Design and Simulation of a Piezoelectric Ultrasonic Micro Motor

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Abstract: Micro machined motors are a recent development in the domain of electrical machines. As compared to conventional electromagnetic motors, micro machined motors offer higher torque at lower speeds, and are they are compact in size. This paper focusses on the study of a piezoelectric ultrasonic micro motor that is based on inverse piezoelectric effect. Here, the stator with segmented piezoelectric ring is designed with ten wave number operation. This is achieved by a new polarization pattern of the segment, and a new electrode configuration of the ring. The design and analysis of the stator is the main step in designing these motors. Eigen frequency analysis resulted in different mode shapes and the corresponding natural frequencies. Frequency analysis gives the resonant frequency which was observed to be 52 kHz with tenth mode shapes. In the transient analysis the stator reaches a steady state after 1.8ms. This analysis is crucial in optimizing the motor design which will be considered in future. The analysis is carried out using COMSOL.

Keywords: Ultrasonic motor, Piezoelectric, COMSOL

1. Introduction

Miniaturization of systems is required in aerospace, satellites, aircrafts, automobiles, marine and biomedical applications, where weight and size are important. We can integrate arrays of subsystems that manipulate or control on a small scale. These are micro-systems, and have been possible because of inventions such as microelectronics, VLSI (Very Large Scale Integration) and MEMS (Micro Electro Mechanical System). MEMS are 3D structures, involving mechanical moving components and electronic materials. They are economical, consume less power, and are faster, reliable and accurate. They enable complex and versatile functions. A lot of effort has been spent over the last decade in the field of MEMS.

One of the major fields of applications is the micro motors where it is aimed to reduce their dimensions. They find applications in micro robot, lens focusing systems in cameras, in surveillance camera platforms, in biomedical and aerospace engineering. In these applications, the important requirements of motor are high torque at low speeds, self-locking, low rotor inertia, quiet operation and light weight.

2. Comparison of different types of micro motors

Micro motors can be classified as electromagnetic motors, electrostatic motors and piezoelectric motors. The electromagnetic micro motors provide high torque at high speed. But it requires a gear box for rotary motion. This increases the size and weight of the motor and its efficiency decreases. The electrostatic micro motors provide low torque at low speed only. It also requires a gear box and thus the motor becomes bulky. It is also affected by electromagnetic fields.

On the other hand, piezoelectric motors have a number of advantages over conventional electromagnetic motors. They are generally small and compact when compared with their power output. They provide greater force and torque than their dimensions would seem to indicate. They have high holding torque maintained at zero input power, and offer low inertia from their rotors providing rapid start and stop characteristics. Additionally, they are unaffected by the electromagnetic fields. The present work focusses on the study of piezoelectric micro motors.

Piezoelectric micro motors are widely classified as impact drive, inchworm and ultrasonic micro motors. The study of piezoelectric ultrasonic micro motor is very recent. The working principle, materials used and the design of structure are discussed in [1]. The first few comprehensive studies of ultrasonic motors were undertaken by Shasida and Kenjo [2], and Ueha et al [3]. These articles provide a good introduction of the construction and operation of piezoelectric ultrasonic motors. Many piezoelectric ultrasonic micro motors with different excitation, structures, and performances have been developed. Piezoelectric ultrasonic micro motors can be classified according to their operation as rotary type or linear type. Further they can be classified based on the device geometry as rod type, ring type, disc type and cylinder types. They can also be classified depending on the generation of the wave – as standing wave or travelling wave. Standing-wave type is sometimes referred to as a vibratory-coupler type or a "woodpecker" type, where a vibratory piece is connected to a piezoelectric driver and the tip generates flat-elliptical movement. The structure of the standing wave type motor is less complicated and more suitable of miniaturization. Standing wave type motor uses only one electrical voltage source. They require all the piezo segments to be polarized in the same direction and fewer electric lead wires.

