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Study of the piezoelectricity inside an actuator

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Abstract: *In this paper, we consider a mathematical model which describes the piezoelectricity between an elastic body and ceramics. The process is assumed to be dynamic. We present a piezoelectricity concept and the governed equations. An efficient numerical method is presented to analyze this piezoelectric effect. This approach exploits some special finite element. This is exploited to study the contact and the piezoelectricity between the rotor and the stator inside an ultrasonic motor SHINSEI USR60 adding the piezoelectric ceramic. Numerical results are presented and show the efficiency of the adopted approach.*

Keywords: *finites elements, modulization, piezoelectricity, Shinsei USR60 actuator, simulation.*

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I. Introduction

The direct piezoelectric effect was first reported by Hauy in 1817. Some authors claim that it was already known before and also speak of Dutch chemists who would have written a book about it in 1703; however, it was not until 1880 that Pierre Curie and his brother Paul Jacques Curie undertook the systematic study of the piezoelectric effect in the crystals. This is why they are generally regarded as the inventors of piezoelectricity. In 1880 Pierre and Paul Jacques Curie published the first experimental demonstration showing that there was a link between the phenomenon of piezoelectricity and the crystalline structure of certain materials. During the Second World War, the Americans, the Japanese and the Russians discovered that ceramics had dielectric constants more than 100 times greater than natural crystals. Unlike the Americans, the Japanese created an association between companies and universities to promote research into piezoelectricity. This policy was quickly paying off: the development new knowledge, new applications and processes, and even a new family of piezoelectric materials with performances comparable to piezoelectric ceramic (PZT) but lacking any patent. Thanks to these new piezoceramics, Japanese companies developed numerous filters, which were widely used in televisions and radios. The commercial success of Japan has encouraged other countries to increase their research on piezoelectric components. Beginning in 1980, the number of patents filed each year and the number of publications (scientific articles, books, etc.) on the subject increased considerably. The current goal is to design small, inexpensive, low-power actuators that require low power and low energy consumption, while being reliable even in hostile environments. Research into the development of piezoelectric products is progressing. And the prospect of significant economic and technological development around piezoelectricity seems certain.

On can cite some advantages compared to a conventional motor of the same size (DC, a few watts): potential power is potentially higher, output speed is low and torque is high, no need for a reduction gear (smaller and lighter), the noise level is very low or zero (ultrasonic vibrations), reactivity is on the order of milliseconds (instead of a few hundred MS), when stopped, the motor is naturally blocked without energy consumption due to the pressure of the rotor on the stator.

Electro-active materials represent an attractive research focus for several electrical engineering laboratories worldwide [1]. These materials make possible, due to their intrinsic characteristics and when judiciously exploited, the production of structures capable to develop a very encouraging mass power for applications in electrical engineering [2]. The piezoelectric ceramic is an electro-active material, which undergoes deformation under the effect of an electrical volt- age. It may also be the seat of an electrical voltage when subjected to mechanical stresses. Indeed, the operation of this ceramic is reversible. Recent research has shown that the latter can be exploited to produce actuators [3].

An actuator may be obtained from a set of piezoelectrically arranged and specially powered. The movement resulting from the deformation can be manipulated to obtain the desired displacement: rotary, oscillatory or linear. Their operating principle relies on the friction con- version of an ultrasonic mechanical vibration of the stator, in a continuous movement of the rotor. The deformation of the elastic structure (substrate) is caused by the piezoelectric ceramics. The latter have the property of undergoing deformation when they are under the action of an electric field (inverse piezoelectric effect). Due to his discreet sound, compact size and performance: high torque at low speeds, the piezoelectric motor represents a definite interest for the industry. Thus, it finds its place in a universe relatively conquered by conventional elec- tromagnetic motors. In addition, the absence of audible operating noise makes the application of piezoelectric motors very attractive

