A FINITE ELEMENT METHOD EXPLORATION OF TECHNOLOGICALLY RELEVANT GEOMETRIES IN PIEZOELECTRIC ENERGY-HARVESTING PZT-4

EXPLORACIÓN POR ELEMENTOS FINITOS DE GEOMETRÍAS TECNOLÓGICAMENTE RELE-VANTES PARA LA RECOLECCIÓN DE ENERGÍA PIEZOELÉCTRICA EN PZT-4

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In a piezoelectric material, any external action that can generate a mechanical deformation could be a potential source of electrical energy. This phenomenon is studied for the development of microscale devices, using as external agents the hydraulic pressure of a fluid, the movement of human beings and others. Nowadays, the main research efforts focus on optimizing the properties of developed piezoelectric materials and also to the simulation of different situations that allow the optimization of the energy harvesting devices. The present paper shows some simulations, which have been made by using the finite element method to simulate the energy harvesting; the results are presented for a commercial piezoelectric, PZT-4.

En un material piezoeléctrico cualquier acción externa que pueda generar una deformación mecánica puede ser una potencial fuente de energía eléctrica. Este fenómeno se estudia para el desarrollo de dispositivos en la microescala, utilizando como agentes externos, entre otros, la presión hidráulica de un fluido o el propio movimiento del ser humano. Las investigaciones actualmente están dirigidas, por una parte a la optimización de las propiedades de los materiales que se desarrollan para tales fines, y por otro lado, a la simulación en diferentes escenarios que permitan optimizar los dispositivos a desarrollar. En este trabajo presentamos algunas simulaciones, empleando el método de elementos finitos, para la recolección de energía piezoeléctrica; se presentan los resultados para un piezoeléctrico comercial, PZT-4.

PACS: Piezoelectricity (piezoelectricidad), 77.65.-j; piezoelectric materials (materiales piezoeléctricos), 77.84.-s; energy conversion (conversíon de energía), 84.60.-h.

I. INTRODUCTION

Energy harvesting is the transformation of any form of energy from the medium into electrical energy for powering autonomous devices or circuits. Harvesters produce an amount of energy compared to industrial-scale generators that use coal, oil, nuclear power or other sources. The difference is that the energy source of collectors are residual, i.e. gradients of temperature of a combustion engine, electromagnetic energy in urban centers by radios, telephones and televisions, movement of sea waves or deformations in a piezoelectric material [1,2].

The main application of these collectors is found in microelectronic devices. The remote location of facilities that depend on the electricity grid makes it necessary to alternative energy source and although these methods do not produce much energy could be used to extend the life of batteries or other means that are to supply them [3,4].

Piezoelectric energy harvesting has become a growing area of interest due to its ability to generate electricity from movements and everyday mechanical vibrations, such as walking and the passage of vehicles. Unlike other forms of energy harvesting, such as solar or wind, piezoelectric devices are not condition-dependent and can be implemented in a variety of urban environments, from pavements to the structure of buildings. This versatility allows easier integration into existing infrastructures, maximizing energy efficiency without requiring major modifications. In addition, their compact size and low maintenance cost make them ideal for applications in areas where access to sources of conventional energy is limited [2,5].

The phenomenon of piezoelectricity is the result of the mechanical-electric coupling existing in some dielectrics and can be direct or inverse. The application of mechanical stress on the material providing a bias is known as direct piezoelectric effect; a mechanical deformation of the material by applying an external electric field corresponds to the inverse piezoelectric effect [6,7].

Lead-based piezoelectric compounds, such as $Pb(Zr,Ti)O_3$ and $PbTiO_3$, and others based on them, have attracted most of the attention of the scientific community for several decades due to their excellent piezoelectric properties; special attention have also received lead-free piezoelectric materials [6–14].

Nowadays, the main researches on piezoelectric harvesting are directed to the optimization of the piezoelectric properties of the developed materials and also to the simulation of different situations that allow the optimization of the energy harvesting devices [15–18].

In this context, the present paper shows some simulations, which have been made by using analytical methods and the finite element method to simulate the energy harvesting in piezoelectric materials in specific geometries relevant to applications and our experimental setup. A standard simulation package was used (COMSOL, 6.2 version).

II. FINITE ELEMENT METHOD

The finite element method (FEM), developed by the mathematician Richard Courant is today a common calculation procedure in structural mechanics and solid mechanics in general. Its use is also widespread in problems solving heat transfer, fluid mechanics and electromagnetism [19].