The need for a high frequency power source is the largest challenge in this motor design. While many motors use multiple high frequency input signals, it should be avoided if a more economical motor is desired. Each high frequency source used to drive a motor increases the total cost of piezoelectric ultrasonic micro motor. Standing wave type motor is used to reduce the number of drive circuit components. In general the standing wave type has high efficiency. However, there is a lack of control in both

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clockwise and counter clockwise directions [4]. It can be used for linear motion only.
A travelling wave type piezoelectric ultrasonic micro motor can be used to achieve rotary motion. A travelling wave can be generated by superimposing two standing waves whose phases differ by 90 degree to each other, both in time and in space. This principle is necessary to generate a travelling wave on a limited volume/size substance, as only the standing waves can be excited stably in a finite size. The travelling-wave type (a surface-wave or "surfing" type) combines two standing waves with a 90 degree phase difference both in time and in space. A surface particle of the elastic body draws an elliptical locus due to the coupling of longitudinal and transverse waves. This type requires, in general, two vibration sources to generate one travelling wave, leading to low efficiency (not more than 50 %), but it is controllable in both the rotational directions just by exchanging sine and cosine supply voltages [5]. Due to the necessity of the dual drive system, the travelling wave type is more complicated in structure and expensive in manufacturing than the standing wave type.
A significant problem in miniaturizing this travelling wave motor can be found in the ceramic manufacturing process. Without providing a sufficient buffer gap between the adjacent electrodes, the electrical poling process (upward and downward) can easily initiate a crack in the electrode gap due to the residual stress concentration. This may restrict further miniaturization of the travelling wave type motors [2-3].The difficulty can be overcome by polarizing all the piezo segments of the piezoelectric ring in the same direction [6].
Another problem encountered in these travelling wave type motors is the support of the stator [2]. In the case, of a standing wave motor, the nodal points or lines are generally supported. This causes minimum effects on the resonance vibration. On the contrary, a travelling wave does not have such steady nodal points or lines. Thus, special considerations are necessary. The stator is fixed on the inner side so as not to suppress the bending vibration [7]. As feedback sensors are used to generate certain amplitude of the travelling wave [8], it complicates the design and fabrication of the motor and requires large numbers of components. The structure can be simplified and the number of components can be reduced if the sensors can be eliminated and the motor can be constructed only with its main parts, i.e. the stator and the rotor [6-7]. One of the challenges with piezoelectric ultrasonic micro motor is frictional drive surfaces. High forces during sliding can cause considerable wear on the drive tip of the motor limiting its useful life [2-3]. Not only must the drive surface and the friction bar (the driven surface on the rotor) be wear resistant, they must also have a fine surface roughness. The surface roughness must be smooth enough to allow the drive tip adequate clearance to travel over the surface of the rotor during part of its elliptical path [9-10]. The key factors for the commercialization of ultrasonic motors are to develop piezoelectric materials with lesser losses and higher mechanical quality factors. These properties are essential to suppress the heat generation during driving, which limits the continuous operation of motor [5]. The newly developed ceramic series is based on PZT systems [11], which can be used for 10 times higher input/output power range than the commercially available hard PZT's without generating significant heat.

3. Working of piezoelectric ultrasonic micro motor

A piezoelectric micro motor uses inverse piezoelectric effect i.e. when an electric voltage is applied to a piezoelectric material, it deforms mechanically. These motors basically have two parts – a stator and a rotor. Stator converts electrical energy of the piezoelectric element into oscillations, at one of its resonant frequencies, in the ultrasonic range. The movements of the stator are converted into the movement of a slider pressed (the rotor) into frictional contact with the stator. The consequent movement may either be rotational or linear, depending on the design of the structure. Large mechanical torques can be achieved by combining several of these rotational units.

4. Design of piezoelectric ultrasonic micro motor

Figure 1 shows the widely studied piezoelectric micro motor viz. the shinsei motor [1]. It consists basically a stator, a rotor and the casing. In the stator, a segmented piezo-ceramic ring is attached to the bottom part of an aluminum annular plate with a conductive adhesive. Teeth are cut on the upper part of the aluminum annular plate, which increases the horizontal deflection of the stator at the contact interface with the rotor. Stator is fixed on the inner side. The rotor is directly placed on the stator. To reduce the wear between them, either of the interface surfaces is coated with a wear resist material. The rotor is made of an aluminum plate. It is placed on the stator and is supported by the upper part of the case of the motor. The upper part of the motor case acts as a spring. The upper and lower parts of the motor are joined together with screws.

