1-3 COMPOSITES FOR TRANSDUCERS

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1.INTRODUCTION

1-3 composites in which ceramic rods are aligned in a polymer matrix are of interest for both medical and sonar applications [1,2]. This paper outlines some of the work carried out during the EURAM contract no. MA1E-0075-C, "Piezoelectric Ceramic/Polymer Composites", supported by the Commission of the European Communities. The partners in the project were Ferroperm A/S (Denmark), Leeds University, Morgan Matroc, Unilator Division and the Technical University of Denmark (TUD). In particular, a model developed by TUD is described and composite properties presented as a function of the volume fraction of ceramic phase.

2.MODELLING OF 1-3 COMPOSITES

2.1 Introduction

The periodicity of a 1-3 composite readily lends itself to analysis using simple models. For a tubular element (Fig.6) in which a ceramic rod is encapsulated in a polymeric cylinder, the elastic constant of the assembly can be predicted from the elastic constants of the two phases by assuming a uniform strain state in the z direction (Voigt model) and a uniform stress state in the transverse direction (Reuss model). This approach has been successfully developed by Haun and Newnham [3] who predicted the variations in d and g coefficients with volume fraction of ceramic, V_f. A more general technique, developed by TUD, which satisfies both the Voigt and Reuss conditions is presented here.

2.2 TUD Model

The problem is to determine a full set of piezoelectric, dielectric and elastic constants for the composite. It is assumed that during thickness resonance both the rods and the polymer move in phase; indeed, without this constraint no macroscopic properties can be assigned to the composite. The material constants relate the stress, T, and strain, X, or the electric field, E, and dielectric displacement, D, by the equations.

$$d = \frac{\{D\}}{\{T\}_E} = \frac{\{X\}}{\{E\}_T} \quad (1)$$

$$e = \frac{\{D\}}{\{X\}_E} = -\frac{\{T\}}{\{E\}_X} \quad (2)$$

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$$g = \frac{\{E\}}{\{T\}_D} = \frac{\{X\}}{\{D\}_T} \qquad (3)$$

$$h = -\frac{\{E\}}{\{X\}_D} = -\frac{\{T\}}{\{D\}_X} \qquad (4)$$

The model described here calculates the stresses, strains, electric field and dielectric displacement in idealised element from the material constants for both the ceramic and the polymer phases. A simple unit cell consisting of a ceramic rod in a polymer tube is considered. Using the material constants for each phase, the stresses, strains and dielectric displacement are calculated at constant electric field. Having done this a new set of material constants are calculated for a homogeneous material (the composite) which, on average, give the same stresses, strains etc.
A tube element (Fig.6) is used which consists of a ceramic rod in a polymer tube. At any point in each phase the displacements, u, are given by the equations:

$$u_r = a_r r + \frac{b_r}{r} \qquad \text{(radial)} \qquad (5)$$

$$u_z = a_z z \qquad \text{(axial)} \qquad (6)$$

where the subscripts r and z refer to the radial and axial directions respectively, r is the radius of the rod and b_r is the coordinate in the radial direction.
The electric potential, Ø, is given by the equation:

$$\emptyset = a_{\emptyset} z \qquad (7)$$

This tube element has four degrees of freedom, namely radial displacement at both inner and outer radii, axial contraction and axial potential difference. Note that in each element only three degrees of freedom are required as the polymer is not piezoelectric and the inner radius of the ceramic rod is zero.
A stiffness matrix can now be generated which relates the degrees of freedom of the ceramic (u_z, u_r) and the polymer (u_z, u_R) and the potential V to the faces F_r, F_z, F_R and F_z and the electric charge Q.
For the ceramic rod the matrix is given by

$$\begin{Bmatrix} F_z \\ -Q \\ F_r \end{Bmatrix} = 2\pi \begin{bmatrix} C^E_{33}\frac{r^2}{2l} & -e_{33}\frac{r^2}{2l} & C^E_{13}r \\ -e_{33}\frac{r^2}{2l} & -\epsilon^S_{33}\frac{r^2}{2l} & -e_{31}r \\ C^E_{13}r & -e_{31}r & (C^E_{11}+C^E_{12})l \end{bmatrix} \begin{Bmatrix} u_z \\ V \\ u_r \end{Bmatrix} \qquad (8)$$

where C_{ij} are the stiffness constants,
ϵ_{33} is the permittivity,
l is the length of the tube element

