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Estudio del estator de un motor ultrasónico piezoeléctrico

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TÍTULO: Study of a stator of a piezoelectric rotary ultrasonic motor

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Abstract

This study presents mathematical modeling and numerical simulation results that are part of a study concerning the dynamics of the stator of piezoelectric (PZ) traveling wave (TW) rotary ultrasonic motor. The stator is divided mainly in three parts; a PZ composite ring, an adhesive and a metallic ring that transmit the vibrational waves to the rotor. The rotational torque is produced by exciting the stator into a flexural traveling wave, transmitted to the rotor through the stator-rotor friction (it will be explained throughout this document).

A modal analysis provides for the structural eigenfrequencies of the stator. When the AC powering stage providing for two voltages of same amplitude and shifted in quadrature is adapted to a frequency close to the flexural resonance of the stator, the TW reaches higher amplitudes that result in higher rotational velocities because the rotor speed is proportional to the stator TW amplitude. To build the geometry and do the simulations is used the finite element software "Comsol Multiphysics 3.5".

Also in this study is explained briefly the different uses of this kind of ultrasonic motors in nowadays and, for better understanding of the ultrasonic motor operation, is explained the piezoelectricity phenomenon and the finite element method.

Keywords: piezoelectric ultrasonic rotary motor, flexural traveling wave, eigenmodes, numerical simulation, finite element.

Resumen

En este estudio es presentado un modelo matemático y los resultados de simulación numérica que son parte del estudio acerca de la dinámica del estator de un motor ultrasónico de onda viajera. El estator está dividido principalmente en tres partes; Un anillo de material piezoeléctrico, un adhesivo y un anillo metálico que transmite las ondas vibratorias al rotor. El momento giratorio es producido por la excitación del estator con una onda de flexión transmitida al rotor a través de la fricción entre el estator y el rotor (Como será explicado a lo largo de este documento).

Un análisis modal proporciona para la estructura, las frecuencias propias del estator. Cuando la etapa de alimentación suministra dos corrientes alternas de la misma amplitud y en cuadratura y está adaptada a la frecuencia de resonancia del estator, la onda viajera alcanza la máximas amplitudes que resultan en altas velocidades giratorias porque la velocidad del rotor es proporcional a la amplitud de la onda viajera generada en el estator. Para construir la geometría y hacer las simulaciones es utilizado el software de elementos finitos "Comsol Multiphysics 3.5".

También en este estudio es explicado brevemente los diferentes usos de este tipo de motores ultrasónicos en nuestros días y, para mejor comprensión del funcionamiento del motor ultrasónico, es explicado el fenómeno de la piezoelectricidad y el método de los elementos finitos.

Palabras clave: Motor ultrasónico giratorio piezoeléctrico, ondas de flexión, frecuencias propias, simulación numérica, elementos finitos.

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1. INTRODUCTION

1.1. Description

The ultrasonic motor that is described in this paper, works using the piezoelectric principles. When it is applied an electrical potential to the stator, appear in this a traveling wave and the motor generates torque by using the friction force between a piezoelectric ring and a metallic ring. The motor speed is proportional to the amplitude of this traveling wave and you can obtain different amplitudes if the stator is excited with different frequencies. If you want to obtain large amplitudes we have to excite the stator with frequencies close to its resonance frequency.

In this document is presented a non-empirical partial differential equations model for the stator and the results are compared with the stator of “Shinsei USR60” piezoelectric motor. In [1] and [3] you can find operating details and construction characteristics of this motor.

The mainly piece of this motor consist in a ring of piezoelectric material in which it is applied an electrical potential and it is obtained a deformation. Above the piezoelectric ring there is a metallic ring that vibrates for this deformation. This vibration makes that the rotor starts to rotate.

This paper presents an empirical equivalent circuit model of a piezoelectric traveling wave rotary ultrasonic motor.

For solve the model is used the finite element method (FEM) [4], with the software Comsol Multyphisics 3.5 [12]. With this program is built the geometry of the motor and are obtained the results by simulation.

By this way it can be estimated the motor’s characteristics. One limitation of this simulation is that the model does not calculate the operating frequency of the motor, it has to be determined experimentally.

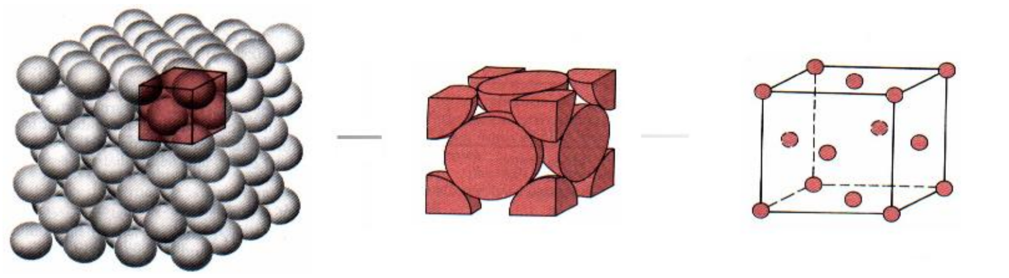
1.2. Piezoelectricity

Piezoelectricity is a phenomenon that happens in some crystals. If one of these crystals is submitted to a mechanical stress then an electrical polarity situation occurs and electrical charges are generated in the surface.

This phenomenon is reversible; if the crystal is subjected to an electrical field it will be deformed and if the electric field is suppressed the crystal recovers its shape.

The origin of the piezoelectric property is in the internal structure of the material. In most crystals (e.g. metals), the unit cell is symmetrical, in piezoelectric crystals, it isn't.

The unit cell is the simplest portion of the crystal structure that repeated by translation reproduces the whole crystal.



Crystalline solid — Unit cell represented by rigid spheres — Unit cell of a crystal lattice

Fig.1. Unit cell [14]

This concept represents the symmetry of a particular crystal structure. There are different kinds of unit cells and all of them have different properties depending of their internal structure.

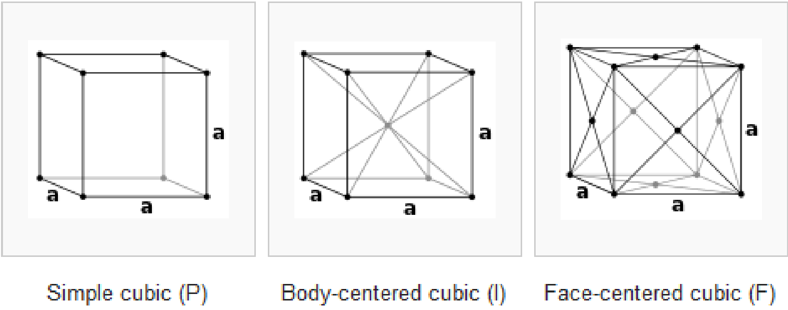


Fig.2. Some examples of unit cells[13]

Piezoelectric effect is exhibited by 20 out of 32 crystal classes that exist and is always associated with noncentrosymmetric crystals.