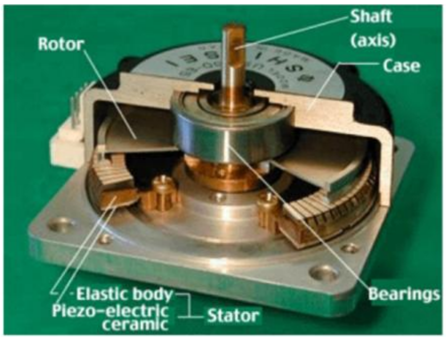

Fig.1 Shinsei Motor USR60 (www.shinsei-motor.com)

The design of the stator is very important part of designing the piezoelectric ultrasonic micro motor. This work aims to study various aspects of the stator of a piezoelectric ultrasonic micro motor using COMSOL Multyphysics 4.2a.
The building model of piezoelectric ultrasonic micro motor is shown in Fig. 2 and the simulated model of the stator is shown in Fig. 3.
The outer diameter of the stator is 60mm and the inner diameter is 47mm. Stator is made of an annular plate of aluminum with thickness of 2.0mm. It has 72 teeth of 1.0mm

height on the top as in [6]. A piezoelectric plate with the thickness of 0.5mm is bonded on the lower surface of the annular plate with a conductive adhesive. Piezoelectric plate is made of material PZT-5H. The piezo ring has the same inner diameter of 47mm and outer diameter of 60mm. The rotor comprises of an annular aluminum plate with a 1.0mm thick contact layer of polytetraflouroethelyene (PTFE) bonded on its lower surface. The inner diameter of the rotor is 54mm and the outer diameter is 58mm. This geometry has been modeled in software by considering all the dimensions and material.
The material basic properties like Poisson's ratio, Young's modulus and Mass density are mentioned below.
For Al, Young's Modulus = 70GPa, Poisson's Ratio = 0.33, Mass density = 3700kg/m^3.
For conductive adhesive the Young's Modulus = 0.7GPa, Poisson's Ratio = 0.43, Mass density = 3500kg/m^3.

Voltage sources are applied to the piezoelectric ring to generate the travelling wave in it. All the piezoelectric segments have the same polarization direction, in Z direction. Since the motor has to operate in tenth mode shapes as in [5], it is necessary to divide the piezoelectric ring in 40 equal parts. The applied voltages on the segment electrode are over one wavelength and denoted as +s, +c, -s and –c, with phase shift of 90 degrees. Here, total numbers of voltage sources are 4, so 10 segments are supplied with one source as shown in Fig. 4.