From a mathematical point of view, the FEM can be understood as a procedure to numerically solve problems posed by partial differential equations (PDEs), similar to other procedures, such as the Finites Differences Method (FDM) [20]. Considering the difficulty of solving analytically the majority of partial differential equations describing physical phenomena, except in very simplified cases or some in which the PDEs are not extremely complicated, the need arises to resort to these methods.

Most piezoelectric energy collectors which use a cantilever beam, as a structure on which the piezoelectric material is mounted, have been modeled by the use of analytic approaches. However, as more structurally complex devices are developed, these analytical models lack precision due to the simplifications introduced. In this context, the FEM has been very useful; its approach allows for the resolution of difficulties such as the complexity of the structure and employ theories of higher order (non-linear) [20].

III. SIMULATIONS

The most common geometries used in developing devices with piezoelectric materials, such as disks and plates, will be analyzed. The simulations will be carried out considering a commercial piezoelectric, PZT-4 [21].

III.1. Piezoelectric cylinder

Consider a commercial piezoelectric PZT-4 disk [21] with a diameter of 8 mm, to which a force (F) of -10 N is applied in the thickness direction (z axis). It has been also considered that the disk is fixed at the lower base, the lateral area is free and the upper face is subjected to the applied force F.

Two different thicknesses (z), 2 and 5 mm, have been considered. These dimensions have been selected considering common dimensions in the development of these materials. The analytical method and the finite element method have been used for simulations. Table 1 shows the corresponding elastic and piezoelectric parameters for the simulations.

For the analytical method, by using the equations of piezoelectricity [7], the output voltage (V) in the thickness direction (z axis), can be obtained:

$$V = -\frac{d_{33}F}{\varepsilon_{33}A}z \quad (1)$$

where d_{33} is the piezoelectric coefficient, ε_{33} is the dielectric permittivity and A the area of the parallel surfaces.

Table 1. Elastic and piezoelectric parameters for the commercial piezoelectric PZT-4 [21]

Parameter	Value
s_{11}	12.3×10^{-12} Pa^{-1}
s_{12}	4.05×10^{-12} Pa^{-1}
s_{13}	5.31×10^{-12} Pa^{-1}
s_{33}	15.5×10^{-12} Pa^{-1}
s_{44}	39×10^{-12} Pa^{-1}
s_{66}	32.8×10^{-12} Pa^{-1}
ε_{r11}	1475
ε_{r33}	1300
d_{31}	1.23×10^{-10} m/V
d_{15}	4.96×10^{-10} m/V
d_{33}	2.89×10^{-10} m/V

Figure 1 shows the thickness dependence of the output voltage considering z = 2 mm. Figure 1 shows the same dependence considering z = 5 mm.

It can be observed that the output voltage shows an important dependence with the thickness of the piezoelectric sample. Also, the disagreement between the applied models increases for the finest sample.

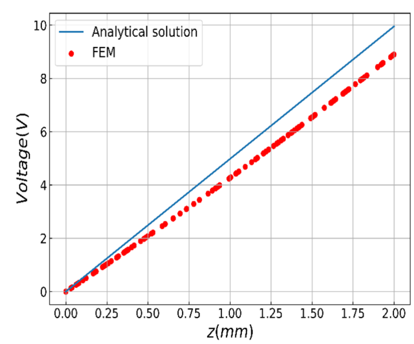

Figure 1. Thickness dependence (until 2 mm) of the output voltage for PZT-4, obtained by analytical method and FEM.

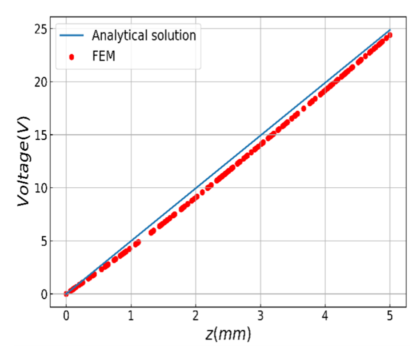

Figure 2. Thickness dependence (until 5 mm) of the output voltage for PZT-4, obtained by analytical method and FEM.

III.2. *Piezoelectric cantilever plate*

One of the studied applications considering piezoelectric materials is the collection of wave energy through the mounting of cantilevered plates in floating boxes on the sea [21].

In a previous research [21], simulations were performed using an analytical method and the FEM considering a cantilever plate, whose dimensions are shown in Fig. 3, which was composed of an aluminum sheet and another PZT-4 sheet, both 0.5 mm thick. Both sheets have the length (a) and width (b) shown in the figure.

It has been considered that the face at the origin of the coordinates is fixed (the plate is fixed at one end), while the upper face is considered subject to a pressure of 10000 N/m2 in the thickness direction (z axis); the rest of the faces are considered free.