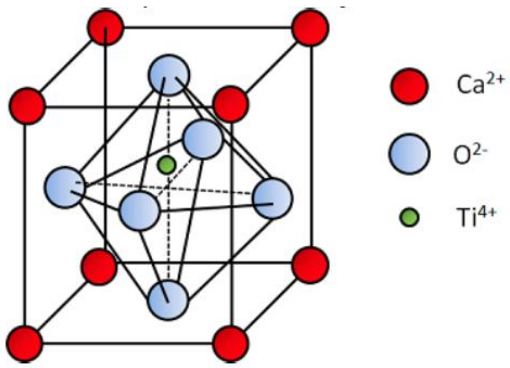


Fig.3. A perovskite unit cell showing the off-centered titanium ion.[15]

Normally, the piezoelectric crystals are electrically neutral: the atoms inside them may not be symmetrically organized, but their electrical charges are perfectly balanced (a positive charge in one place cancels out a negative charge in other place).

But, as a result off-centered ion, if you constrain or stretch this crystal, you deform the structure, pushing some of the atoms closer together or further apart, changing the balance of positive and negative, causing that electrical charges appear. This effect carries through the whole structure so net positive and negative charges appear on opposite, outer faces of the crystal.

The reverse-piezoelectric effect occurs in the opposite way. Put a voltage across a piezoelectric crystal and you're subjecting the atoms inside it to "electrical pressure." They have to move to rebalance themselves—and that's what causes piezoelectric crystals to deform (slightly change shape) when you put a voltage across them. Some examples of these materials are quartz, berlinite, perovskite or engineered materials like lead zirconate titanate.

More information about the internal structure of the materials and about the origin of the piezoelectricity can be found in [11],[13],[14] y [15] .

Piezoelectrical materials are subjected to a process called poling to impart the piezoelectric behavior

[anexo 1]

2. ULTRASONICS MOTORS

The recent technological advances emphasize the importance in the piezoelectric ultrasonic motors (PZ-UMs) making them convenient competitors to electromagnetic actuators: simple design, fast reaction time, high torque at low speed, high holding torque, good steering capability, higher positioning accuracy, minimal EMI/RFI noise, for a smaller packaging size. Because PZ-Ums comply to the stringent constraints of contemporary product technologies, they are used in many industrial applications, e.g. in computer hard disk drives, systems for micropositioning, process control for manufacturing, positioning in fiber optics, ensembles for pick-and-place, autofocus for camera, test equipment for semiconductors, positioning systems for robotics, positioning of medical devices (e.g., catheters), pharmaceuticals manipulators, etc. [1].

There are different types of ultrasonic motors [17] but the motor that is studied here is a Travelling wave piezoelectric ultrasonic motor (TW-PZUM) that uses the inverse piezoelectric effect to obtain either linear or rotary motion. The modeling of the stator dynamics makes the object of intense research [3]. Rotational motion happens through flexural propagating waves that are produced on a composite laminated stator, which is made of an elastic layer and one or two piezoelectric layers. The propagating waves result through the superposition of two flexural standing waves, excited in quadrature in the piezoelectric layer. Traveling waves (TWs) produce result in an elliptical motion of the stator surface, and transmitted by direct contact to the rotor [3-9].

The Shinsei US type is rated at 100÷150 rpm, for 40÷45 kHz AC powering [2]. The rotary torque is produced through friction force between the piezoelectric ring and the metallic ring with the rotor. The motor speed is proportional to the amplitude of the TW. Different amplitudes may be obtained if the stator is excited with different frequencies, and larger amplitudes are obtained when the stator is excited with frequencies close to its flexural, structural resonance frequency.

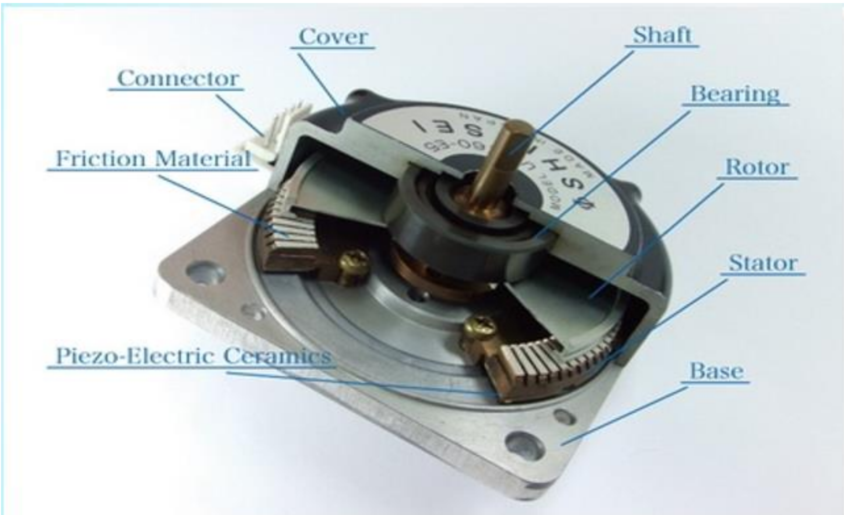


Fig.4.Internal structure of USM (USR 60 S4)

3. MODELING AN ULTRASONIC MOTOR STATOR

The stator of the ultrasonic motor is studied. The stator is composed of a piezoelectric ring, a metallic ring and an adhesive between the piezoelectric and the metallic rings. All this pieces compose the stator of the motor.

It considered that the model consists in two equivalent RLC circuits. The inductor (L) represents the mass effect, the capacitance (C) represents the spring effect and the resistance (R) represents the losses of the ceramic and metal rings. In [10], it is presented an empirical equivalent circuit model for the motor of a piezoelectric traveling wave rotary ultrasonic motor.
In this document is not represented a simulation of this model. The main parts of a piezoelectric rotary motor considered in this studio are detailed next.

3.1- The piezoelectric ring

The ring is divided in two semicircular sectors and each sector is divided in eight regions labeled with "+" and "-" (see **fig.5**).

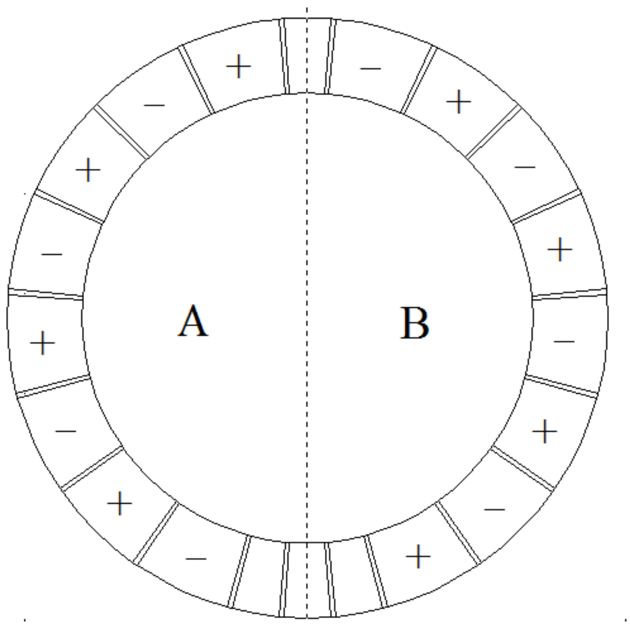


Fig. 5. Piezoelectric ring [15]

This regions are connected with a common electrode. Thus if you apply a positive DC voltage in both electrodes ("+" and "-") the positive region will be expand and the negative one will be contract, also if you apply a negative DC voltage, will happen the opposite effect.

