FINITE ELEMENT MODELLING OF AN ULTRASONIC ROTARY MOTOR

OANA CHIVU, Polytechnic University of Bucharest, Romania, Department of Materials and Welding Technologies, e-mail: virlan_oana@yahoo.co.uk
DAN DOBROTA, Constantin Brancusi University of Targu Jiu, Romania, Department of Systems Engineering and Management Technology, e-mail: ddan@utgjiu.ro
CLAUDIU BABIS, Polytechnic University of Bucharest Romania, Department of Materials and Welding Technologies, e-mail: c.babis@yahoo.com

Abstract. This paper tackles the use of ultrasonic motors with three degrees of freedom in view of various applications. In nanotechnology, due to their high precision values, fast speeds and response, the piezoceramic and turret disk of the ultrasonic motor. Hence, the variation of nodal displacements for two driving values of the. Electrodes and the angular velocity in time will be illustrated. Moreover, the research renders the frequencies of the piezoelements and ultrasonic motor drive systems according to the travelling wave and various nodal displacements.

Key words: ultrasonic motors, positioning system, finite element, rotary motor

1. INTRODUCTION

The state-of-the-art field of nanotechnology includes another sub-field called nanopositioning which has become a field of study with numerous applications in almost all the research areas as well as in the military and the civil.

Therefore, nanopositioning has proved a prerequisite for the following research areas: nano-metrology, integrated optics, optical and electron microscopy, optics and astronomy, laser techniques, nano-automation, telecommunication techniques, databases technologies, microelectronics, precision systems, biotechnology and genetic engineering, microsurgery.

Due to the performances of the piezoceramic actuators related to the precision of positioning and uniform movement, they have brought about various applications in the field of nano-metrology based on with or without optical contact measurements, [1, 2].

In optics and optical scanning, piezoceramic actuators, have the advantage of an response time under a millisecond. In the field of photonics, the applications, contain laboratory stands, automated alignment of fibers or matrices and also multichannel waveguides testing systems. Piezoactuators can work continuous.

Piezopositioning systems have applications in nanomanufacturing processes, removing nonlinear dynamics, positioning errors and vibration problems, giving the possibility of building for some extremely rapid mechanisms.

In nanotechnology applications, the piezopositioning systems with extremely high accuracy, high speed and quick response, have become vital components in nanoprint, nanomanufacturing, nano assembly and high-density data acquisition, [3, 4, 5, 10, 11].
Ultrasonic motors turns vibration of an a piezoceramic element called -"active element" in the motion of a rotating or translation element, "activated element" by friction.

The working principle of ultrasonic motors is similar to the general class of mechanisms that convert vibratory motion in continuous motion with frequencies above 20 KHz and displacement increments in the nanometer range.

With ultrasonic motors we can achieve devices with more degrees of freedom. For this and to validate the proposed design steps in the actual research were built several ultrasonic linear motors, rotary and complex, which have several advantages as follows: ultrasonic motors are relatively simple in terms of construction, have a low weight, high precision positioning, a superior start-stop regime as against step-by-step motors and an energy-efficient; due to the fact that the principle of operation is based on the phenomenon of friction, the ultrasonic motor has not constructive components which require lubrication, so that it can operate under conditions of absolute vacuum; ultrasonic motor can produce high torque at low speed and high efficiency and direct drive is possible; ultrasonic motor operation is not affected by electromagnetic fields but is affected by temperatures above the Curie point of piezoceramic element.

In the design of rotary and linear ultrasonic motors, dimensioning of their assets was performed by modeling and simulation by finite element method. For both engines, the design starts from the respective piezoelectric elements (disc and slide sectorized) chosen from the product catalogs of specialized companies, [7, 8, 9].

2. THE ROTARY ULTRASONIC MOTOR

For research purposes, the rotary ultrasonic motor MUR-1OC (Figure 1) has been built. It consists of an active element – a piezoceramic sector disk with a “traveling wave” type of elliptical deformation in the case of a mode of vibration (Figure 1, b). This deformation is transmitted to an intermediate component (a turret disk) which drives a driving system (a disk mounted on the motor axis).

![Image](image.png)

**Fig. 1.** Rotary ultrasonic motor, MUR-1OC model:
a – bird’s eye view picture; b – interaction of the main structural components
The MUR-1OC rotary ultrasonic motor is made up of (Figure 2): a housing (stator) assembly consisting of a piezoceramic sector disk and a turret disk, the driven member – a disk mounted on the motor axis, case, bearings and pre-tightening devices (springs, bushings, locking devices etc.).