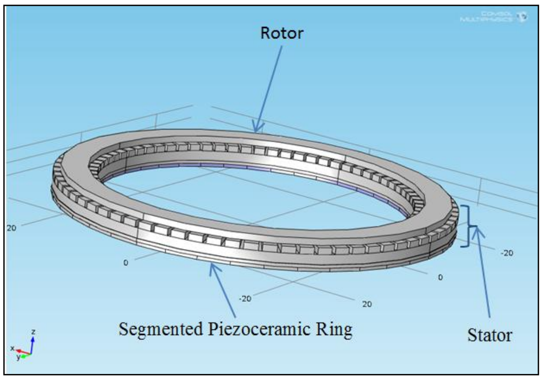

Fig. 2: Structure of piezoelectric ultrasonic micro motor

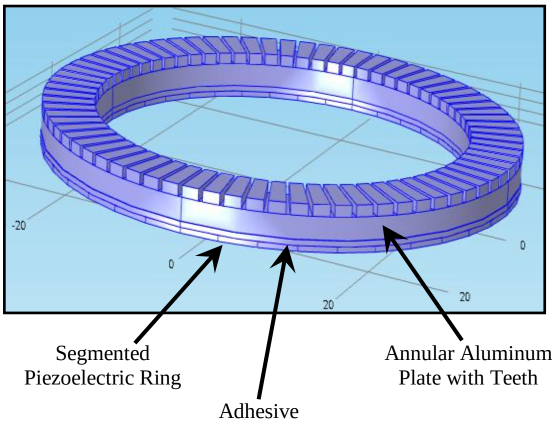

Fig. 3: Simulated stator model

For PZT-5H the properties are indicated in Table 1, 2, 3 and 4

Table 1: Basic properties of PZT-5H

Property	Variable	Expression	Unit
Density	rho	7500	kg/m^3
Poisson's Ratio	Nu	0.46	
Young's modulus	E	6.2e10	Pa

Table 2: Relative permittivity of PZT-5H

Relative Permittivity		
1704.4		
	1704.4	
		1433.6

Table 3: Elastic matrix

Elastic Matrix (Symmetric) c_{piezo} [N/m^2]					
1.27e11	8.02e10	8.46e10	0	0	0
	1.27e11	8.46e10	0	0	0
		1.17e11	0	0	0
			2.29e10	0	0
				2.29e10	0
					2.34e10

Table 4: Coupling matrix

Coupling Matrix *e* [N/Vm]					
0	0	0	0	17.0345	0
0	0	0	17.0345	0	0
-6.6228	-6.6228	23.2403	0	0	0

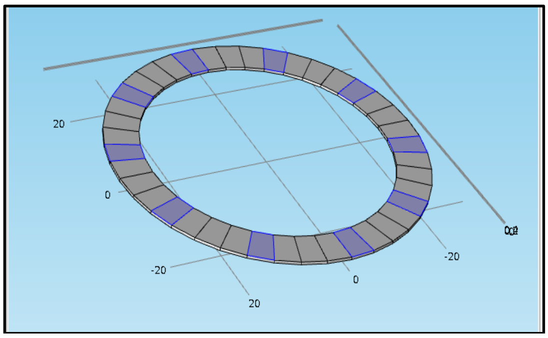

Fig. 4 Segments connection for one voltage source

All the connections are made at the bottom of the piezoelectric ring for easy access to the individual sector. The other side of the piezoelectric ring is connected to ground. By using COMSOL multyphysics, various analyses have been performed on the stator of piezoelectric ultrasonic micro motor.

5. Eigen frequency analysis

Eigen frequency analysis is used to discover the natural frequency and mode shapes of the structure. Natural frequency depends on the geometry of the structure, its material as well

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as boundary conditions (electrical and mechanical). By altering these properties we can design the natural frequency.
In Eigen frequency analysis, the material stress charge form and strain charge form properties have been considered. The inner circumference of the stator is fixed. The stator is deformed in many mode shapes with their corresponding Eigen frequencies. Here, the stator of the piezoelectric ultrasonic micro motor is designed to operate in tenth mode shape. Figure 5 shows the 10^{th} mode shape of the stator of the piezoelectric ultrasonic micro motor. Using this analysis ten mode shapes and its corresponding Eigen frequency has been investigated and is shown in Table 5.

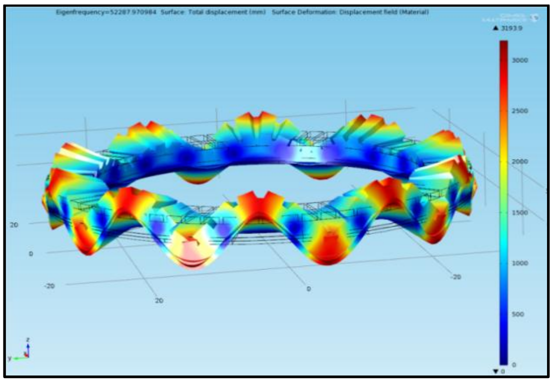

Fig. 5 10^{th} mode shape of the stator

Mode Shape Number	Natural Frequency
1	9.69kHz
2	10.81kHz
3	14.33kHz
4	18.81kHz
5	23.44kHz
6	28.15kHz
7	33.24kHz
8	38.94kHz
9	44.29kHz
10	52.28kHz