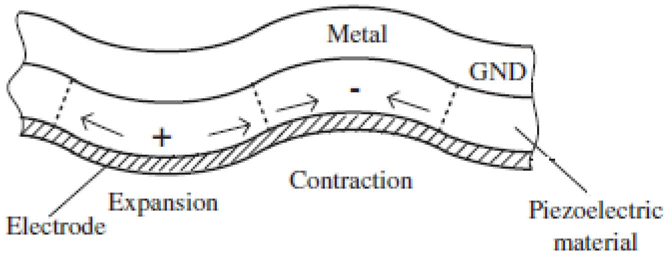


Fig.6. Deformation when is applied a DC voltage

If it is applied an AC voltage at the operation frequency in the side A of the ring, it is obtained a standing wave with nine wavelengths in the stator. If the electrodes of the side B are connected with the same electrode it will have an equal-amplitude AC voltage at the same operation frequency, but this waves are out of phase 90º due to the region that we have without polarity (passive region) that is a quarter wavelength (λ/4). This difference of phase will do that the motor works in two-phases.

There are nine wavelengths: $9\lambda = 2\pi R$ where R is the outer radius. A pair of active region ± corresponds to one ninth of the ring. In total there are eight active regions and one passive region that is situated at the top and at the bottom of the ring. This passive region separates the two regions of the ring. The bottom part is used as a sensor, generating a voltage proportional to the amplitude of the traveling wave.

In [3] the authors explain with detail the operation of the piezoelectric ring. And in [18] it can be found manufacturing details and characteristics about different piezoelectric rings.

3.2. The metallic ring

The metallic ring is a solid piece of copper and is situated over the piezoelectric ring.
The top part of the metallic ring is formed by teeth. This teeth are part of the metallic ring. Each wavelength sector has ten teeth.

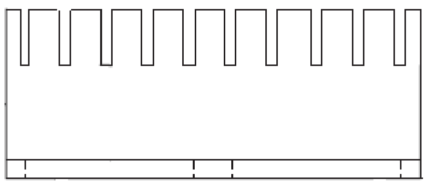


Fig.7. Wavelenght sector with 10 teeth

The teeth have little effect on the rigidity of the material but their mass is included in the geometry for the simulation, is important that the teeth do not touch one another during operation.
The mass density of the copper is 8700 kg/m3.

3.3. The adhesive

The adhesive is situated between the piezoelectric ring and the metallic ring and is thin compared with the piezoelectric and the metal ring. For this reason we can exclude the adhesive in the simulation, but in this model is included.

In [6] we can find an exhaustive study about the contact layer in this kind of motors.

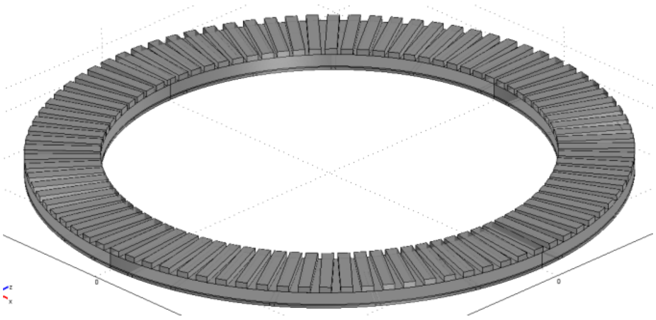


Fig.8. Stator.

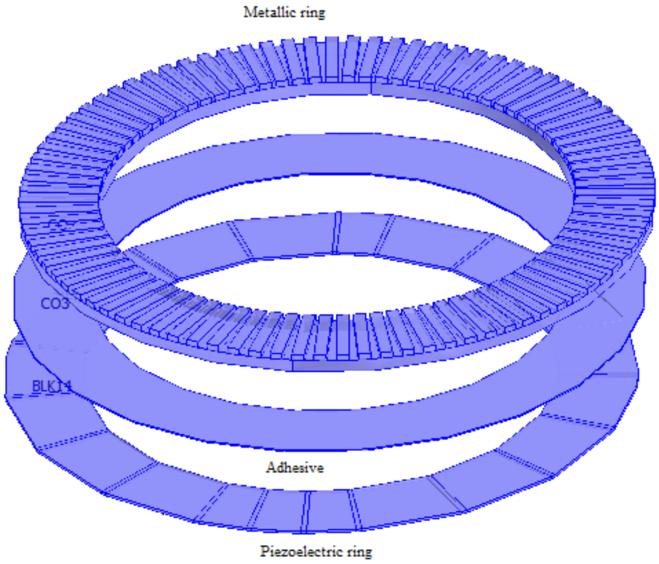


Fig. 9. Views of stator parts.

3.4. Sizes

The ring has an external radius of 30 mm, and internal radius of 22.5 mm.
The thickness of the piezoelectric is 0.5 mm.
The thickness of the metal ring is 0.00255 m. and the thickness of the teeth are 0.001225 m.
The width of the teeth are 0.002356 m. and the space between teeth are 0.001832 m. in the outer part of the ring.

4. MATHEMATICAL MODEL

The dynamic of the piezoelectric ring is determined from Newton`s second law:

$$\rho \frac{\delta^2 u}{\delta^t} = \rho u_g \qquad (1)$$

Where ρ is the mass density of the piezoelectrical material and u is the matrix of local displacements in the x, y and z directions.

The actuator equation is,

$$T = c^E S - e^t E \qquad (2)$$

Where T is the stress, S is the strain, E is the electric field, e is the elecromechanic coupling matrix and c^E is the stiffness matrix.

This equations describes the behaviour of the piezoelectric and the metallic rings but the metal ring has not piezoelectric properties (e = 0) so we have to remove the second part in (2).

This is explained with more detail in [3] and in [Annex II].

5. ELECTRICAL MODEL

Two particles with electrical charges of the same magnitude, q, and different sing, separated by a distance l, produce an electrical torque, p, given by the equation,

$$p = q\, l \qquad (3)$$

In a crystal where exists many dipoles, the total dipolar torque is the vector sum of the moments generated by each dipole. The polarization P is defined as the total dipolar torque per unit volume.

If a material has an electric charge distribution in that the positive charges centroid coincide with the negative charge centroid the total dipolar torque is zero and the polarization too (P = 0). This material is known as no-polar. However if this material is mechanically deformed the charge centroids can let of coincide and turn in a polar material ($P \neq 0$) in the deformed state (case of the piezoelectric materials).