For the polymer tube the matrix is given by

$$\begin{bmatrix} F_z \\ F_r \\ F_R \end{bmatrix} = 2\pi \begin{bmatrix} C^E_{33}\frac{R^2-r^2}{2l} & -C^E_{13}r & C^E_{13}R \\ -C^E_{13}r & C^E_{11}l\frac{R^2+r^2}{R_2-r_2}-C^E_{12}l & -C^E_{11}l\frac{2Rr}{R_2-r_2} \\ C^E_{13}R & -C^E_{11}l\frac{2Rr}{R^2-r^2} & C^E_{11}l\frac{R^2+r^2}{R^2-r^2}+C^E_{12}l \end{bmatrix} \begin{bmatrix} u_z \\ u_r \\ u_R \end{bmatrix} \qquad (9)$$

Assembly of the two elements into one composite element leads to the elimination of u_r. The degrees of freedom u_z and u_Z are combined by assuming $u_z = u_Z$. This new element is represented by an identical matrix to equation (8) from which the composite constants $(C_{11} + C_{12})$, C_{13}, C_{33}, e_{31} and ϵ_{33} can be determined.
The stiffness matrix of a box element of square cross section rod is used to find the individual values of C_{11} and C_{12} along with the shear constants ϵ_{11} and e_{51}. In this way a complete set of e constants for the composite are derived and from these the d, g and h constants are readily found.

3.PREDICTIONS OF THE MODEL

The model can be implemented on a PC. The computer program requires a full set of constants for the ceramic and the polymer in order to estimate the complete set of composite constants. A database is included to which the user can add material data thus permitting composites from different ceramic and polymer types to be modelled. Figs.1 to 5 give examples of output generated using data for PC5H ceramic and a low curing shrinkage epoxy resin (Metset, Buehler UK). The acoustic impedance (Fig.1) varies linearly with increasing volume fraction of ceramic except for $V_f > 0.95$. As expected from a simple parallel model, the relative permittivity (Fig.2) increases linearly with increasing V_f as low as 20%; indeed, it has been shown elsewhere [4] that k_t for a 1-3 composite can exceed k_t for a ceramic disc of the same dimensions. This result is explained by the weak lateral clamping experienced by the ceramic rod in a polymer matrix compared with a similar volume of ceramic in a sintered disc.

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Weak lateral coupling between the composite rods suppresses d_{31} and gives a high d_h (Fig.3) which shows a maximum at a V_f of 25%. The voltage sensitivity, g_h (Fig.3) has a peak at V_f of only 1.5% which would be difficult to confirm experimentally. The product $d_h g_h$ which is often quoted as a useful figure merit for hydrophones shows a maximum at a V_f of 8% (Fig.4).

CONCLUSIONS

A model has been described which predicts the performance of 1-3 composites as a function of the volume fraction ceramic and the elastic, dielectric and piezoelectric properties of the two constituents. This modelling is the first step in designing optimised transducer materials. Subsequent steps involve the incorporation of composite performance data into more sophisticated systems models which account for electrical loading, impedance matching, etc. [5]. Such an integrated approach should provide the engineer with accurate simulations of transducer behaviour in realistic applications.

