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Determination of Macroscopic Electro-Mechanical Characteristics of 1–3 Piezoceramic/Polymer Composites by a Concentric Tube Model

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Abstract—An axisymmetric concentric tube model of a piezoelectric rod and a concentric elastic tube is used to characterize 1–3 piezoelectric/elastic composites macroscopically. The model is based on the following assumptions: the wavelength of mechanical waves is large compared to the distance between adjacent rods, displacements follow the separable static solutions for tubes, the electric field is constant, and displacements are continuous across the interface between the rod and the tube. With average displacements of and total forces on the surfaces as the mechanical degrees of freedom, and with charge and potential at the ends of the rod as the electrical degrees of freedom, the relation between the electromechanical degrees of freedom is given in matrix formulation. The formulation resembles the use of element stiffness matrices in the finite element method. A recursive numerical scheme for combining the matrix for the tube and the piezoelectric rod into one for the composite piezoelectric rod is used to directly identify the majority of the $e$-set of constitutive constants for 1–3 composites. The remaining constitutive constants are estimated from a cubes model, to allow inversion of the $d$-g-, and $h$-sets and calculation of other characteristics.

I. INTRODUCTION

PIEZO ELECTRIC/POLYMER COMPOSITES have promising characteristics for use in ultrasonic transducers. Due to the low transverse coupling factor, $k_t$, they can be used for undiced array transducers, but also as replacement in more conventional transducers, they offer a higher longitudinal coupling factor, $k_{33}$, lower acoustic impedance and higher damping than pure piezoceramics do. In a strict sense they also have a higher degree of anisotropy, stop-bands, and other characteristics that greatly complicate an analysis. For practical use, however, these effects are often negligible. Furthermore there is considerable variation in the characteristics of the constituent materials and some randomness in the structure of the composite, which preclude very accurate estimates. The aim of the present paper is to present a simple, and yet fairly accurate model, the concentric tube model, which can be used to characterize 1–3 composites by average values, as if they were homogeneous piezoceramics. The concentric tube model estimates the six technically most important constants of the nine constants in the $e$-set.

The classical models [1] are the Voigt model, which assumes constant strain in the material, and the Reuss model, which assumes constant stress. For a 1–3 composite, i.e., piezoelectric rods in an elastic matrix, Young's modulus may be found with excellent agreement using the Voigt model [2], and the Bulk modulus of a 1–3 composite can be well estimated using the Reuss model [3]. For other connectivities or constants these models are not appropriate. More refined models are: The parallel-serial model [4], the cube model [5], and the method by Chan and Unsworth [6]. These methods are all based on the assumptions that either a strain component or the corresponding stress component is constant in the two phases, and they lead to selective use of the mixture rules of the Voigt or the Reuss type, possibly to repeated use of such rules. Hashimoto and Yamaguchi solves the one-dimensional problem of a 2–2 composite as well [7].

Unlike the methods in [1]–[7], the concentric tube model introduces explicit displacement assumption that leads to inhomogeneous strains, that are physically realistic, by choosing the quasi-static solutions as displacement functions. The essence of the method is to model a composite rod under axisymmetric load, and then to assume the composite rod to be typical for a larger volume of a 1–3 composite. This assumption is supported by the following observation. Consider a composite of circular rods in a hexagonal pattern. Under uniaxial stress in the axial direction, points with zero transverse displacement will form a hexagonal pattern. The largest distance between one of the hexagons and an average circle, is as little as 0.067 times the radius of the circle. Neglecting this difference is far from equivalent to introducing an error of the same magnitude, but is rather an averaging at an early stage. A consequence of the axisymmetry of the concentric tube model is that it leads to transversely isotropic material data which is true for the circular rods in a hexagonal pattern, but only approximately true for less symmetric structures.

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II. CONCENTRIC TUBE MODEL OF 1-3 COMPOSITES

The building block for the concentric tube model is the circular piezoelectric tube shown in Fig. 1. The displacement, \( u \), and the electric potential, \( \phi \), are assumed to follow the separable axisymmetric quasi-static solutions:

\[
    u_r = a_r x_r + \frac{a_i}{x_r}; \quad u_z = a_z x_z; \quad \phi = a_\phi x_z
\]

(1)

where \( x_r \) and \( x_z \) are the coordinates in the radial and axial direction respectively. The indices on \( u \) refer to the direction of the displacement. \( a_r, a_i, a_z, \) and \( a_\phi \) are constants, that are determined from the voltage, \( V \), across the tube and the following typical (nodal) displacements that are shown in Fig. 1: \( U_r \) and \( U_z \) are the radial displacement at the inner and the outer surface of the tube, and \( U_z \) is the axial displacement difference between the two ends of the tube. The displacements and the electric potential are used to derive the strain vector, \( \sigma_{ij} \), and the electric field vector, \( E_{ij} \). The stress vector, \( \sigma_{ij} \), and the dielectric displacement vector, \( D_{ij} \), are then found, using the \( e \)-set of the constitutive equations [8]:

\[
    T_{ij} = C_{ij} \sigma_{j} - \varepsilon_{ij} E_{k}
\]

\[
    D_{ij} = \varepsilon_{ij} \sigma_{k} + \varepsilon_{sk} E_{j}
\]

where \( \alpha, \beta = 1, 2, 3; \quad i, j = 1, \cdots, 6; \) and summation over repeated indices is implied. Integration of normal stress and dielectric displacement over the surfaces of the tube finally gives the total forces and total electric charge.