II. Problem Statement

2.1 Piezoelectric relations

The systematic characterization of the electromechanical properties of piezoelectric media is based on a tensor representation of the coupling between electrical and mechanical systems. The macroscopic local magnitudes, which are generally chosen as mechanical and electrical variables in continuous media, are respectively the strain tensors and stresses, S and T components, the vectors of the electric displacement D and the electric field E. In an elastic solid subjected to a stress T, the deformation S is:

$$S = sT \tag{1}$$

where s is the flexibility (inverse of Young's modulus), expressed in [m^2/N].
On the other hand, in a dielectric subjected to an electric field, one has the following equation (2):

$$D = \varepsilon E \tag{2}$$

where ε is the dielectric constant of the medium in [Cm/V].
In a piezoelectric medium the mechanical and electrical effect influence each other. This situation is summarized by equations (3) and (4). These are the direct and inverse piezoelectric effects respectively:

$$\frac{\partial D}{\partial T} \neq 0 \tag{3}$$

$$\frac{\partial S}{\partial E} \neq 0 \tag{4}$$

with a good approximation, this interaction can be described by linear relations between the four variables D, E, S and T, only two of which are independent.
The choice of independent variables, one mechanical and the other electric, is arbitrary. Thus, by choosing, for example, the intensive variables (T and E) as a pair of independent variables, the piezoelectric properties are translated, at constant temperature, by equations (5) and (6):

$$S = S^E T + d^T E \tag{5}$$

$$D = dT + \varepsilon^T E \tag{6}$$

with SE is the constant electric field flexibility (matrix 6 × 6) [m2 / N]; T is the constrained permittivity (matrix 3 × 3) in [F/m]; d is the charge constant (matrix 3 × 6) in [C/N]; the exponent T in equation (5) indicates that it is the transposed matrix of d.

Relations (5) and (6) refer to an identification of the directions given in Fig (1). According to this system of axes, the direction of polarization in the positive direction is defined along the axis 3 (z axis in an orthogonal system). One defines the different matrices presented in equations (5) and (6).

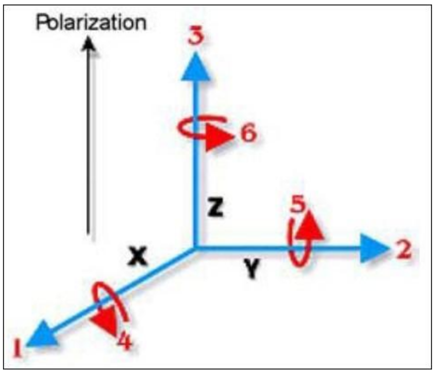

Figure 1: Repere associated with stress and strain vectors

The stress and the deformation act on the axes defined in Fig (1). The flexibility is defined for each of the cases, that is to say for the three translations (elongations) and the three rotations (shears). As the PZTs are symmetrical with respect to the polarization axis, the matrix SE takes a simplified form [3]. For example, S^E is the constant electric field flexibility for a constraint in direction 1, with a deformation component in the direction 3 along the Z axis. The flexibility matrix SE is written as [6]:

$$S^E = \begin{pmatrix} S_{11}^E & S_{11}^E & S_{33}^E & 0 & 0 & 0 \\ S_{11}^E & S_{11}^E & S_{13}^E & 0 & 0 & 0 \\ S_{13}^E & S_{13}^E & S_{33}^E & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{44}^E & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{44}^E & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{66}^E \end{pmatrix} \quad (7)$$

The field and the electric displacement are defined only in the three main directions (no rotations). Moreover, there is no interaction between different axes and ε^T is therefore a diagonal matrix. Thus, with constant stress, ε^T is the direction of polarization. The permittivity matrix ε^T is written as [6]:

$$\varepsilon^T = \begin{pmatrix} \varepsilon_{11}^E & 0 & 0 \\ 0 & \varepsilon_{11}^T & 0 \\ 0 & 0 & \varepsilon_{13}^T \end{pmatrix} \quad (8)$$

The first index corresponds to the direction of the electrical quantity (field or displacement) and the second to the direction of the mechanical magnitude (stress or deformation). As an example, d_{31} is the ratio between the deformation in direction 1 and the electric field in direction 3 (the ratio between the dielectric displacement in direction 1 and the stress in direction 3). One can write:

$$d = \begin{pmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{15} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{pmatrix} \quad (9)$$

Thus, with respect to PZT ceramics, mainly used in the studied actuators, the different flexibility matrices SE of permittivity T and load constants d take the forms given by the successive relations (7-9) when the polarization is directed along axis 3 [6].