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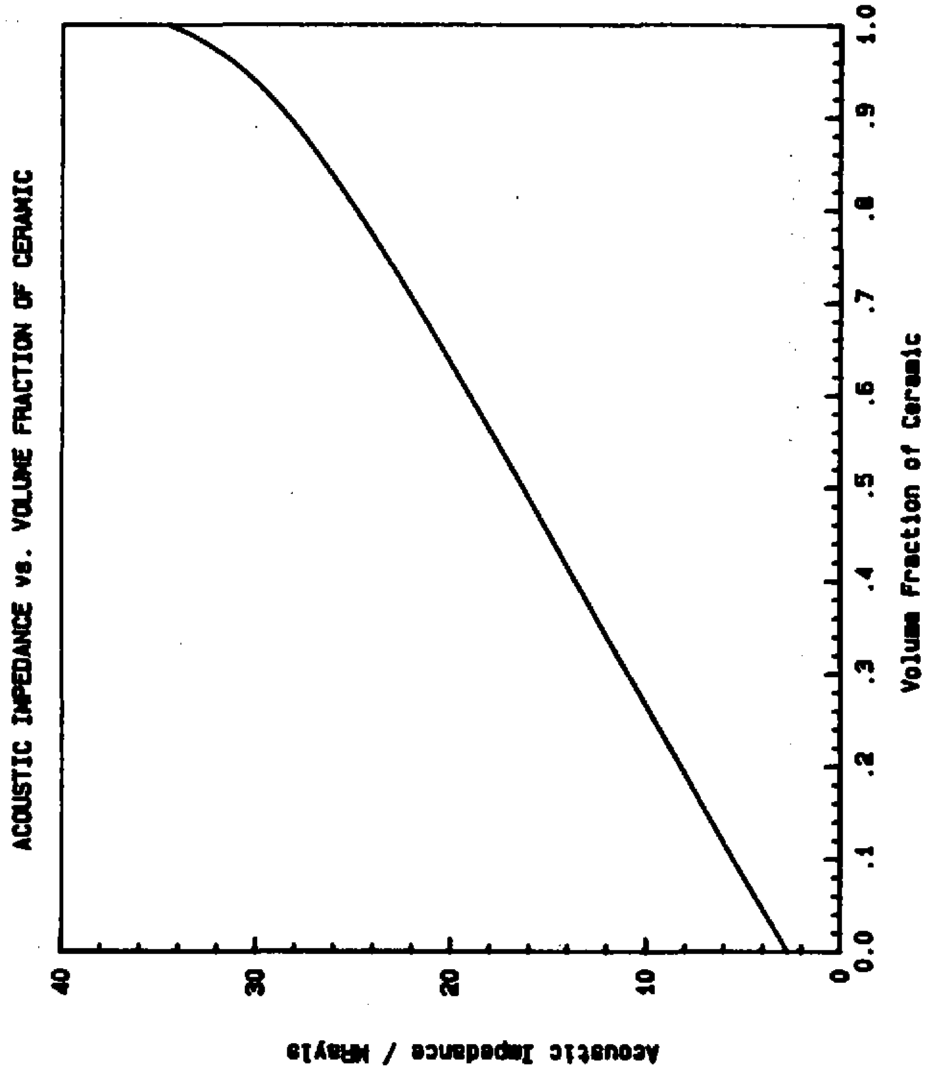

Fig.1

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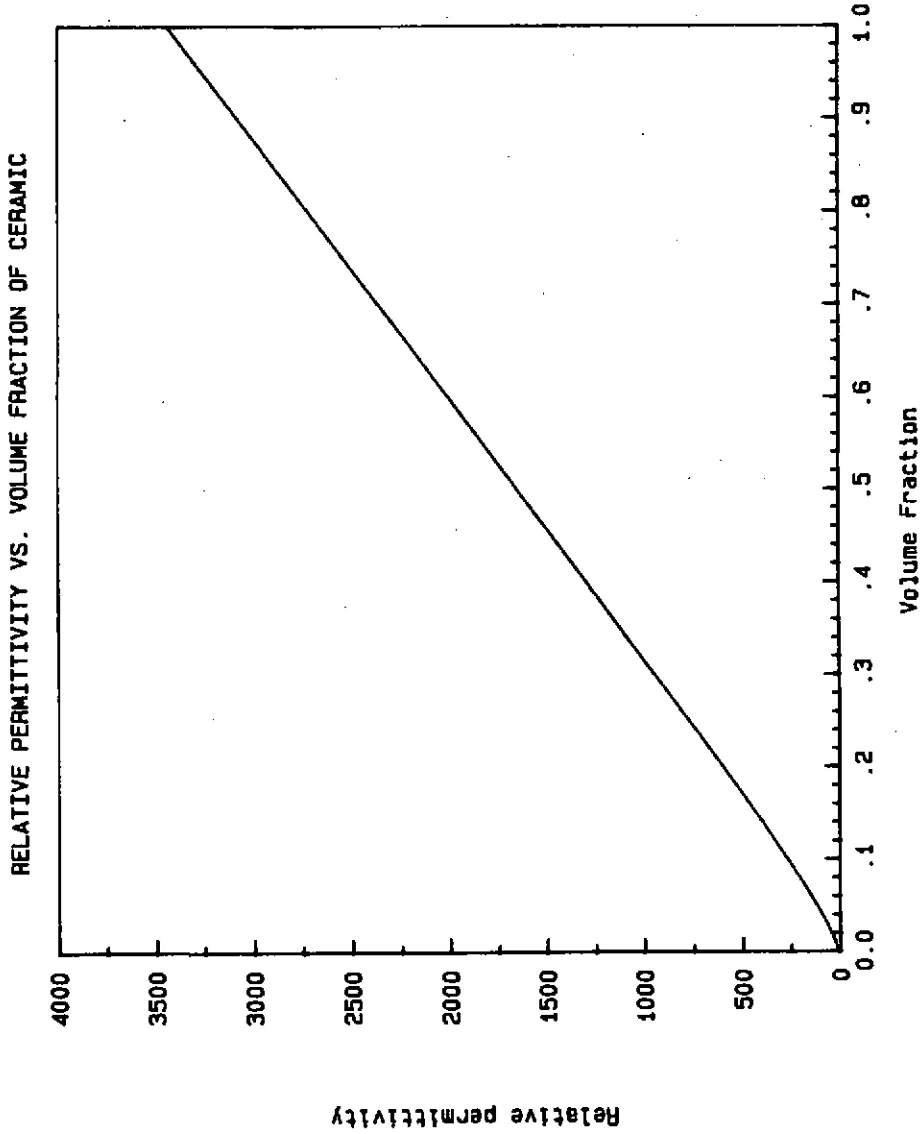