In this situation the polarization cause the existent of an electric field E inside the material. The total electric field is a potential difference V on the surface of the material. The ratio between the electrical field E and the voltage V is:

$$E = -\nabla V \qquad (4)$$

Where ∇ is the vector operator that in ortogonal cartesian coordinates takes the form:

$$\nabla = \frac{\partial}{\partial x}\, i + \frac{\partial}{\partial y}\, j + \frac{\partial}{\partial z}\, k \qquad (5)$$

6. NUMERICAL SIMULATION RESULTS

Once the geometry is finished are set the boundary conditions in the different stator parts. These conditions allow to control the stator movement.

There are two types of boundary conditions in the ring. For the piezoelectric ring, the side surfaces (inner and outer), their constraint condition is roller and the top and the bottom part are considered free. This is because we want that the ring only can move up and down.
For the metallic ring and the adhesive all surfaces are considered free.

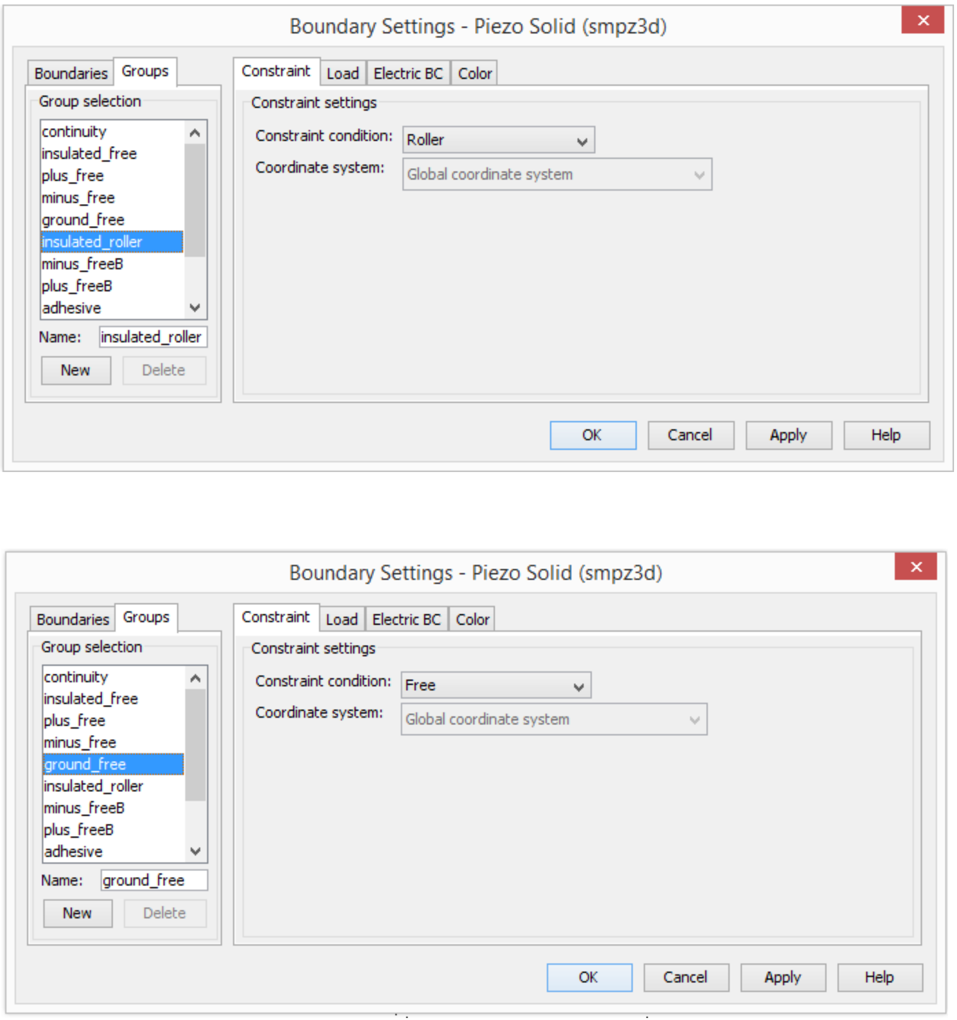


Fig.10. Images from COMSOL in where the properties are set.

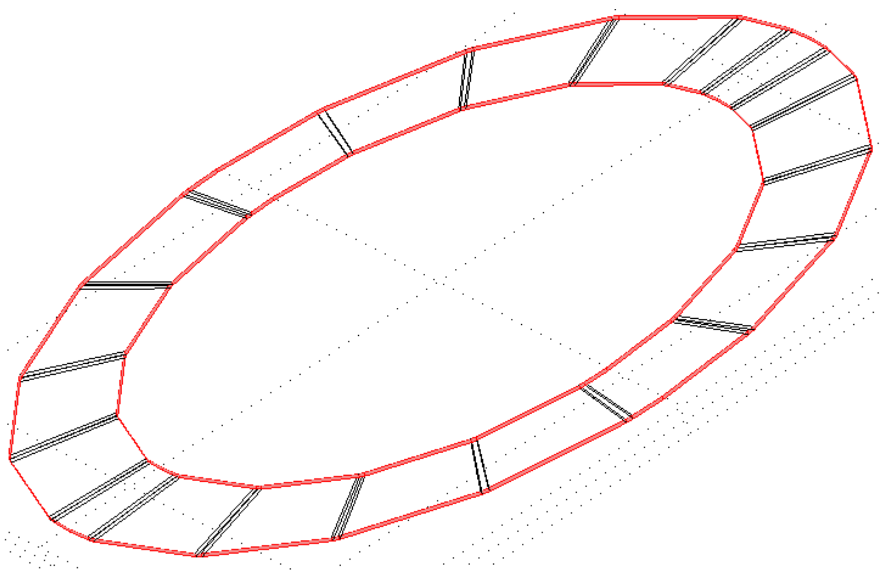
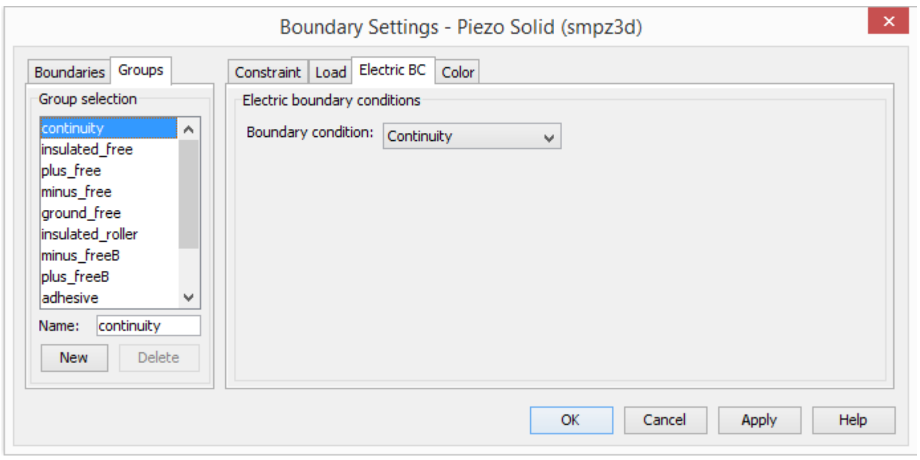


Fig.11. View of the piezoelectric ring. The colored parts are the surfaces inner and outer of the stator that are considered 'roller'

Also the electrical properties of the stator have to be stablished in the boundary conditions. There are four types of electric boundary conditions that are used in this model; electrical potential (positive or negative), ground, zero charge/symmetry and continuity.



