Ferroelectrics, 1999, Vol. 228, pp. 257-269
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Fabrication and Finite Element Modelling of Interdigitated Electrodes

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(Received 6 April, 1998; In final form 25 February, 1999)

Interdigitated electrode patterns have been fabricated on piezoelectric materials as a method of increasing the transverse actuation. Due to the non uniform electric field distribution within an interdigitated device, finite element modelling has been undertaken to investigate the electric field distribution, the strain distribution and any subsequent stresses developed within the device. Experimental mesurements of strains developed by the interdigitated device compare well with finite element predictions.

Keywords: interdigitated; electrodes; finite element; IDE

INTRODUCTION

Piezoceramics have been extensively used as sensors and actuators for micropositioning and acoustic purposes, but are currently coming under investigation for adaptive structure and vibration control [1]. They are well suited to these tasks due to the ease with which their deformation can be accurately controlled with an applied electric field. This paper presents an investigation into increasing transverse actuation of piezoceramics using interdigitated surface electrode patterns to create a component with the electric field in the direction of desired deformation [2].

Conventionally, transverse actuation is achieved by applying an electric field in the longitudinal direction between the two opposing electrodes on either side of the ceramic (Figure 1a). The applied field produces a strain in the z direction but due to coupling between the modes an isotropic deformation will also occur in the x and y direction. The electric field and direction of polarisation in this case is normal to the direction of actuation (x and y) and the piezoelectric strains are dependent on the d_{31} piezoelectric coefficient (d = strain per unit field).

Interdigitated electrodes (IDE) consist of a series of opposing polarity electrodes printed onto the surface of the piezoelectric material. This electrode geometry has the advantage of being able to create an electric field in the direction of actuation and polarisation (x), as shown in Figure 1b. The x direction strain in this case is related to the d_{33} piezoelectric coefficient (rather than d_{31}). For the material used in this work (PZ-26), the relationship between d_{33} and d_{31} is,

$$|d_{33}| \approx 2.3|d_{31}| \qquad \text{equation 1}$$

Therefore, it is clear that an increase in the x direction strain per unit electric field may be attained using an IDE. A typical geometry of an IDE device is shown in Figure 1b.

Using conventional electrodes the electric field is uniform throughout the sample. However, for IDE's the electric field distribution is irregular, producing uneven strains and generating internal stresses. In order to quantify these effects, finite element (FE) modelling of the IDE was undertaken to determine the extent of these variations. To complement this, an experimental program was undertaken to examine the actuation capabilities of these IDE's and validate any solutions from the FE modelling.

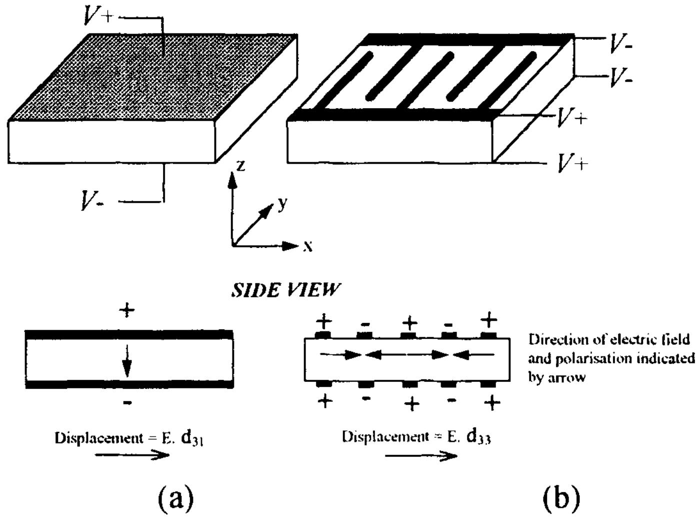


FIGURE 1

(a) Conventional electrodes; poled and generating a field in in the z axis.

(b) Interdigitated electrodes; poled and generating a field in the x axis.

