connectivity have been used extensively for hydrophone applications because of the improved hydrostatic performance over a homogeneous piezoceramic. A typical 1-3 piezocomposite is shown schematically in Fig. 1 and consists of an array of aligned, piezoelectric ceramic rods embedded in a passive polymer matrix.

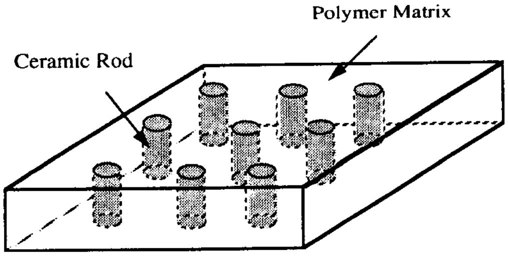

FIGURE 1. Schematic of a 1-3 piezocomposite.

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For a homogeneous piezoceramic, the volume average of the pure hydrostatic pressure-induced electric displacement is given by

$$D_z = -d_h p \tag{1}$$

where p is the pressure and the hydrostatic piezoelectric coefficient d_h of the piezoceramic is defined as $d_h = 2d_{31} + d_{33}$. Due to the opposite sign of the piezoelectric charge coefficients d_{33} and d_{31}, the net hydrostatic piezoelectric effect is small even though the magnitudes of both d_{33} and d_{31} are large. In a piezocomposite, the volume average of the hydrostatic pressure-induced electric displacement is given by

$$\langle D_z \rangle = \langle d_{31} T_{rr} \rangle + \langle d_{31} T_{\theta\theta} \rangle + \langle d_{33} T_{zz} \rangle + \langle \varepsilon_{33}^T E_z \rangle \tag{2}$$

where ε_{33}^T is the dielectric constant of the piezoceramic, E_z is the electric field, T_{ij} are the stress components induced in the rod, and $\langle \bullet \rangle$ represents volume average. Hence, the effective hydrostatic piezoelectric constant of the 1-3 piezocomposite is expressed

$$\bar{d}_h = \frac{\langle D_z \rangle}{-p}. \tag{3}$$

The volume average of the stress-induced electric displacement $\langle D_z \rangle$ is dependent on the volume average axial stress and volume average lateral stress in the piezoceramic rods. Because of the stress transfer from the passive polymer phase to the piezoelectrically active ceramic phase, the hydrostatic response of this piezocomposite can be dramatically improved over the single-phase piezoceramic. For the design of 1-3 piezocomposites, the goal of maximizing the electromechanical coupling can be achieved either by increasing the axial stress or by effectively reducing the lateral stress in the piezoceramic rods. In the current work, a novel graded interlayer design is introduced which enables both reduction in lateral stress and axial stress amplification, simultaneously. The interlayer design is motivated by the mechanisms for improved hydrostatic performance summarized in the next section.

2. MECHANISMS FOR IMPROVED HYDROSTATIC PERFORMANCE

In a previous study by Li and Sottos[2], a micromechanics model was developed for studying the hydrostatic response of 1-3 and 1-1-3 piezocomposites. A parametric study was performed to systematically examine the influence of matrix stiffness, rod aspect ratio, interlayer stiffness, and rod volume fraction on the hydrostatic performance in terms of the effective hydrostatic piezoelectric coefficients. The rods were chosen to be PZT-5H and the matrix to be Spurr epoxy. Material properties for the piezoceramic and the epoxy are listed in Tables I and II, respectively. Relevant geometric data for the calculation include a rod radius of 0.75 mm, interlayer thickness of 0.1 mm, and rod length of 10 mm. Effects which led to either an increase in axial stress or reduction in lateral stress are summarized below.

2.1. Stress Amplification in 1-3 Piezocomposites

Li and Sottos[2] calculated the effective hydrostatic piezoelectric constant $\bar{d}_h$ for a range of rod volume fractions (no interlayer) as shown in Fig. 2a. The effective $\bar{d}_h$ for the piezocomposite exceeds the d_h of the constituent ceramic, approaching a value three times as high as that of pure PZT-5H ($d_h = 45 \times 10^{-12}$ m/V) at a rod volume fraction of 20%. The product of the normalized average stresses in the PZT rods, the appropriate piezoelectric constant and the rod volume fraction are also plotted in Fig. 2a. According to Eq. (2), the difference between the curve corresponding to the average axial stress and the curve related to the lateral stress is exactly the effective hydrostatic constant $\bar{d}_h$. There is a large amplification in the axial stress T_{zz} especially at lower rod volume fractions. Although the lateral stress is also slightly increased, competition between the axial stress, the lateral stress and the volume fraction of the PZT rod leads to an enhanced effective hydrostatic piezoelectric constant $\bar{d}_h$. Thus, axial stress amplification is beneficial for the enhancement of $\bar{d}_h$. .