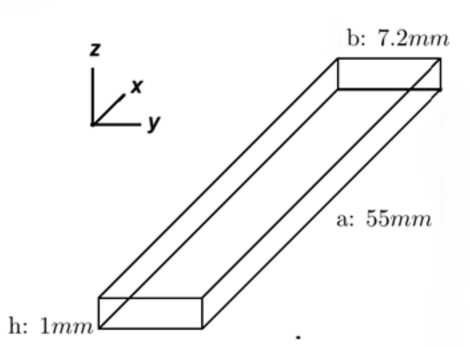

Figure 3. Dimensions of a piezoelectric cantilever for simulation [21].

The simulations have showed maximum values for the output voltage around 360 – 400 V [21].

What will be the result if the plate is considered only composed by the piezoelectric materials PZT-4 with the dimensions shown in Fig. 3?

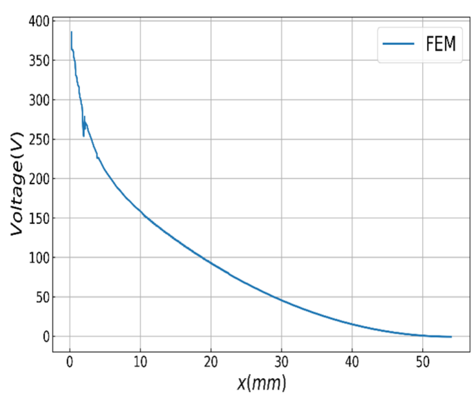

Figure 4. Output voltage vs x (length) for a PZT-4 cantilever plate, obtained by FEM.

Considering the origin at the fixed end of the plate, Fig. 4 and 5 show the dependence of the output voltage on the length of the plate (keeping the other dimensions fixed) and its thickness (keeping the other dimensions fixed), respectively, showing different dependencies for both directions. Figure 6 shows a better view for both dependences, considering output electric field.

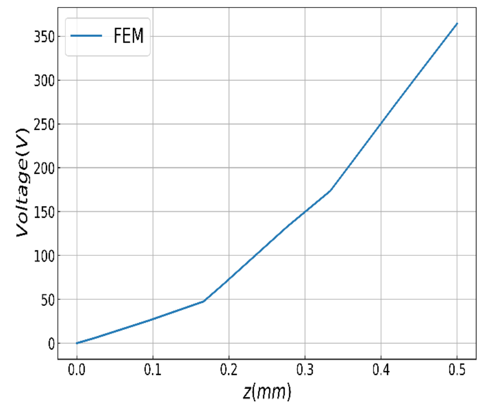

Figure 5. Output voltage vs z (thickness) for a PZT-4 cantilever plate, obtained by FEM.

Considering the thickness direction an out voltage of 364 V has been obtained for z=0.5 mm, which is in the same order than that of the previous report considering a composite of aluminum and PZT-4 [21]. From the technological point of view, it could suggest that cantilever plates developed from composites could offer better results that by using only piezoelectric plates.

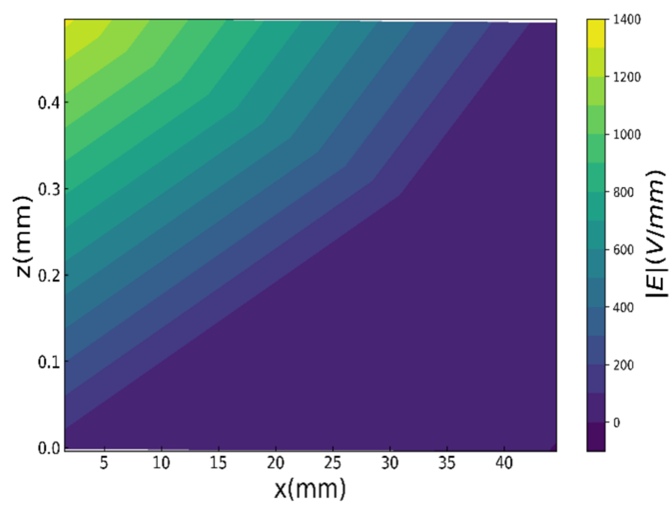

Figure 6. Output electric field as a function of x and z dimensions for a PZT-4 cantilever plate, obtained by FEM.

IV. CONCLUSIONS

Simulations by using the finite element method have been presented for disk and plate geometries in a commercial piezoelectric material, PZT-4. The results for a piezoelectric disk have shown an important dependence of the output voltage on the thickness. The piezoelectric cantilever plate showed similar results of the output voltage considering only a PZT-4 plate respect to aluminum/piezoelectric composite plates.

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