EXPERIMENTAL

The geometry and electromechanical properties of the piezoelectric and electrode configuration (spacing, thickness etc.) will determine the device performance and stress distribution. A large spacing between opposing electrode lines would produce a more uniform field and hence a more optimised strain coefficient, but larger voltages and increasing power consumption are needed to produce an equivalent electric field.

Alternatively, a decrease in the electrode spacing will make the manufacturing process more difficult and increase the likelihood of rogue conductive paths.

A compromise between these factors seemed the appropriate choice. An electrode spacing of 1.7mm and width of 0.7mm were chosen to be deposited on a 50mm x 25mm x 1mm piezoelectric substrate. A volume element of this geometry is shown in Figure 2a. Electrode lines on the face plate are of opposite polarity, while the electrodes through the thickness of the plate above and below one another are of the same polarity.

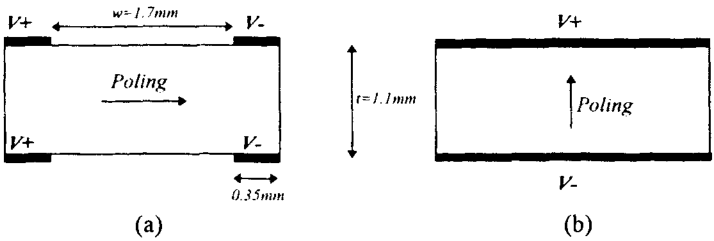


FIGURE 2 (a) geometry of IDE (b) conventional electrodes

The manufacturing route used to produce the IDE's had to satisfy the following requirements. Firstly, the two electrodes of differing voltage must be substantially isolated from each other to prevent voltage arcing, particularly during poling. Secondly, the resistance of each individual electrode line must be negligible so as to acquire an equal potential difference throughout the electrode. A technique found to be successful and efficient at laying down the designated electrode pattern was essentially a 'lift-off' technique.

IDE device fabrication

The process begins by using a Computer Aided Design (CAD) package to create a mask in the negative form of the desired electrode pattern. A layer of photoresist was subsequenlty laid down upon the piezoelectric substrate. Using the mask to shield the photoresist, the sample was exposed to ultra violet light. By soaking the sample in a suitable etchant, the negative of the desired electrode pattern was created in photoresist, onto which a layer of copper was evaporated. The photoresist and overlying copper was removed using a solvent, leaving only the copper which had deposited directly onto the piezoelectric substrate, thus forming the electrode pattern. This process was performed on both sides of the piezoelectric plate. Lastly, the sample was subjected to electroplating in a copper sulphate - acid solution to improve the conductance of the electrodes. It was decided to lay the IDE's on PZ-26, a hard lead zirconate from Ferroperm. This material has a high modulus and hence good stress characteristics if embedded in an adaptive structure.

Due to the alternating electric field directions between the IDE's the material had to be poled using the applied electrode pattern. Once fully electroded a potential difference of 3kV was applied to the sample for 15 minutes to produce the net polarisation necessary to exhibit the converse piezoelectric effect. This procedure was performed at 90°C to enhance the dipole alignment within the material and took place in a silicon oil bath to prevent voltage arcing.

Strain measurements

The strain achievable with these devices was measured using Measurements Group Incorporated strain gauges and conditioner. The gauges were placed in both parallel (y direction) and normal (x direction) to the electrode lines. Using a Hewlett Packard 8116A Function Generator and a Trek Amplifier

(Model P0615M), the potential difference across the test sample electrodes was ramped up to 700V in 100V steps and the corresponding strain monitored. These measurements were also performed on a conventionally poled and electroded plate to calculate any improvements in transverse strain due to the IDE pattern.