![Diagram of MUR-1OC rotary ultrasonic motor](image)

*Fig. 2. MUR-1OC model of a rotary ultrasonic motor*

The rotary ultrasonic motor movements change due to the tension induced to the spring (speed, moment, increment of movement), which has an optimum value.

The driven member of the rotary ultrasonic motor is, in fact, a piezoceramic disk, axially poled PZT 5. The electrode on one side breaks down into eight sectors based on phase shifted power supply. The other electrode is grounded. The piezoceramic disk has a 60 mm outside diameter, 20 mm inside diameter and a 2 mm width.

On a phase shifted power supply for a 24.22 kHz frequency, the piezoceramic disk produces a “traveling wave” mode of vibration and deforms the turret disk. Figure 3 and Figure 4 show the geometrical dimensions of the piezoceramic disk.
The two shapes of the turret disk are illustrated in Figure 5: the initial state (undeformed); and deformed by the driven member (the piezoceramic sector disk) and the driving mechanism. As a result of the movement wave, the teeth of the disk drive trigger an alternating back-and-forth movement and thus, by friction, they set in motion the driving mechanism which is, in fact, a disk parallel to the motor axis (Figure 5, c).

The rotary movement obtained is reversible. The direction of the movement can be changed by reversing the polarity of phased shifted tensions applied to the sector electrode of the piezoelectric element disk. The increment of movement depends on the applied tension and is of nanometric size.
3. FINITE ELEMENT MODELLING OF THE TURRET DISK

The second element of the stator assembly of the ultrasonic rotary disk is the turret disk. It is deformed by the piezoceramic sector disk. The modal analysis of the piezoceramic sector disk has revealed a “travelling” type of vibration in a 24.22 KHz frequency. The analysis of finite elements of the turret disk aims at checking the frequency value likely to trigger the same type of vibration.

Once the volume geometry of the turret disk has been modelled (Figure 6, a), discretization by element Solid 45 is conducted. As the modal analysis illustrates, at a 24.32 KHz frequency, the turret disk for the vibration mode 17 is deformed (Figure 6, b) and, hence, the teeth of the turret disk mounted on the travelling wave have a forward and backward movement and, therefore, they can drive, by friction, the disk parallel to the motor axis.

![Figure 6. The turret disk of the stator assembly of the ultrasonic rotary motor; a – volume of the turret disk; b – deformation of the turret disk.](image)

Figure 7 shows the displacements on the Z axis (Figure 7, a) and the sum of displacements (Figure 7, b) for the vibration mode 17 of the turret disk.

![Figure 7. The vibration mode 17 at 24.32 kHz frequency: a – displacement along OZ axis; b – sum of displacements.](image)
The finite element analysis has also helped determine the angular velocity. The values of the positional error (expressed in radians) obtained for the angular velocity are illustrated in Table 1. The precision of positioning is extremely high as the values do not exceed ± 0.8 x 10^{-3} radians.

Table 1. Values of the positioning error

<table>
<thead>
<tr>
<th>Angular velocity [rad/sec]</th>
<th>Positioning error x 10^{-3} [rad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.5</td>
</tr>
<tr>
<td>5</td>
<td>-0.2</td>
</tr>
<tr>
<td>6</td>
<td>0.4</td>
</tr>
<tr>
<td>9</td>
<td>0.4</td>
</tr>
<tr>
<td>13</td>
<td>-0.2</td>
</tr>
<tr>
<td>15</td>
<td>-0.1</td>
</tr>
<tr>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>0.7</td>
</tr>
<tr>
<td>23</td>
<td>0.2</td>
</tr>
<tr>
<td>26</td>
<td>-0.8</td>
</tr>
<tr>
<td>30</td>
<td>0.4</td>
</tr>
</tbody>
</table>

The graphical representation of the values in Table 1 is shown in Figure 8. A key observation in the research is the variation of the positioning error and angular velocity that break the law of variation. Nevertheless, there are values of the angular velocity 5, 12 and 24 rad/s respectively, for which, the error of positioning tends to zero. A 0.5 miliradians precision of positioning is possible unless a moment of resistance is given.