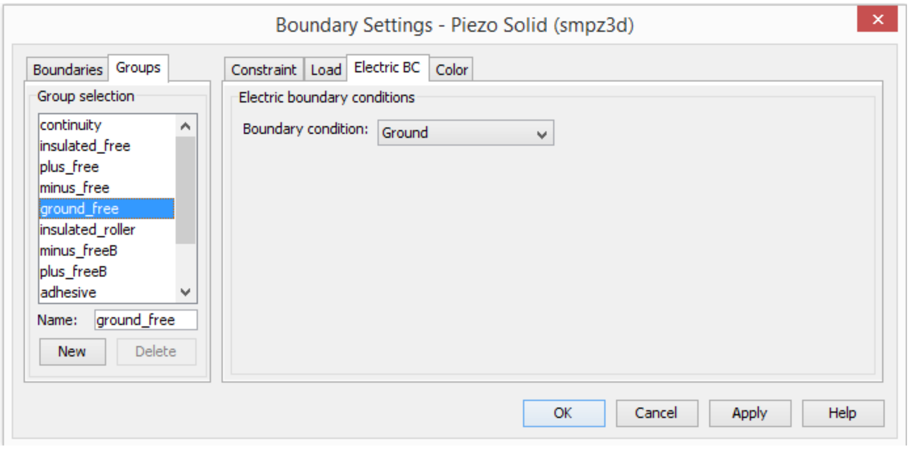


Fig.12. Images from COMSOL in where the electric properties are set.

In the next table are shown all constraint and electric boundary conditions of all parts of the stator ring that were set to the simulation.

Groups	Constraint	Electric BC
continuity	free	continuity
insulated_free	free	zero charge/symmetry
plus	free	electric potential
minus	free	electric potential
ground	free	ground
insulated_roller	roller	zero charge/symmetry
minus_B	free	electric potential
plus_B	free	electric potential
adhesive	free	zero charge/symmetry
copper	free	zero charge/symmetry
theet	free	zero charge/symmetry

Table 1. Constraint and electric conditions of the different stator parts

Several working conditions were analyzed: first, DC powering schemes, and then an AC powering scheme. In the next points are shown the different analysis of the stator and it can be observed and studied the different results that are obtained.

The frequency of the voltage used in the AC analysis was selected based on a modal structural study.

5.1. Stationary wave

A DC voltage (25V) is apply in the side A and is obtained the next figure,

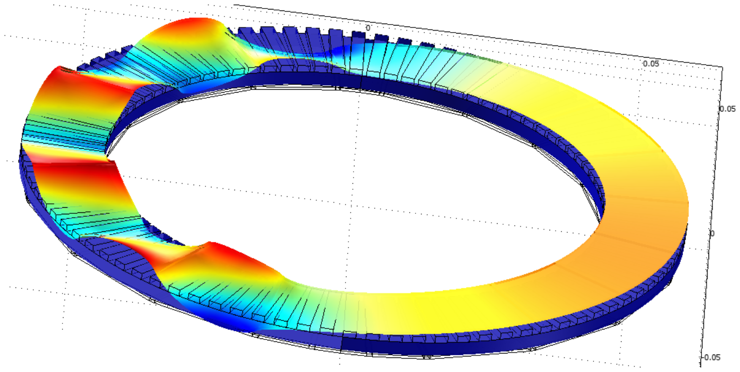


Fig. 13. Deformation in the side A

In fig.5 is observed the deformation of the piezoelectric material in this side (side A), the positive regions are expanded and the negative regions are contracted, as is explained in previous points, and this causes that the metallic ring is moved appearing a movement in the rotor of the motor.

The side B keeps the same shape.

The same happens if it is applied the same voltage in the other side (side B). See fig. 14.

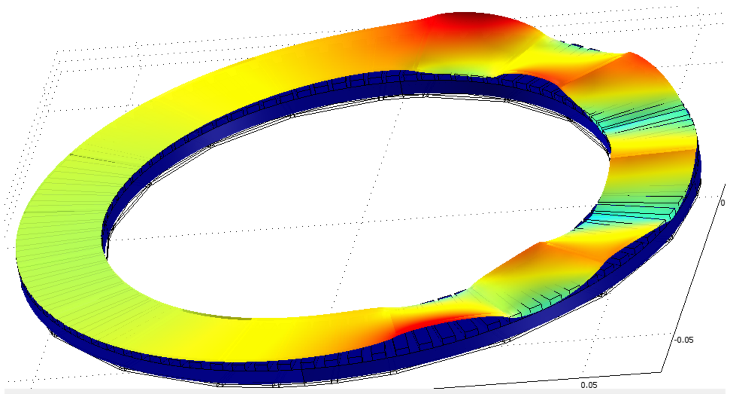


Fig. 14. Deformation in the side B

Now a positive DC voltage of 25 V. is applied in the two parts of the stator, and the piezoelectric material is deformed as it is shown in fig 15.

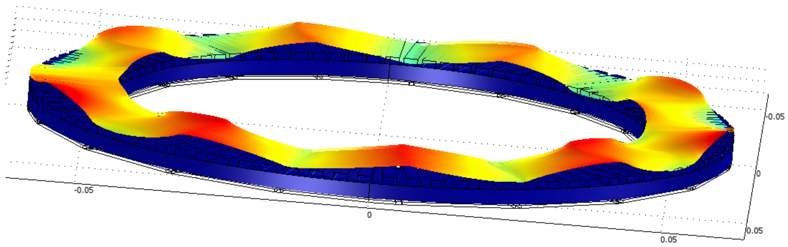


Fig. 15. Deformation in the whole ring

It is observed that the whole ring is deformed, contracted or expanded, depending the previous polarization "+" or "-".

Also in this picture is observed that the piezoelectric material is displaced upward (a maximum of 1.691e-6 m. see fig. 16). This causes that the metallic ring is pushed too. In a real motor the rings cannot be displacement upward, this movement is constrained for the rotor of the motor or for an internal mechanism. The rotor is only moved for the stator vibrations.

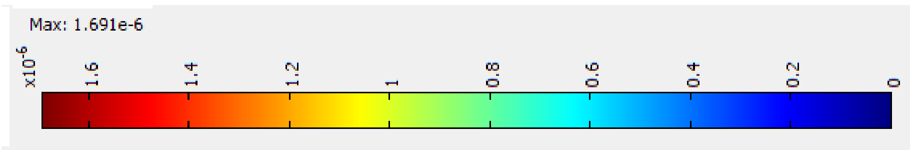


Fig. 16. Displacement [m]

There are no more movements in the rotor if we keep this DC voltage. So if we want that our rotor spins we have to apply other kind of waves. [Annex III]

5.2. Traveling wave

An AC voltage is applied in the stator, and the piezoelectric material is deformed as is shown in the figure (17).

The positive part and negative part are continuously expanded and contracted, so that the material starts to vibrate.