A parametric study was carried out to assess the influence of PZT-5H rod aspect ratio, $2l/d$, on $\bar{d}_h$. The peak value of $\bar{d}_h$ was found to increase with increasing aspect ratio, but there was a saturation of the effect for $2l/d > 500$. Thus, the enhancement of axial stress in the PZT rod from increasing the rod aspect ratio has an upper limit. The influence of matrix stiffness on $\bar{d}_h$ was also investigated. The peak $\bar{d}_h$ increased with decreasing matrix stiffness but also saturated for a very soft matrix. The effect of softening the matrix is similar to the effect of increasing the PZT rod aspect ratio, causing axial stress amplification which is significant at low PZT rod volume fractions.

TABLE 1. Elastic and piezoelectric properties of PZT-5H rod.

Property	PZT 5H	Property	PZT 5H
$c_{11}^{(1)}$ (GPa)	126	e_{31} (C/m^2)	-6.55
$c_{12}^{(1)}$ (GPa)	79.5	e_{33} (C/m^2)	23.3
$c_{13}^{(1)}$ (GPa)	84.1	e_{15} (C/m^2)	17.0
$c_{33}^{(1)}$ (GPa)	117	d_{31} $(10^{-12}\, m/V)$	-274
$c_{44}^{(1)}$ (GPa)	23.0	d_{33} $(10^{-12}\, m/V)$	593
ε_{33}^{T}	3400 ε_0	d_h $(10^{-12}\, m/V)$	45

TABLE 2. Elastic properties of Spurr Epoxy.

Y^0 (GPa)	ν
2.101	0.3

2.2. Lateral Stress Reduction in 1-1-3 Piezocomposites

Because the actual stress transfer is through the interface between the rods and the matrix, the introduction of a thin interlayer between the rods and the matrix can influence composite behavior. Kim, Rittenmyer and Kahn[3] showed that by casting a soft epoxy interlayer between PZT rods and a stiff polymer preform matrix, a 1-1-3 piezocomposite with a high hydrostatic charge constant can be obtained. Sherrit, Wiederick and Mukherjee[4] also described a 1-3 type PZT-air piezocomposite with extremely high effective hydrostatic piezoelectric constants and figure of merit.

Theoretical predictions by Li and Sottos[2] demonstrated that the introduction of a thin soft interlayer greatly reduces the lateral stress in the PZT rod. The effect of the lateral stress reduction for the case of a soft interlayer is illustrated in Fig. 2b. The product of the average stress in the PZT rods, the piezoelectric constant and the rod volume fraction are plotted along with $\bar{d}_h$ for an interlayer 100 times more compliant the surrounding matrix modulus ($Y_{interlayer} = Y^{\circ}/100 = 0.021$ GPa).

A comparison with Fig. 2a reveals that there is a large reduction in the lateral stress for the compliant interlayer. Although the axial stress is also slightly decreased, competition among the axial stress, the lateral stress and the volume fraction of the PZT rod gives an enhanced effective hydrostatic piezoelectric constant $\bar{d}_h$ for rod volume fractions between 20% and 45%. The lateral stress reduction through the introduction of a thin, soft interlayer is also beneficial for the enhancement of $\bar{d}_h$ at higher volume fractions.

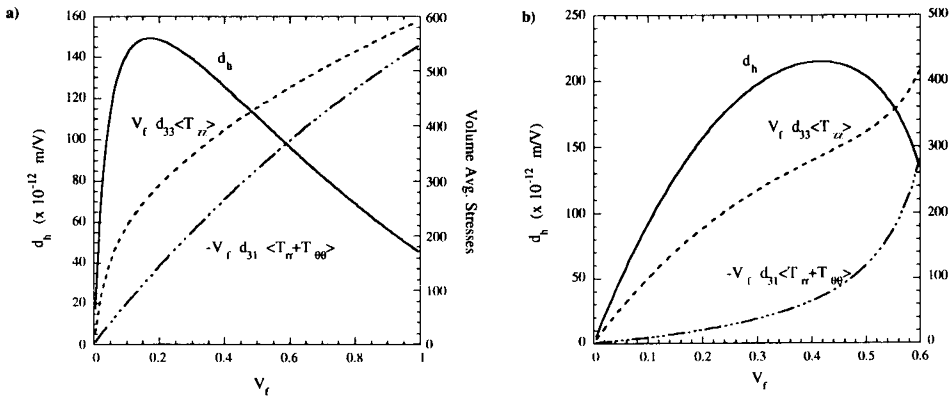


FIGURE. 2. Interactions between $\bar{d}_h$, the axial stress and the lateral stress as a function of rod volume fraction for a) no interlayer and b) a compliant interlayer.

3. A TAILORED INTERLAYER FOR IMPROVED PERFORMANCE

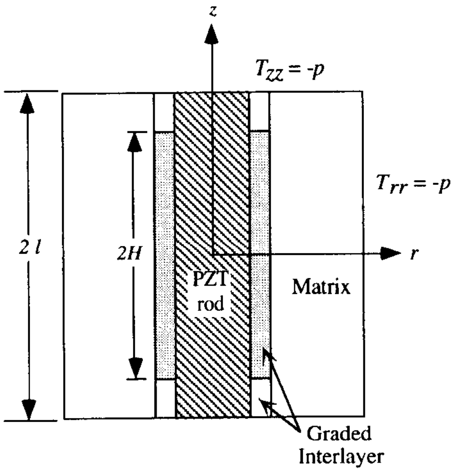
The lateral stress reduction and axial stress amplification summarized in Section 2 were not obtained simultaneously. In order to improve the hydrostatic performance further, the interlayer in a piezocomposite can be tailored to enhance both these effects. An interlayer that is functionally graded along the axis of the rod, such that it is stiffer at the edges of the rod to enhance axial stress amplification and softer along the interior region of the rod to reduce lateral stresses should be able to exploit both effects. Based on this concept, a tailored interlayer design was developed as shown schematically in Fig. 3. Evaluation of the hydrostatic response of a composite with such an interlayer was conducted using the finite-element method.