Table 5: Mode shapes and its corresponding natural frequency

6. Frequency analysis

The designed stator is operating in tenth mode shape. Here, it is required to find the frequency at which stator develops 10 wave length. The frequency analysis is carried to find out this resonance frequency. The resonance frequency here, is in the ultrasonic range (20 kHz to 100 kHz), and hence it is named as ultrasonic motor.
In dynamic analysis of structures, damping plays important role. Damping is an effect that reduces the amplitude of oscillations in an oscillatory system. It is achieved by absorbing energy and reducing the amplitude of the vibrations. There are advanced research results to identify a general model of damping or the estimation of damping in a random vibrating system [12]. In this analysis Raleigh damping coefficients are considered. In these computations, the natural frequencies calculated in the Eigen frequency analysis are used to compute Rayleigh damping coefficient. Here,
β = 5.7198e-8 s (Stiffness damping parameter)
α = 397.02 1/s (Mass damping parameter)
Four voltage sources are used to generate the travelling wave. Total segment of the rings are 40. So to each voltage source are connected to the 10 segments of the piezoelectric ring. The connections are made on one side of the ring and the other side of the ring is grounded.
The voltages applied to the piezoelectric ring are 60V and 150V. From the Eigen frequency analysis it is observed that stator tenth mode shape is at a frequency of around 52000 Hz. Thus in this analysis, the sweep of frequency is taken from around 45000 to 60000 Hz. First, the frequency analysis has been performed by using 60V. The frequency response is as shown in Fig. 6. Next the frequency analysis has been performed by using 150V. The frequency response is shown in Fig. 7. The observed parameter is displacement of the stator in the Z-direction.
From Fig. 6, it is observed that when the applied voltage is 60V, the maximum displacement occurs at a frequency of 53000Hz. This is the resonant frequency. The maximum displacement achieved by the stator in the Z direction is 52.67 nanometer. Similarly from Fig. 7, it can be seen that when the voltage is increased to 150V, the resonant frequency becomes 52000Hz and maximum displacement in the Z direction is 0.372 micrometer. From this it can be concluded that, as the supply voltage amplitude increases the stator displacement increases and the resonant frequency decreases. The relationship between the supply voltage amplitude and the stator displacement is linear. The simulation has been carried out to know the relation between the voltage and the displacement. In simulation, the voltage has been swept from 20V to 80V. The displacement is linear with respect to voltage, as shown in Fig. 8.

7. Time dependent analysis

Time dependent analysis is carried out to find the tangential velocity of the stator. The Z-direction displacement and the tangential velocity of the material are plotted as in Fig. 9. The blue colour graph indicates the Z-direction displacement and green graph indicate the tangential velocity of displacement and green graph indicate the tangential velocity of the material. It is seen that, if the displacement of the stator in the Z direction is maximum, then tangential velocity of the stator will also be maximum. Further, the phase difference between the longitudinal displacement (X component of the displacement) and the tangential displacement (Y component of the displacement) is $\pi/2$ as shown in Fig. 10. It shows that the motion of a point on the contact interface area between the rotor and the stator is elliptic.

The displacement Z component has been observed with respects to time as shown in Fig.11. It indicates that at particular point on the stator surface the Z-component of the displacement is displaced around 0.3 micro meters. The stator

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enters steady state after 1.8millisecond and then continuously operates in 10^{th} mode.

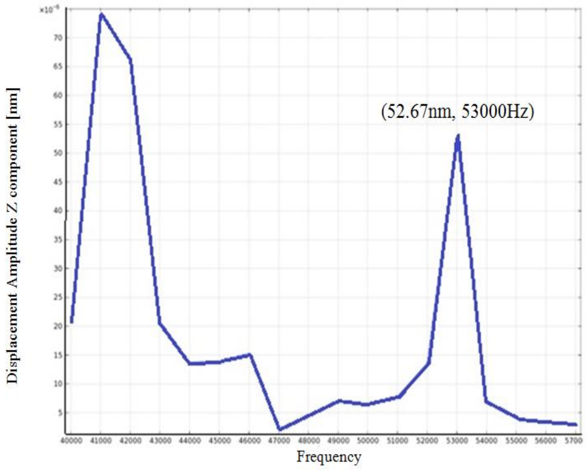

Fig.6 Displacement amplitude in Z direction vs. frequency (60V)