2.2 Electromechanical coupling in PZT ceramics

It describes the relative conversion of electrical energy into mechanics. It is defined as the K_{EM} factor which characterizes the electromechanical conversion quality in piezoelectric ceramics [2], in other words the ability of the material to transform electrical energy into mechanical energy. Kem is defined as follows:

$$K_{EM} = \sqrt{\frac{w_{EM}^2}{w_E . w_M}} \quad (10)$$

with W_E are the density of electrical energy; W_M is mechanical energy density; W_{EM} is the density of electromechanical energy. By means of this parameter, the efficiency of the piezoelectric material used can be evaluated. This is one of the specific parameters for selecting a piezoelectric material.

It is the ratio of electrical energy which is converted into mechanical energy with respect to the dissipation of heat [3]. Therefore, Q_m makes it possible to quantify the mechanical losses and is proportional to the ratio between the resonant frequency and the bandwidth. Piezoelectric materials with a high mechanical loss coefficient Q_m are characterized by narrow resonance peaks, while those with low Q_m factors have larger bandwidths [3].

III. Study Of The Piezoelectric Actuator

3.1 Principles of Shinsei USR60 actuator

The principle is described on figure 2. This motor is made of two main parts: (i) the stator, which is a beryllium-copper annular plate. At its circumference, teeth are machined to amplify the vibration movement and eliminate the wear particles. At its bottom surface, piezoelectric ceramics are glued to excite the metallic part. The stator is fixed to the frame at its center. To guarantee the free vibration of the stator ring, a decoupling fold is machined between the center and the circumference and (ii) the rotor, that can be separated in 3 zones: the axis, whose rotating is output of the motor, the friction track in contact with the stator and the spring fold linking the axis to the track and giving the elasticity needed to connect the rotor to the stator.

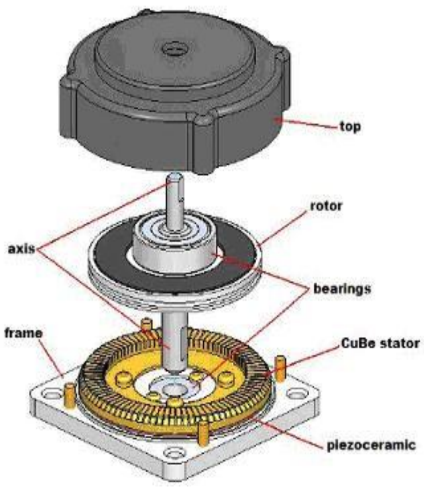

Figure 2: Motor Shinsei USR60

Other parts are the frame, the top and the bearings. The piezoceramic ring is metalized on one face. The cube stator constitutes the ground electrode. Metallization and polarization are designed to excite a particular bending mode (depending of the motor's size). This frequency is generally between 30 kHz and 100 kHz, thus the name of ultrasonic motor (USM). Excitation at a natural frequency creates a traveling wave; each point of the top surface of the stator has an elliptic motion [4]. The stator is in permanent contact with the peaks of the wave which have all the same elementary. All these elementary displacements drive the rotor by friction. To have good contact conditions, a thin polymer layer can be stickled on the rotor or the stator [5].

Many sources of energy were explored to ensure the excitation of the vibrations of volume on the stator element of the motor. The most significant results were recorded with devices exploiting forces: electromagnetic, electrodynamic, magnetostrictive or piezoelectric. Japan took over this work since the beginning of the years 1980, with significant means which in particular allowed the design and then the first industrial developments of piezoelectric motors (driving SHINSEI, motors of Zoom of the apparatuses auto focus GUN, etc.) have appeared.

The generation of a progressive volume wave imposes the respect of geometrical and mechanical constraints related to the periodicity of the motor's structure. Under normal conditions of operation, the motor (see Fig 2) is subjected to: (i) an axial static loading of pre-stressing producing axial and radial deformations in stator and rotor, (ii) a dynamic excitation of the stator, involving deformations of bending out of the plane, which produces by drive a rigid displacement of the rotor's body and (iii) efforts of contact and friction, static and dynamic in the contact zone between the stator and the rotor.