3.1. Finite Element Model

A composite cylinder model was used to represent a single piezoceramic rod, the interlayer and the surrounding matrix. The interlayer consisted of two parts, the core and the edge, each with distinctive material properties. The composite model was developed with 8-node quadrilateral elements (CAX8RE elements in ABAQUS) for a total of 5400 elements. The finite-element analysis was conducted using ABAQUS (Hibbitt Karlsson & Sorenson Inc.) software. The boundary conditions applied to the outer edge of the composite are also shown in Fig. 3. Symmetry is enforced along both the r and z axis. Material properties for the piezoceramic and epoxy matrix are taken from Tables I and II. Relevant geometric data are rod radius of 0.75 mm, interlayer thickness of 0.1 mm, rod length ($2l$) of 10 mm and interlayer core length ($2H$) of 8 mm. For this preliminary study, the modulus of the interlayer edge was chosen as same as the matrix (Y_{edge}= 2.1GPa) and the modulus of the interlayer core was chosen to be one hundreth of the matrix moduls (Y_{core} = 0.021 GPa).

3.2. Predictions of $\bar{d}_h$ for the tailored interlayer

The effective piezoelectric constant $\bar{d}_h$ for the graded interlayer is plotted in Fig. 4. The theoretical predictions by Li and Sottos[2] for a uniform interlayer are also shown in Fig. 4. Finite-element results are depicted by open or closed symbols while solid or dashed lines represent analytical solutions from Li and Sottos[2]. The current finite element analysis is in excellent agreement with the theoretical solution for the case of no interlayer. The composite with the graded interlayer has a much broader peak in $\bar{d}_h$ when compared to the composite with a uniform compliant interlayer. At low rod volume fractions, the graded interlayer shows improved performance over the uniform interlayer. At higher volume fractions, however, the $\bar{d}_h$ value for the graded interlayer levels off and is slightly lower than that of the uniform case.



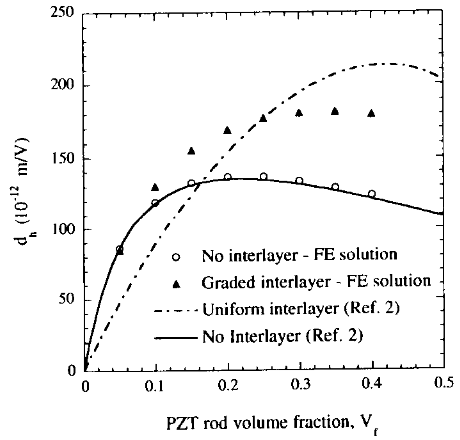


FIGURE 3. Schematic of a 1-3 piezocomposite with a tailored interlayer.

FIGURE 4. Prediction of $\bar{d}_h$ for a 1-3 piezocomposite with a tailored interlayer.

4. DISCUSSION AND CONCLUSIONS

To optimize electromechanical coupling in a piezocomposite, a composite structure must be designed that transfers the external stresses to the active piezoelectric component in a manner that most nearly approximates the piezoelectric's maximally coupled stress pattern. Improvement in hydrostatic performance of 1-3 piezocomposite can be obtained through amplification of axial stress and/or reduction in lateral stress in the piezoceramic. Increasing the rod aspect ratio or decreasing the matrix stiffness both increase the $\bar{d}_h$ due to axial stress amplification and increased load transfer. However, piezocomposites are typically fabricated with small rod aspect ratios due to poling limitations and difficulties may exist in fabricating an entire composite with a very compliant matrix. The $\bar{d}_h$ can also be increased by introducing a compliant interlayer around the PZT rods. A compliant interlayer significantly increases the $\bar{d}_h$ by effectively attenuating the lateral stress in the PZT rods without decreasing the overall stiffness of the composite. Unfortunately, a higher volume fraction of rods is also necessary in order to obtain increased performance using a compliant interlayer.

To improve the hydrostatic performance of a 1-3 piezocomposite further, the interlayer can be tailored to enhance both reduction in lateral stress and axial stress amplification. An interlayer that is functionally graded along the axis of the rod, such that it is stiffer at the edges of the rod to enhance load transfer and axial stress amplification and softer along the interior region of the rod to reduce lateral stresses, exploits both effects. The graded interlayer design shows improved performance over a uniform compliant interlayer at low rod volume fractions. Hence, the graded interlayer design provides higher electromechanical coupling and greater design flexibility.

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