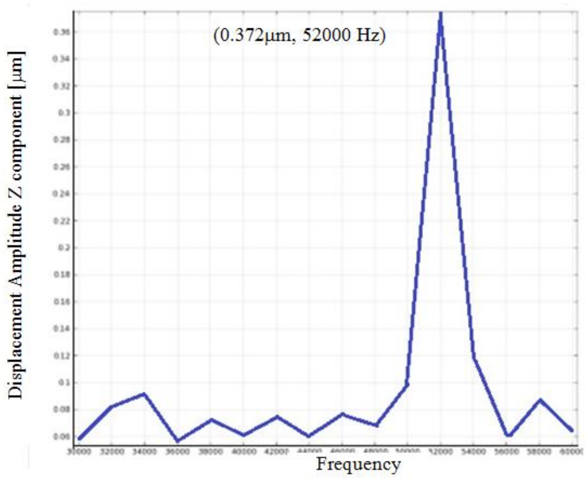

Fig. 7 Displacement amplitude in Z direction vs. frequency (150V)

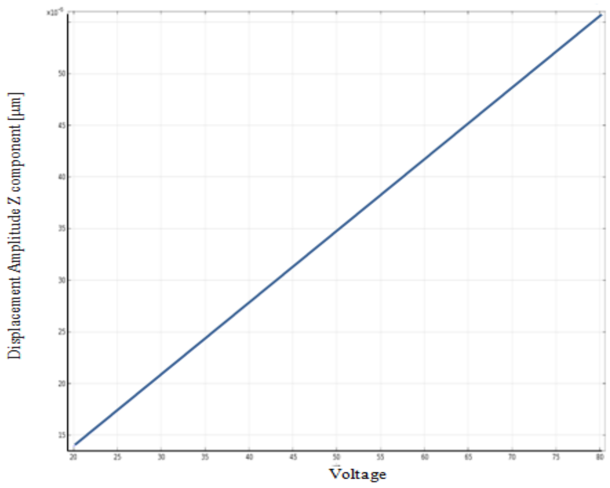

Fig. 8 Displacement amplitude in Z direction vs. voltage

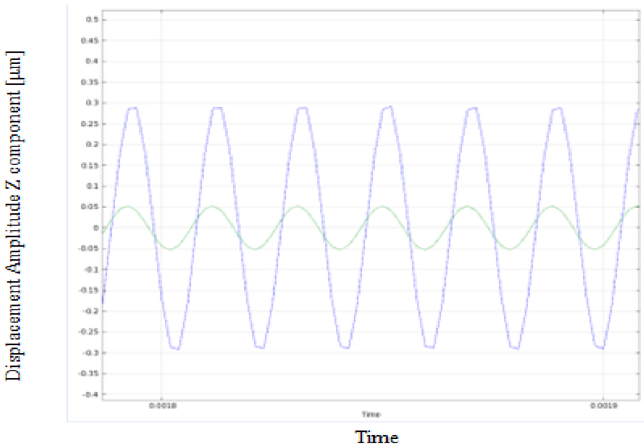

Fig. 9 Displacement z component, tangential velocity vs. time

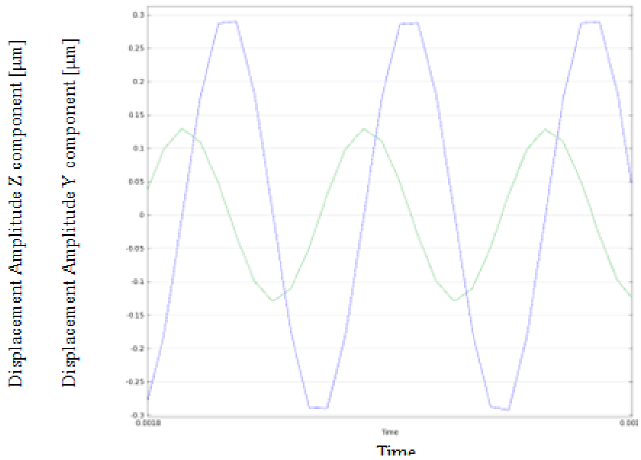

Fig. 10 Displacement at the contact surface vs. time

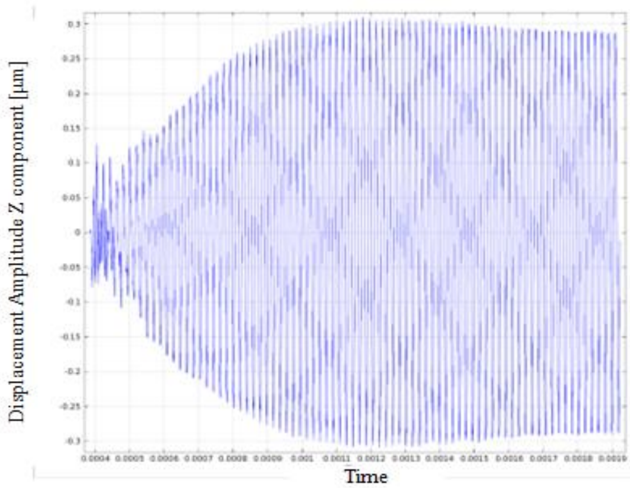

Fig. 11 Displacement z component vs. time (point evaluation)

During this analysis the travelling wave generation in piezoelectric ring has been also observed. The deformed stator has been also observed. While measuring the total displacement and Z-component of the total displacement, the deformed stator snapshot has taken after stator becomes steady at 1.8 millisecond. This is shown in Fig 12 and Fig.13 respectively. The deformation of the ring, in the form of a travelling wave can be seen in the animation of the results.

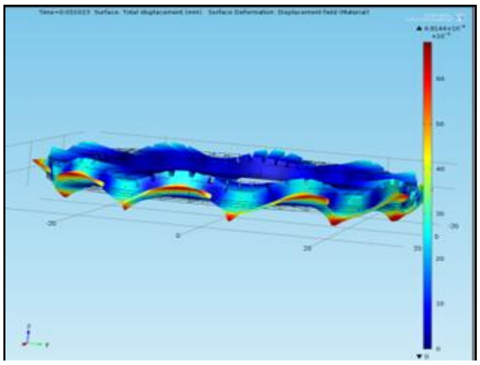

Fig. 12 Transient state of deformed stator (Total displacement)