Fig.2

1-3 COMPOSITES

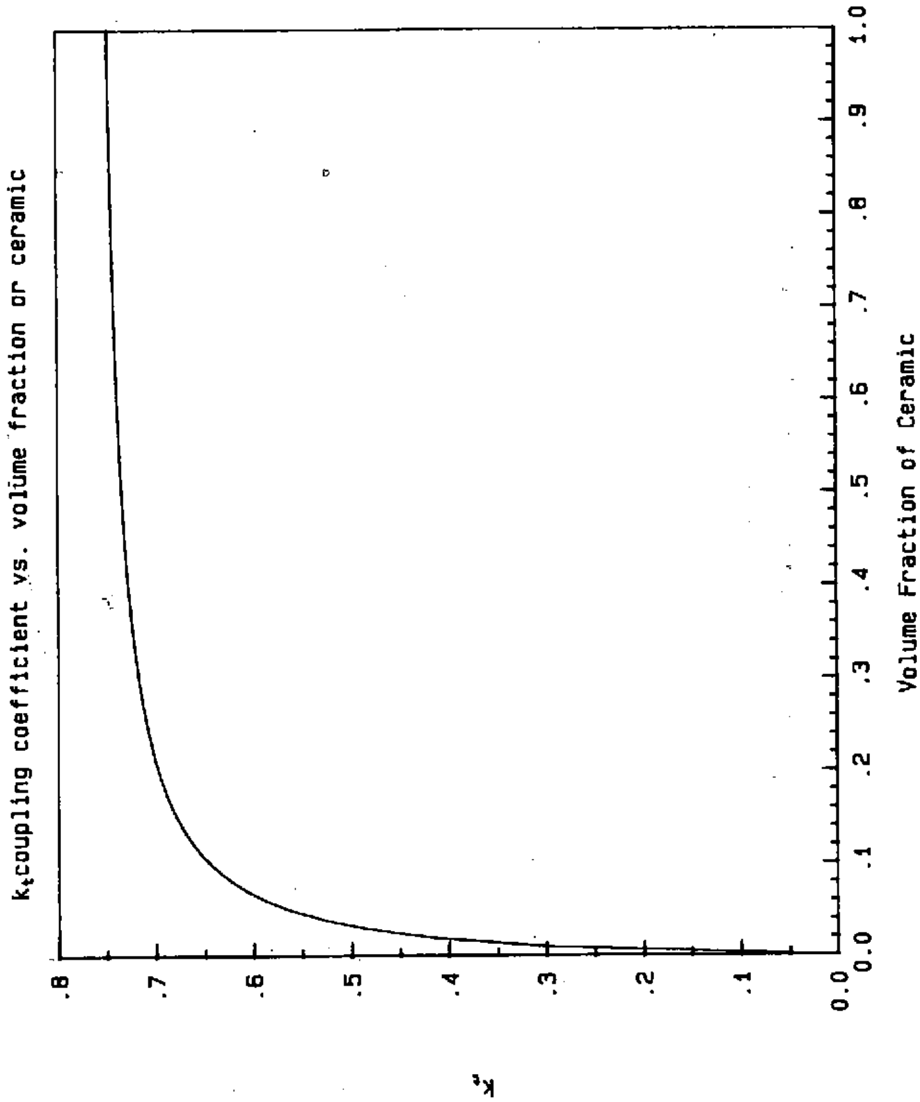

Fig.3

1-3 COMPOSITES