This vibrations make that the metallic ring starts to vibrate too and thus the rotor starts to move.

The speed and torque of the motor can be controlled depending of the frequency that is used in our input signal.

This kind of motors can work with frequencies close to 40 KHz, (the resonance frequency of this motor is 40 KHz) , this feature makes that it can be obtained speeds and movements with high accuracy.

Details and features of the function of this motor can be found in [6].

When the frequency of the TWs "equals" the eigenfrequencies of the structural resonance may occur, leading to higher amplitudes for the flexural deformations of the PZ stator. As the rotor speed is proportional to this amplitude, the PZ-UM then attains higher rotary velocity.

The Fig. 17 presents six eigenfrequencies about 40 kHz, which are associated to the largest deformations. Recall, the intrinsic polarization (electrical “poling”) is in Oz direction.

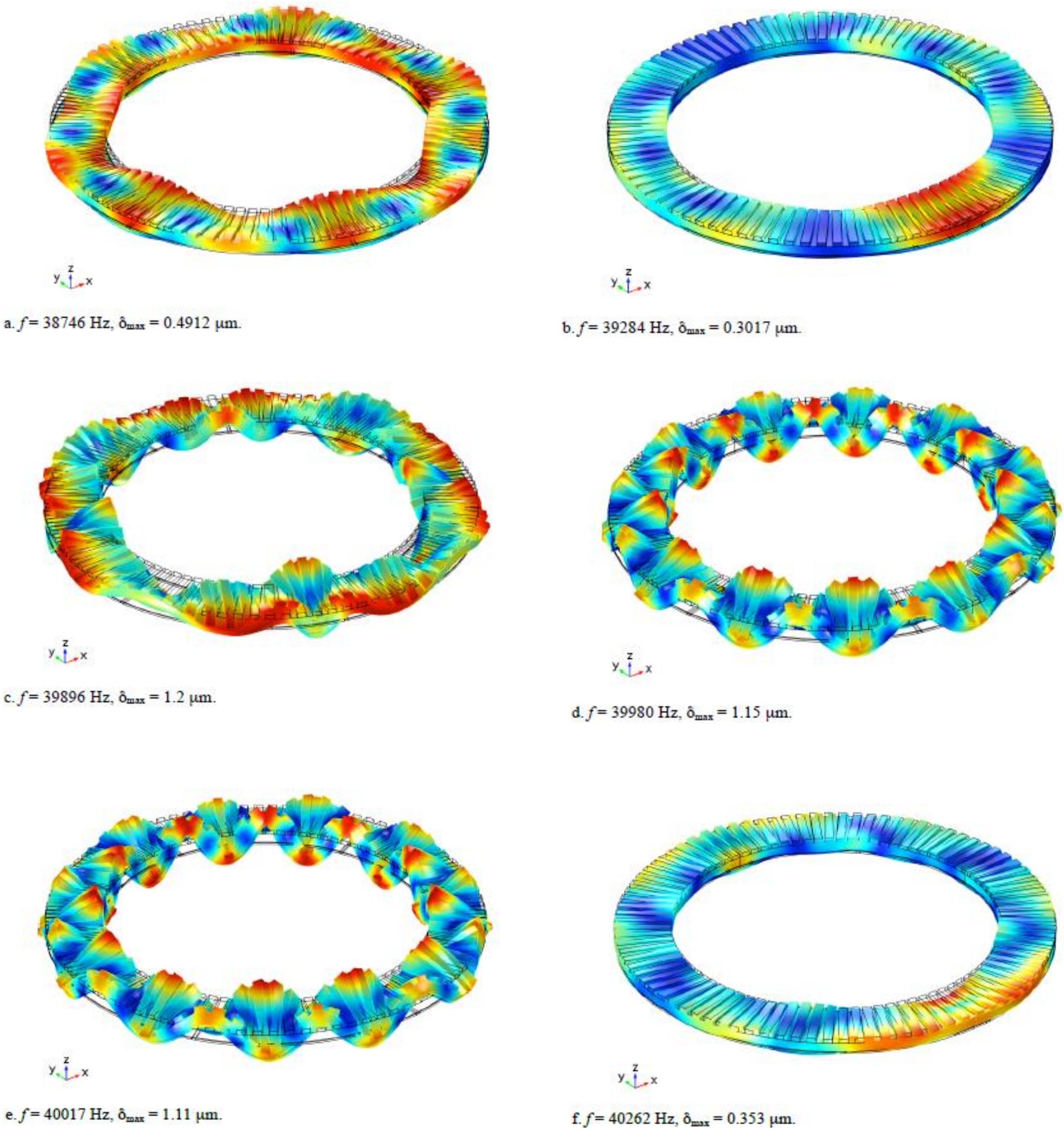


Fig. 17. The PZ stator ring deformation for six eigenfrequencies about 40 kHz, related to the largest deformations, δmax. The amplitudes are magnified 6800 times for better viewing.

The largest deformation, 1.2 μm, occurs for f ~ 39896 Hz.

This frequency is selected for the AC voltage that produces the TW utilized in the numerical simulations presented next.

5.3. Traveling Waves – AC Powering Scheme

When AC voltage is applied to the stator the PZ material deforms into what is called a flexural traveling wave. The PZ ring vibrates as each sector expands and contracts continuously. The vibrations are transmitted – through frictional contact – from the PZ ring to the metallic ribbed ring (the stator) and from the metallic ribbed to the rotor, and a rotary motion is produced. This information helps tuning the PZ-UM: the speed and torque of the rotor can be controlled with high accuracy then by adjusting the frequency of the input signal.

The PZ-UM control uses as feedback the voltage produced by the sensor, which is filtered and rectified by an electronic conditioning unit built by the manufacturer into the motor [3].

The largest the amplitude of this voltage is the higher amplitude of the sensed TW. The PZ-UM-dependent resultant peak voltage may be represented versus the frequency of the powering stage, and the resonance frequencies are identified then through the voltage peaks. There are two sensor stations in this numerical study, P and Q as is shown in Fig.18.

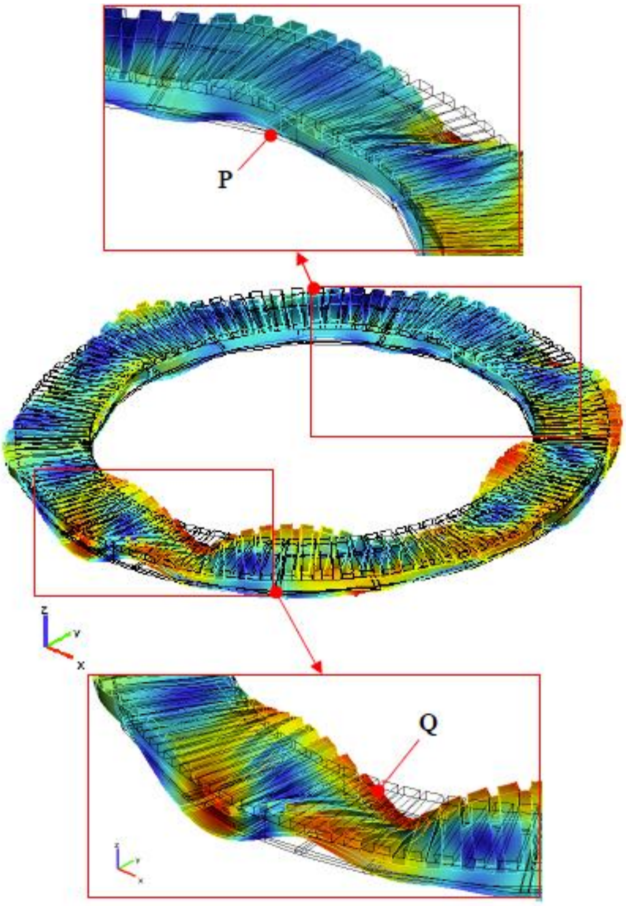


Fig. 18. The PZ ring deformation at t = 4.877488.10-4 s – magnified 7000 times.