Another feature of the rotary ultrasonic motor is the angular velocity in time. The values of the angular velocity for a time interval 0...0.8 s, when there is no moment of resistance (no load) are illustrated in Table 2.
Table 2. Values of angular velocity in time

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Velocity [rad/sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
<td>1.2</td>
</tr>
<tr>
<td>0.2</td>
<td>2</td>
</tr>
<tr>
<td>0.3</td>
<td>3</td>
</tr>
<tr>
<td>0.4</td>
<td>5.5</td>
</tr>
<tr>
<td>0.5</td>
<td>8</td>
</tr>
<tr>
<td>0.6</td>
<td>10</td>
</tr>
<tr>
<td>0.7</td>
<td>7.5</td>
</tr>
<tr>
<td>0.8</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Figure 9 shows the graphical representation of the angular velocity variation in time. It is noted that up to 0.6 s, the angular speed has a quasi-linear increase, reaches a maximum of 10 rad/s and it is followed by a similar quasi-linear decrease.

4. CONCLUSIONS

A rotary or linear ultrasonic motor has an unlimited resolution. Such a motor can trigger position changes of extreme precision that may reach the nanometric sub-domains and the small variations of tension can be turned into continuous movements.

A rotary or linear ultrasonic motor may ensure higher forces and moments. The positioning piezoelectric systems can lead to a thousand of times Newton force (there are drive units that can bear loads of several tons), achieving nanometric resolution based traveling. The ultrasonic motors run fast. The research has shown that ultrasonic motors run on microseconds.
Due to the way they are built, any ultrasonic motor is devoid of a magnetic field. The piezo effect is induced by the magnetic field. The ultrasonic motors do not produce magnetic fields and are not affected by magnetic fields. Therefore, they can be used in applications based on disturbing magnetic fields.

The ultrasonic motors run on low energy. The direct piezo effect transforms the electrical energy into motion as long as it absorbs the electrical energy during traveling, with no losses.

The elements of an ultrasonic motor will never run out. Traveling is based on the solid dynamics with no wear-off.

Another key observation is that ultrasonic motors do not require lubrication. There is no need to lubricate them, and, thus, they are ideal for vacuum applications.

The ultrasonic motors can run at cryogenic temperatures. The piezo effect is produced by electric fields up to almost zero degrees Kelvin. Nevertheless, what counts more is the Curie temperature.

The finite element analysis helps research the static and dynamic behaviour of the active and driven elements of the linear and rotary ultrasonic motors.

The modal analysis determines the frequencies at which both the piezo the active elements of the ultrasonic motors record a “travelling wave” type of vibration.

The harmonic analysis illustrates various modal displacements.

The entry data in the case of harmonic analysis are obtained by means of measurements and the results are compared with the theoretical ones.

Both sector piezo ceramic disk and turret disk of the stator assembly are modelled by the finite element method.

A rotary ultrasonic motor has not a r limit resolution. An ultrasonic motor can produce very fine changes of position, in the sub-nanometer range and small changes in voltage, can be converted to continuous movement.

A rotary ultrasonic motor allows large forces and some big moments. Piezoelectric positioning systems can produce a force of tens of thousands of Newtons (it exists drive units that can handle loads of several tons), making movements with nanometer resolution.

Ultrasonic motors have a quick response. Experimentally it is found that ultrasonic motors have a microseconds response time.

Ultrasonic motor design is without any magnetic field. The motor is connected to piezoelectric effect through the electric field. Ultrasonic motors do not produce magnetic fields and can be used in applications where the presence of the magnetic field is disturbing.

Ultrasonic motors have a low energy consumption. Direct piezoelectric effect converts electrical energy into motion only by absorbing energy during movement, with no loss.

The Elements of an ultrasonic motor operates without wear. An ultrasonic motor movement is based on solid growth without causing wear.
Experimental found not require lubrication. Ultrasonic motors do not need any lubricant and makes them ideal for applications in vacuum.

The ultrasonic motors can operate at cryogenic temperatures. The effect is based on piezo electric fields and produce up to nearly zero degrees Kelvin, the only important being the point Curie temperature.

Finite element analysis method allows the study of static and dynamic behavior of the active and activate elements of rotary and linear ultrasonic motors.

Rotary ultrasonic motor are modeled by finite element method those two elements of the stator, - sectorized piezoceramic disk and notched disk.

REFERENCES