Material	Young's Modulus (MPa)	Poisson Ratio	Mass density (kg/m3)
Stator	123000	0.31	8250
Rotor	72000	0.3	2700
Polymer	800	0.33	-

Table 1: Material's data

3.2 Numerical simulation

The Fig 3 shows the model meshes of the stator and the rotor. It is realized with 900 hexahedral elements with 8 nodes per elements and 3 degrees of freedom per node. But the geometry of revolution of the structure and the axial loading of pre-stressing allows a two- dimensional axisymmetric model mesh.

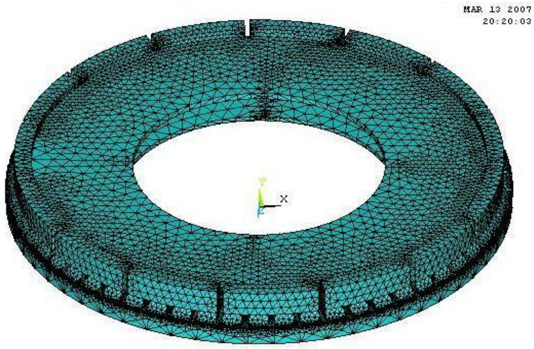

Figure 3: Meshing the stator and rotor

Using the axisymmetric of the structure, the reduction of the structure's study to a two- dimensional axisymmetric problem allows a refined grid of these two surfaces while preserving the size of the system of equations after reasonable finite elements approximation. The time step of $\Delta t = 10^{-2}$ s was selected. Accurate evaluations of the width of contact stator/rotor and of the radial distribution of the contact stresses are possible. The deformed structure's study gives an access to the radial and the axial behavior components of the motor under the static loading of pre-stressing. Effects of bending, due to the application of the thrust load, involve significant axial displacements of the components of the motor. A strong crushing of the friction material is observed on the contact surface between the stator and the rotor (Fig 4).

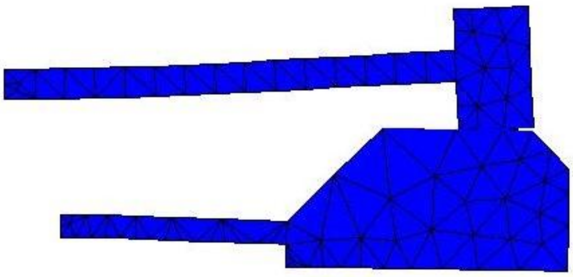

Figure 4: contact between the stator and the rotor

d_{31} ([C/N])	2.2 × 10−11
d_{32} ([C/N])	0.3×10^{11}
d_{33} ([C/N])	−3 × 10−11

Table 2: Piezoelectric stress coefficient

The application of the static loading of pre-stressing causes the separation between the two surfaces of contact over a width of 1.8 mm. Deformations of the two components of the motor are not in conformity and surfaces of contact are not fully in contact. The Fig 5 shows the first mode of the stator. The study of the dynamic contact is done in [7].

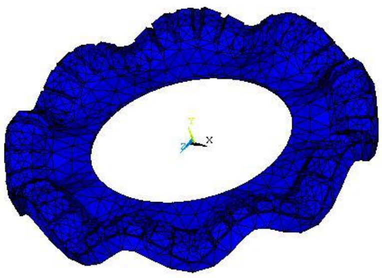

Figure 5: The first mode of the stator

The piezoelectric stress coefficient is given in table 2. The piezoelectric geometry is given in the Fig (6) with $R_1 = 22.5$ and $R_2 = 30$.

The finite element PLANNE223 has eight knots with up to four degrees of freedom per knot. Structural capabilities include elasticity, plasticity, viscoelasticity, large deformations, large deviation, stress stiffening effects, and pre-stress effects. Thermoelectric capacities include Seebeck, Peltier and Thomsen effects. In addition to thermal expansion, thermal structural capabilities include the piezoelectric effect in dynamic analyzes. The geometry, node locations, and coordinate system for this element are shown in Fig 7.