For the actual model only two special cases of the piezoelectric tube are needed, the piezoelectric rod and the elastic tube. The “stiffness” matrix for the piezoelectric rod can be written as

\[
    \begin{pmatrix}
        F_z \\
        F_r \\
        F_R
    \end{pmatrix}
    = 2\pi
    \begin{pmatrix}
        C_{33} \frac{R^2 - r^2}{2h} & -C_{13}r \\
        -C_{13}r & C_{11} \frac{R^2 + r^2}{2h} - C_{12}h \\
        C_{13}R & -C_{11}h \frac{2Rr}{R^2 - r^2} + C_{12}h
    \end{pmatrix}
    \begin{pmatrix}
        U_z \\
        V \\
        U_r
    \end{pmatrix}
\]

(3)

where \( h \) is the height of the rod, \( r \) is the radius of the rod that equals the inner radius of the tube; \( F_z \) and \( F_r \) are the forces on the plane and the curved face of the rod and \( Q \) is the electric charge. The elastic tube gives

\[
    \begin{pmatrix}
        U_z \\
        U_r
    \end{pmatrix}
    = \frac{C_{11}R}{Q}
    \begin{pmatrix}
        U_z \\
        U_r
    \end{pmatrix}
\]

(4)

which is the radial force at the outer surface of the tube. Superscript \( E \) on the elastic constants has been omitted, as the material is not piezoelectric.

By assuming \( U_z \) and \( U_r \) to be equal for the two elements, the matrices of (3) and (4) can be assembled into one \( 4 \times 4 \) composite matrix with \( U_z, V, U_r, \) and \( U_R \) as independent degrees of freedom.

\[
    \begin{pmatrix}
        C_{11}R \\
        0 \\
        0 \\
        C_{11}R
    \end{pmatrix}
    \]

(5)

The displacement at the interface between rod and tube, \( U_z \), is an internal degree of freedom and is eliminated. The elimination of internal degrees of freedom can be described as follows. First the matrix equation is partitioned into

\[
    \begin{pmatrix}
        F_a \\
        F_r
    \end{pmatrix}
    = \begin{pmatrix}
        K_{aa} & K_{ar} \\
        K_{ra} & K_{rr}
    \end{pmatrix}
    \begin{pmatrix}
        U_a \\
        U_r
    \end{pmatrix}
\]

(6)

where \( U_a \) is a vector of the displacements or electrical potential of the degrees of freedom that are retained. \( U_r \) is the displacement that is eliminated. \( K_{aa}, K_{ar}, \) and \( K_{rr} \), and \( K_{ra} \) are submatrices of the assembled matrix. The external force on the interface between the rod and the tube, \( F_z \), is set to zero whereby \( U_a \) can be expressed as \( U_r = -K_{ra}^{-1} K_{ra} U_a \). This is inserted in the upper part of (6) to give

\[
    F_a = (K_{aa} - K_{ar} K_{ra}^{-1} K_{ra}) U_a.
\]

(7)

This result is valid for any number of eliminated degrees of freedom, but in the actual case, the result is a \( 3 \times 3 \) matrix, a superelement for the composite piezoelectric rod, with exactly the same degrees of freedom as the piezoelectric rod. An equivalent homogeneous rod would therefore have the stiffness matrix already given in (3).
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Fig. 1. Tube element.

Fig. 2. Comparison of $d_{33}$ and $e_{33}$ estimates. PZT/Stycast comparison of methods.

The constitutive constants, $(C_{11}^E + C_{12}^E)$, $C_{13}^E$, $C_{33}^E$, $e_{31}$, $e_{33}$, and $e_{33}$, can be seen to be directly identifiable in the composite stiffness matrix by the use of (3). The remaining constants, $e_{15}$ and $e_{11}$, plus $C_{11}$ and $C_{12}$ individually are found using a cube model. The last three constants may be of little technical interest, but with the complete $e$-set of constants, the $d$-, $g$-, and $h$-set can be found directly from their definitions by (partial) inversion of the material constant matrices.

III. RESULTS

For comparison the $d_{33}$ and $d_h$ coefficients have been calculated for the PZT5/Stycast example from [8]. The result is shown in Fig. 2. The results are calculated with the method of Haun and Newnham (H) [4], Chan and Unsworth (C) [6], and the concentric tube model (T). The material data used in the calculation can be found in Table I and II. It can be seen that all three methods agree on the value of $d_{33}$ whereas there is some difference in the estimates of $d_h$. The concentric tube model gives results in between the other two methods, but agrees best with the results of Chan and Unsworth. The difference between the methods is so insignificant, that it is not possible from available experimental results to tell which gives the most reliable estimates.

The Figs. 3–6 show the $d$-, $g$-, $e$-, and $h$-constants for a PZTSH/Araldite composite. It can be noted that these
The idea of averaging by elimination of internal degrees of freedom followed by matching the reduced matrices for a homogeneous and a composite system is also applicable to the finite element methods as an alternative to using the finite-element method to simulate experimental characterization [10], [11].

REFERENCES


Henrik Jensen was born in Copenhagen, Denmark in 1957. He received the M.S. in electrical engineering and the Ph.D. in mechanical engineering from the Technical University of Denmark, Lyngby, Denmark in 1981 and 1985.

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