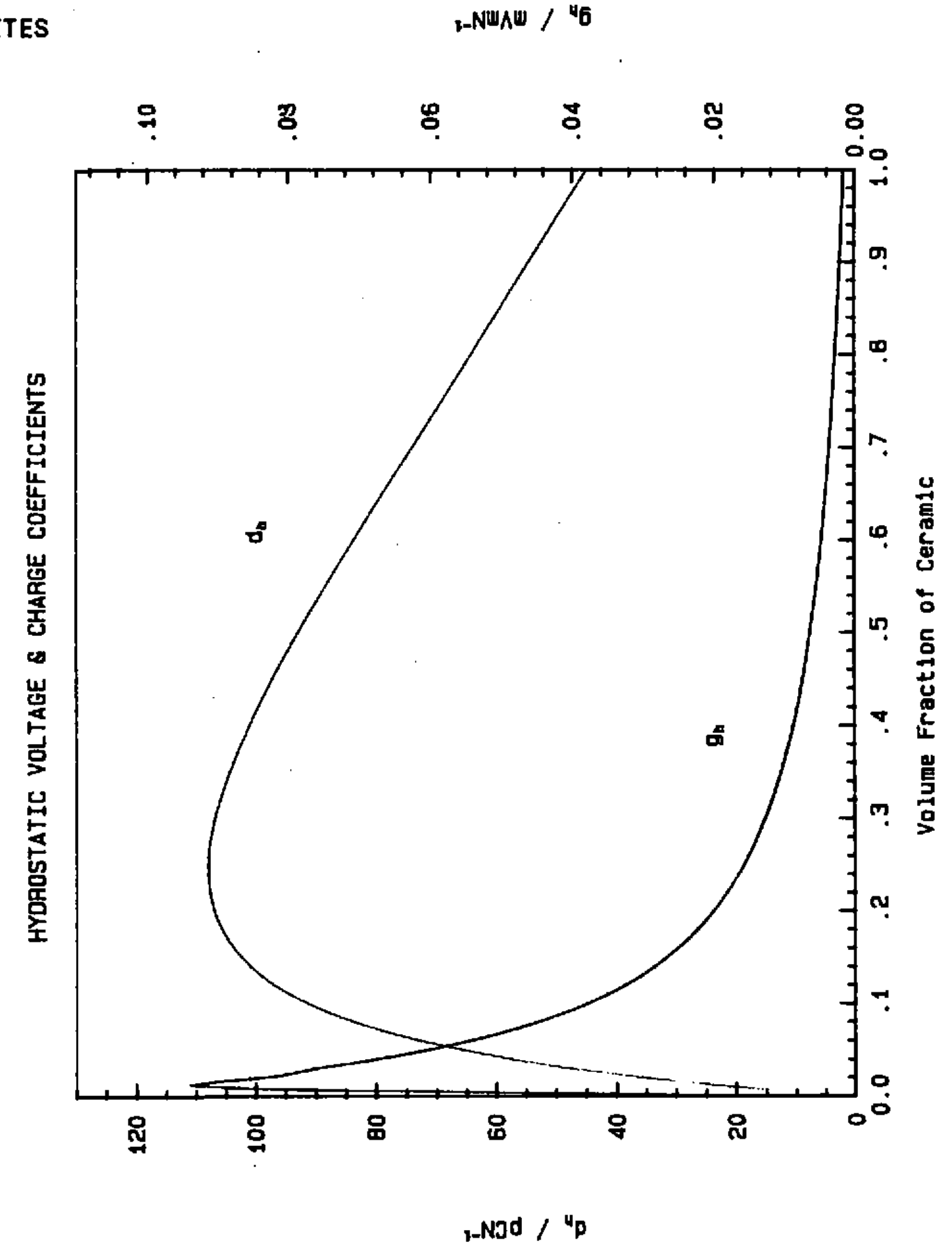

Fig.4

1-3 COMPOSITES

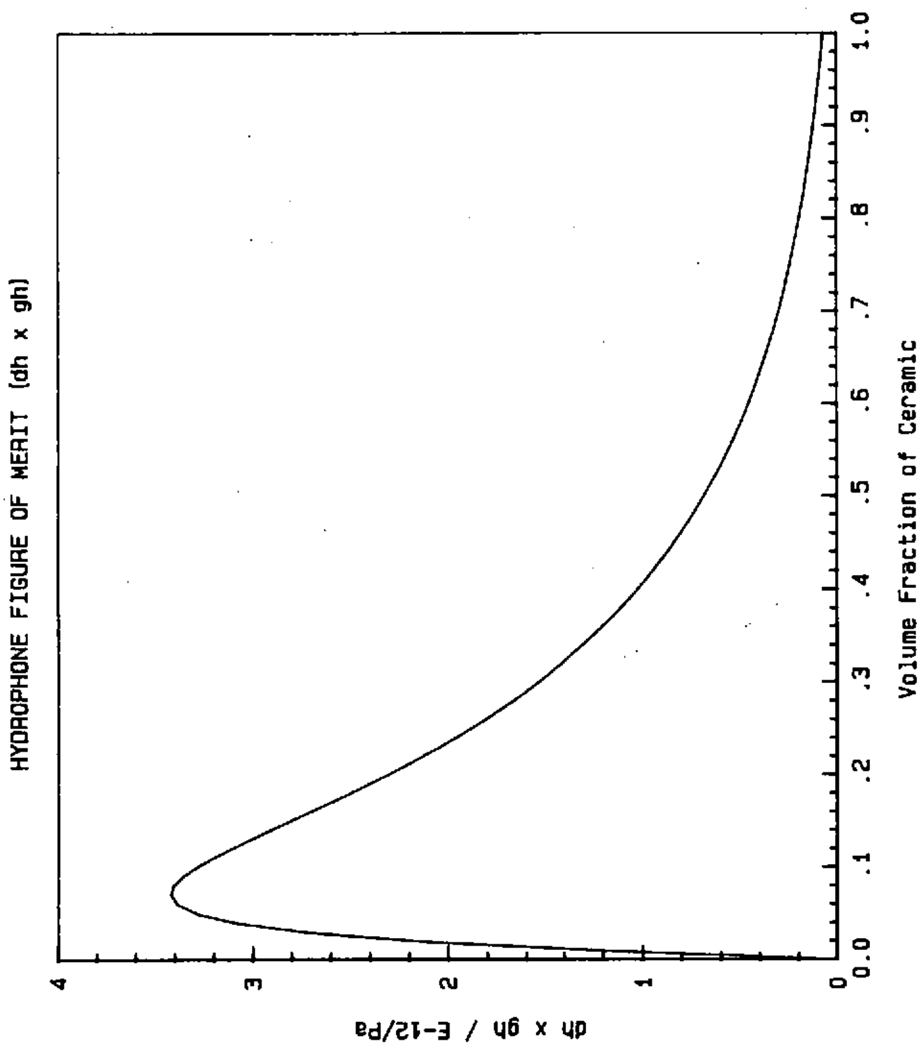

Fig.5