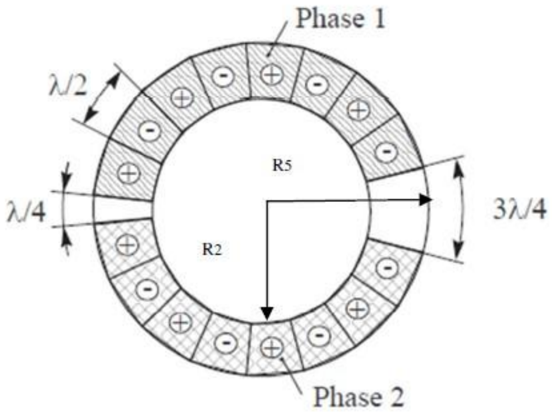

Figure 6: sectorization of a piezoelectric ring used in a progressive wave motor

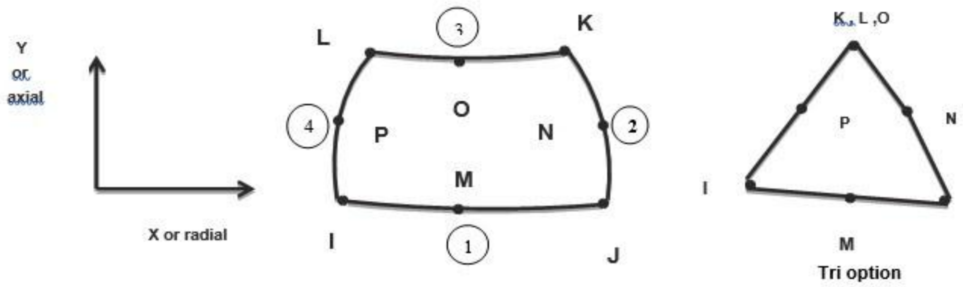

Figure 7: geometry of PLANE223

The Fig 8 shows the result of a numerical simulation, showing the deformation of a sectorial and reverse biased PZT subjected to an electric field. The generation of a progressive wave requires a spatial and temporal quadrature. This requires placing the ceramic rings in pairs, orthogonally spinning heads (spatial phase shift) to each excite a bending mode.

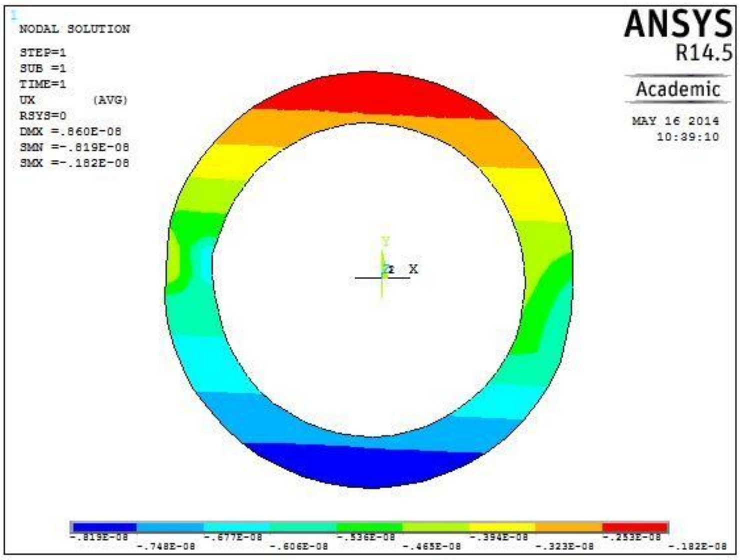

Figure 8: Deformation of a PZT ceramic subjected to an electric field

IV. Conclusion

The work presented is the functional analysis of a progressive wave piezoelectric actuator. The physical principles related to the operations of the piezoelectric motor shareholders are presented. The most popular inventions during the past decade related to the hypothesis of the piezoelectric motor energy conversion model and retained is the most popular piezoelectric motor at SHINSEI USR60 Progressive Wave. The numerical simulation shows the effect of the piezoelectric ceramic in the movement of the stator and the first mode is given.

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