Fig. 19 presents the voltages produced in the sensors, as computed through numerical simulations.

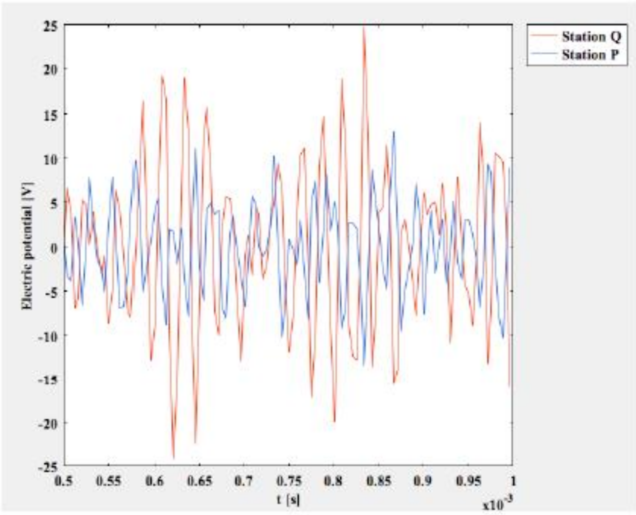


Fig. 19. The voltages produced by the sensors as computed at locations P and Q (fig. 17). The first two periods are discarded.

Although the amplitudes and phases of these signals differ, they exhibit the same dynamics, an image of the flexural TW.

The two signals may be used to optimize the PZ-UM design and to adjust the control. The morphology of these signals (Q and P) shows off a carrier signal, at the powering stage frequency (and TW), modeled by a pulsating envelope at a lower frequency, which is related to the number of pairs of PZ sectors, i.e., ~9 times lower than the carrier frequency.

7. CONCLUSIONS

This study presents a detail description about the stator parts of the ultrasonic motor “Shinsei USR60” and its operation, also is described the mathematical method that is used for the simulation with Comsol 3.5 and finally the results that are obtained with this program are shown.

Part of the project consists in compile information about the working and construction characteristics of the motor “Shinsei USR60” and understand its behavior. After that, create the geometry of the stator with the software Comsol Multiphysics, set the properties of the materials and set the simulation conditions.

The final part is do the simulations with different kind of signals (different voltages, different frequencies) and analyze the results. In this study were tested many signal that could be used in different applications of the motor but the signal that provided the highest amplitude in the stator (see fig 16.c) was chosen to study the outputs of the sensors.

A rotational torque is produced a flexural traveling wave, which is obtained by exciting the PZ stator with two AC voltage, in of same amplitude and in quadrature. The stator deformation is then transmitted to the rotor through the stator-rotor friction. When the AC powering stage of the PZ-UM is adapted to a frequency close to the flexural resonance of the stator, the TW reaches higher amplitudes that result in higher rotational velocities of the rotor because its speed is proportional to the stator TW amplitude.

Under reasonably realistic simplifying assumptions, numerical simulations were used to study the deformation of the PZ stator when stationary flexural waves are produced through DC powering schemes. Then, a modal analysis was conducted to find the structural eigenfrequencies of the stator.

For the PZ-UM model in this study, the eigenfrequency for which the largest deformation (1.2 μm) occurs is f ~ 39896 Hz (see fig. 16). Finally, the dynamic study of the PZ-UM was conducted for powering AC voltages of this frequency, 100 V in amplitude, and shifted in quadrature.

The dynamics of the rotor motion may be perceived through PZ voltages produced by PZ stator sectors inserted between the PZ sectors of the stator, and used as sensors.

This information may be utilized to sense the resonance frequency of the motor and, further on, to adjust the working frequency of the PZ-UM for best performance. Not the least, it may be used also for design optimization purposes.

My contributions to this project were, the performing of the geometry of the different stator parts, set the properties of the stator materials and the properties of simulation and finally do the simulations with the software Comsol Multyphisics 3.5.

Extensions of this work could be to add the rotor of the motor to study the behavior of the whole motor, and study the electronic devices that are used to control the sensor outputs. Finally all these information could be used to simulate a real application.

ACKNOWLEDGMENTS

I am sincerely grateful to the support offered through the Erasmus exchange program, because if not I could not have had the opportunity of study in the university of other country and know other education system and different working methods.

I would like to show my gratitude to Polytechnic University of Bucharest because the work was conducted in the Laboratory for MultiPhysics Modeling, Alexandru Morega professor that he guided me through this project and also my laboratory mates Alina Sandoiu and Cristina Savastru that helped me to solve the doubts that I had.

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ANNEX I POLING

In a macroscopic crystalline structure that has several unit cells, the dipoles are found, by default, to be randomly oriented. When the material is subjected to a mechanical stress, each dipole rotates from its original orientation toward a direction that minimizes the total electrical and mechanical energy stored in the dipole. If all the dipoles are initially randomly oriented (i.e. a net polarization of zero), their rotation may not significantly change the macroscopic net polarization of the material, therefore the piezoelectric effect exhibited will be negligible.

For this reason is important to create an initial state in the material in that most dipoles will be more-or-less oriented in the same direction. Such an initial state can be imparted to the material by poling it. The direction along which the dipoles align is known as the poling direction.

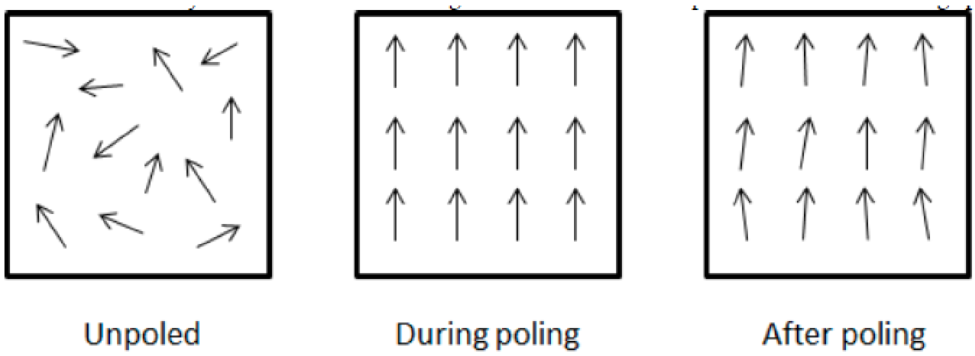

Fig.20. Alignment of electric dipoles [15]

During poling, the material is subjected to a very high electric field that orients all the dipoles in the direction of the field. When the electric field is switched of, most dipoles do not come back to their original orientation as a result of the pinning effect produced by microscopic defects in the crystalline lattice. This gives us a material with numerous microscopic dipoles that are roughly oriented in the same direction. It is important to know that the material can be de-poled if it is subjected to a very high electric field oriented opposite to the poling direction or is exposed to a temperature higher than the Curie temperature of the material.[15]

ANNEX II MECHANICAL DEFORMATION.