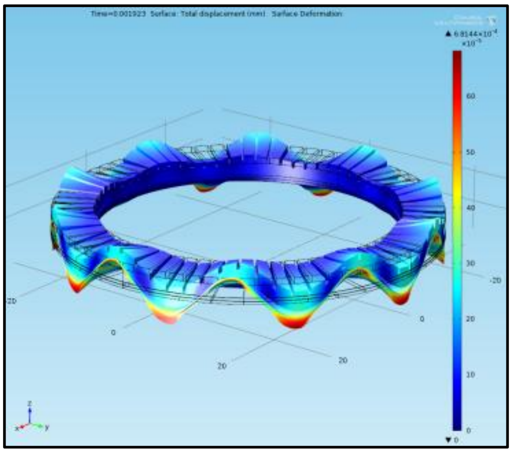

Fig. 13 Transient state of deformed stator (Z-component of displacement)

8. Conclusion

The stator of the piezoelectric ultrasonic micro motor has been designed and simulated in this work. Traditional piezoelectric motors suffer from a fundamental limitation of bidirectional polarization of piezoelectric ring. This problem has been solved by using uniformly polarized piezoelectric ring. It is found that, by using a higher grade piezoelectric material, greater displacement of stator can be achieved. Consequently rotor can generate higher torque increasing the efficiency of the motor. Another important finding is that increasing the supply voltage amplitude increases the stator displacement. Though this is the most crucial element in the design of the motor, there remain a few more aspects to explore. The most obvious future work is to design and simulate the rotor, to place it on the stator, and perform a complete analysis of the motor as a whole.

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