RESULTS

Strain results

Figure 3 shows a graph of strain in both length (x) and width (y) directions versus applied voltage for both the interdigitated and conventional electrodes. It can be seen that IDE strains are lower than those of conventional electrodes for the same applied voltage. This would be expected for this particular IDE geometry the electric field is lower than in the conventional electrodes for the same applied voltage (primarily due to the spacing of the interdigitated electrodes). For the conventional electrodes the electric field (E) is,

$$E_{conv} = \frac{2V}{t} \qquad \text{equation 2}$$

where t = device thickness (1.1mm)

V= applied voltage (V)

The electric field in the IDE can be approximated by [2],

$$E_{IDE} = \frac{2V}{w} \qquad \text{equation 3}$$

where w = interdigitated electrode spacing (1.7mm)

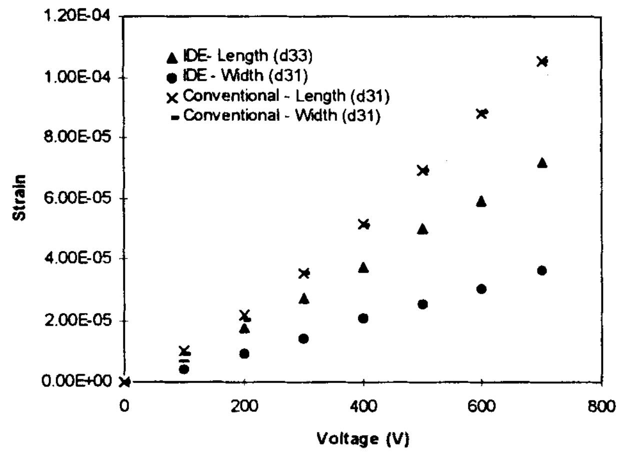


FIGURE 3 Graph of measured strain versus applied voltage for IDE and conventional electrode.

Considering the IDE electrode geometry in Figure 2a, $w=1.55t$ resulting in lower overall electric field for the same applied voltage ($E_{IDE}= 0.65E_{conv}$). In addition, Equation 3 overestimates the electric field as it calculates the electric field along the top surface of the specimen between opposite polarity electrodes. To acquire a more accurate measure of mean electric field and distribution, finite element analysis was conducted.

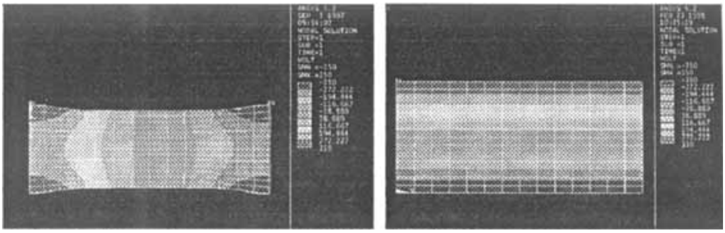
Finite element modelling

Finite element modelling was conducted using ANSYS 5.4 using coupled-field elements to model linear piezoelectric behaviour. Symmetry was used to model the representative volume element shown in Figure 2a. The dimensions used in the model where those of the experimental test specimen to provide a direct comparison between modelled and experimental results. The state of polarisation was assumed to be aligned along its length as in

Figure 2a. As the devices were poled using the IDE a more complex state of polarisation is likely to result, similar to the electric field distribution discussed in the next paragraph. Conventional electrodes were also modelled.

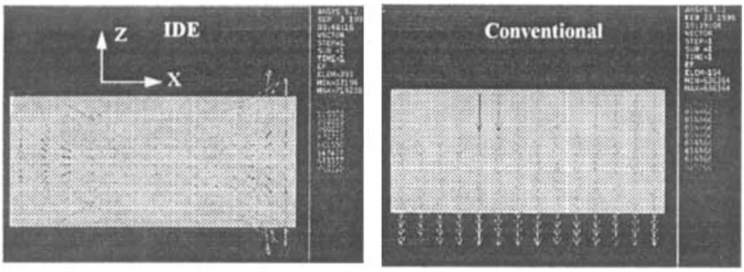
Figure 4 shows a typical voltage distribution between the electrodes in the IDE and conventional case for a voltage of +350V and -350V applied to the positive and negative electrodes respectively. The voltage distributions generate electric fields as shown in Figure 5. In the conventional electrode system the electric field is uniform, while in the IDE the electric field varies considerably throughout the device. Directly below the interdigitated electrodes a 'dead zone' is observed whereby the field is small and normal to the poling direction and little strain is produced. The non-uniform strain in the device generates stresses, particularly near the electrodes edges (Figure 6). For this particular electrode geometry the maximum stress is ~5MPa for an applied voltage of +350/-350V. Although the stress is not at a destructive level it would need to be taken into account for smaller electrode spacing and higher fields where the stress is likely to be larger. The fatigue of the piezoelectric material in this region would also be an issue if the device experiences a large number of strain cycles.