For obtain a mathematical description of the piezoelectric behavior it is defined a reference system N as is shown in the figure (21).

If the mechanic deformation and the electric field are relatively small, the piezoelectric effect can be expressed in constitutive linear terms relations that are derived from energy considerations and thermodynamic.

$$\varepsilon_{ij} = S^E_{ijkl}\,\sigma_{kl} + d_{ijk}\,E_k \qquad i,j,k,l = 1,2,3 \qquad (6)$$

Where ε is the deformation tensor, S^E is the flexibility constant tensor field, σ is the mechanic tensor, d is the electromechanical coupling tensor that contains the piezoelectric deformation coefficients and E is the electric field vector.

Due to the symmetry the tensors σ and ε, only have 6 independent components, therefore we can reduce the order of the tensor S^E and the order of the tensor d. Hence the constitutive equations take the following form:

$$\varepsilon_{ij} = S^E_{ij}\,\sigma_j + d_{ij}\,E_j \qquad i,j = 1,2,\dots,6 \qquad (7)$$

The subscript 4, 5 and 6 in the tensors σ and ε denote the shear stress and the shear deformations respectively.

To indicate the directions of this tensions and deformations we define a reference system (4, 5, 6) associated with the system N and with the same characteristics.

In this work the crystal is considered a rectangular plate of piezoelectric material and its geometry is describe for the length l_p, width b_p and thickness $t_p$as is shown in the figure (21).

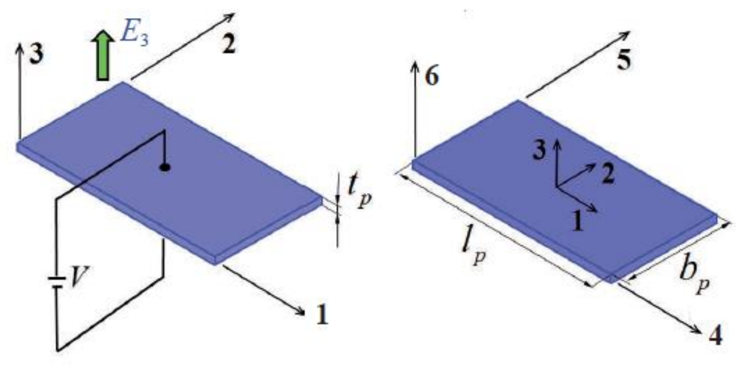

Fig. 21. Piezoelectric plate and reference system N

If we apply a time dependent electrical field E in the direction 3, and the region 1 is constrained, we can find the following relation,

$$\sigma_1 = Y_p(\varepsilon_1 - d_{31} E_3) \qquad (8)$$

Where Y_p is the piezoelectric elasticity module and d_{31} is one of the electromechanical coupling tensor elements. Then if we define $\lambda = d_{31} E_3$, the equation (8) is transformed in,

$$\sigma_1 = Y_p(\varepsilon_1 - \lambda) \qquad (9)$$

If the plate is not constrained in the axial direction, this is deformed freely and consequently $\sigma_1 = 0$ and the equation (9) is transformed in,

$$\varepsilon_1 = \lambda \qquad (10)$$

λ is known as free deformation.

The application of the electric field generates in the plate deformations in ε_2 and ε_3 in the directions 2 and 3 respectively.
Returning to the equation (10), free deformation $\lambda(t)$ can be written in terms of the applied voltage considering the equation (4),

$$\lambda(t) = d_{31} \frac{V(t)}{t_p} \qquad (11)$$

The free deformation obeys the same law of variation than the voltage and is amplified or decreased by the constants d_{31} and t_p. In [4] you can find a complete description of this section and an exhaustive study of the mechanical deformation in a piezoelectric ring is explained with detail in [3].

ANNEX III WAVEFORMS

Depending that movement or the speed that we want we can apply different waveforms and different frequencies in the stator. Also we can apply this waves in one side of the stator (A or B), in the whole stator or alternatively in the sides A and B.

The next figure (Fig 22) shows some examples that the different waveforms that can be used to stimulate the stator,

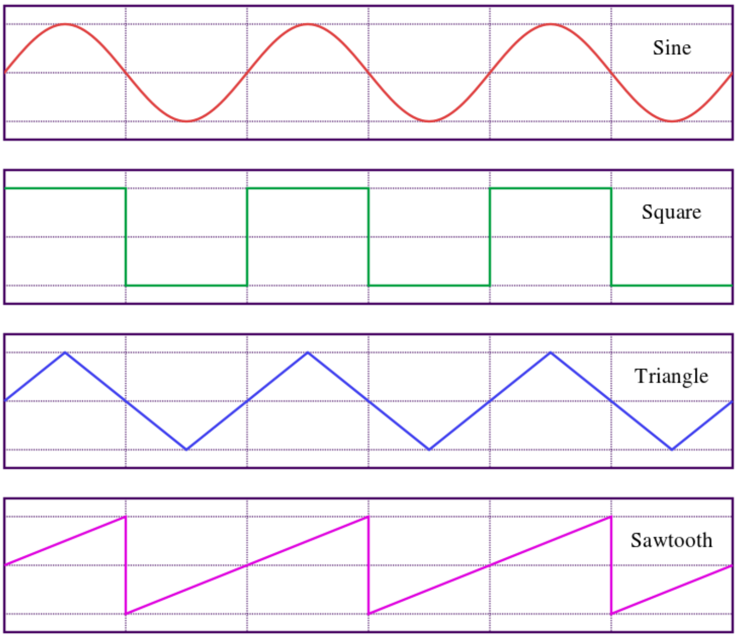

Fig. 22. Sine, square, triangle, and sawtooth waveforms. [8]

Sine wave: sin(2πt). The amplitude of the waveform follows a trigonometric sine function with respect to time.

Square wave: This waveform is commonly used to represent digital information. A square wave of constant period contains odd harmonics that fall off at −6 dB/octave.

Triangle wave: It contains odd harmonics that fall off at −12 dB/octave.

Sawtooth wave: This looks like the teeth of a saw. Found often in time bases for display scanning. It is used as the starting point for subtractive synthesis, as a sawtooth wave of constant period contains odd and even harmonics that fall off at −6 dB/octave.

Other waveforms are often called composite waveforms and can often be described as a combination of a number of sinusoidal waves or other basis functions added together.

More about the waveforms can be found in [8].