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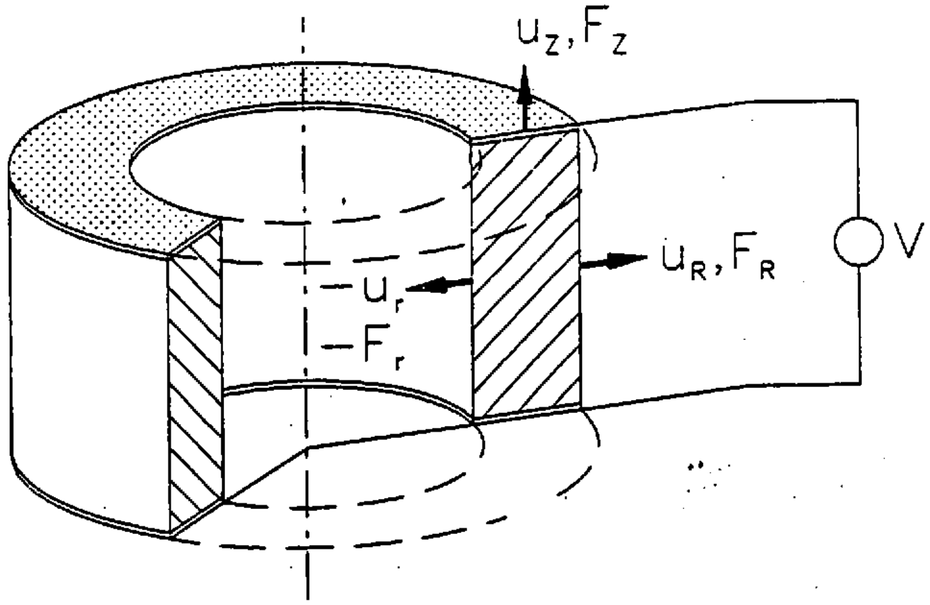

Fig.6