A histogram of electric field distribution throughout the device is shown in Figure 7. A significant fraction of the device volume experiences and electric field less than 60V mm^{-1} due to the 'dead zone'. The mean field is approximately 230V mm^{-1} which is considerably lower than the electric field of 636V mm^{-1} which is experienced by the piezoelectric with conventional electrodes under the same applied voltage. Using Equation 3, the electric field in the IDE is calculated to be 411V mm^{-1}, clearly larger than the FE estimate, indicating the potential errors that can be made using this simplistic assumption.



(a) (b)

FIGURE 4 Voltage distribution in (a) IDE (b) conventional electrodes



(a) (b)

FIGURE 5 Electric field distribution in (a) IDE (b) conventional electrodes

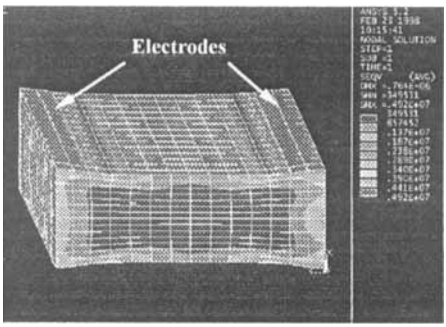


FIGURE 6 Stress developed near electrode edges due to non-uniform field

A comparison of finite element predicted strain and experimental measurements of device strain is shown in Figure 8. Good agreement is observed indicating that the modelled electric field distribution is an accurate indication of the real electric field distribution within the device. The modelling assumes linear piezoelectric behaviour and deviations between model and experimental measurements may observed at higher electric fields where the piezoelectric material can behave non-linearly. Similarly the areas of high stress near the electrode edges can also affect the electromechanical properties of the piezoelectric, which are not accounted for in this case.

Figure 9 shows a graph of strain versus mean electric field for the conventional electrodes and IDE. The electric field for the conventional electrodes was calculated from equation 1 while the electric field in the IDE is obtained from finite element analysis. It can be seen that for the same *electric field*, IDE electrodes produce higher strains. IDE's could therefore be used in applications where electric field is a limiting factor, e.g. if the material behaves non-linearly under high electric field. It should also be noted that the strain in the width direction for the IDE is similar to the conventional electrodes, as would be expected, as both are related to d_{31} coefficient (another indication that the modelled electric field distribution is representative of the real field). Figure 9 also shows that for conventional electrodes strains are identical in the length and width directions. In this case both strains are perpendicular to the direction of poling and are related to the d_{31} coefficient. For the IDE the strains are significantly different, due to the length strain direction being related to the d_{33} coefficient (i.e. strain is in direction of poling) and the width strain being related to the d_{31}. It is this anisotropic actuation which allows torsion to be developed in isotropic hosts with IDE's [2,3].

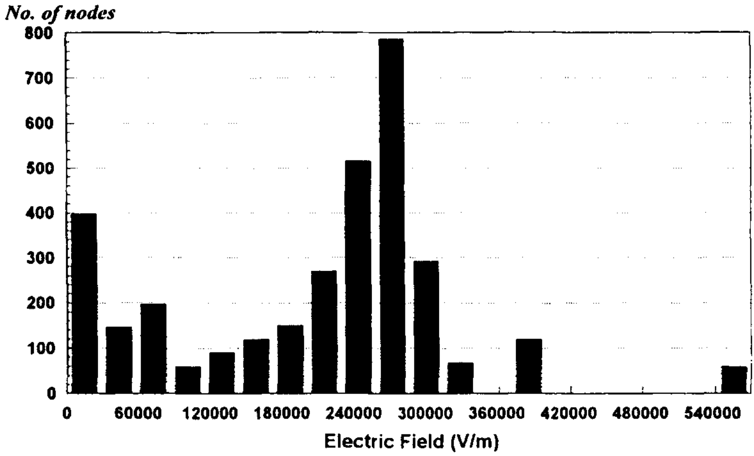


FIGURE 7 Finite element analysis of electric field distribution. Potential of +350V and -350V applied to $V+$ and $V-$ respectively. The mean field is 230 V mm^{-1}.

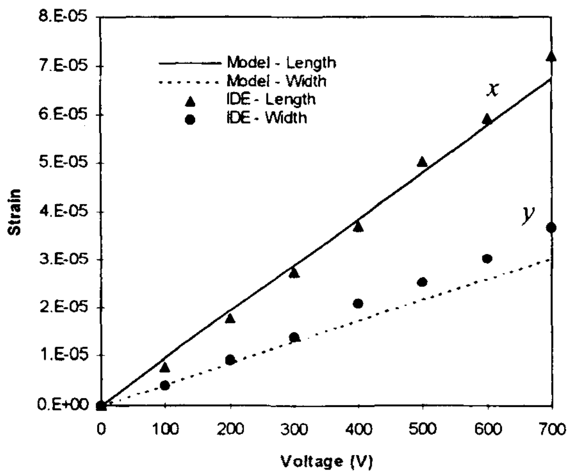


FIGURE 8 Comparison of modelling and experimental results

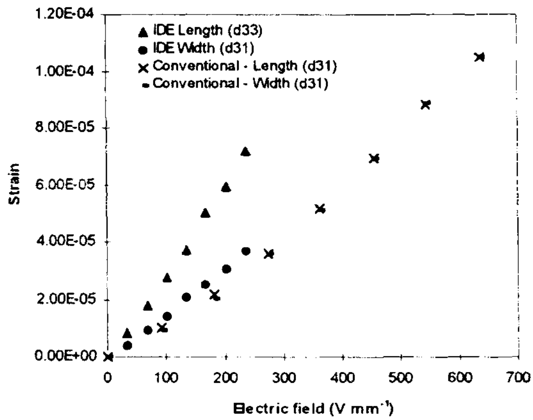


FIGURE 9 Graph of strain versus electric field for conventional and IDE

CONCLUSIONS

It has been shown that IDEs can be used to generate higher strains for a given electric field. Therefore, they would be of benefit in situations where electric field is a limiting factor, an example being piezoelectrics that exhibit non-linear behaviour at high electric fields. A 'dead zone' of low electric field is produced below the electrodes of equal polarity indicating that minimising the electrode thickness is an advantage. If higher strains are required at lower applied voltages the interdigitated electrodes must have a minimal spacing between them to increase the electric field. This is similar to multi-layer actuators where the thin layers of piezoelectric material, separated by electrodes, provide considerably higher electric fields for the same applied voltage.

An inhomogeneous electric field distribution is produced by IDE which generates internal stresses, particularly near the electrode edges. Although this field is not at a destructive level in our specified conditions, it would need to be taken into consideration for smaller electrode spacings and higher fields. Similarly fatigue of the piezoelectric could be an issue for an IDE device subjected to the large number of strain cycles.

Finite element analysis has been proven to be successful in calculating the electric field, stress and strain distribution in IDE devices of differing geometry (spacing, electrode thickness, piezoceramic thickness etc.). Such analysis is an improtant tool in optimising the geometry of IDE device

It was clear that the interdigitated electrode pattern produced a net polarisation vector in the x direction, the largest of its dimensions. This is of use in the poling of long piezoelectric rods or fibres where unfeasibly high voltages are necessary to pole in the conventional manner. Interdigitated electrode patterns can be laid down along side the rod and a net polarisation along the length could be achieved in a safer and more efficient manner [4].

Acknowledgements

Finite element modelling was conducted under the CAM7 DTI programme.

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