Characteristics of π-shaped Ultrasonic Motor

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Seong-Hwa Kang and Jong-Sub Lee*****

Abstract - In this paper, the design and characteristics of a π-shaped ultrasonic motor that is applicable to optical zoom operation of a lens system for mobile phones are investigated. Its design and simulation of performances are carried out by FEM (finite element method) commercial software. As a simulation result, by applying voltage with single phase, a combined vibration is produced at the surface of a stator arm. A prototype of the motor is fabricated and its outer size is 8*4*2 mm^3 including the cylindrical steel rod of 2 mm in diameter as the rotor. The motor exhibits a maximum speed of 500 rpm and a power consumption of 0.3 W when driven at 20 Vpp and 64 kHz.

Keywords: Auto-focusing, Miniaturized motor, Optical zooming, π -shaped USM

1. Introduction

Recently, the function of a digital camera mounted in a PDA and a mobile phone is necessarily equipped by the convergence of information telecommunication technology and multimedia technology. The number of pixels in a camera phone is dramatically increased, which is nearly at equal level with the conventional digital camera. However, the function of automatic focusing (AF) and/or optical zooming in camera phones are not yet sufficient as compared to the digital camera. AF and/or optical zooming in the camera function are necessary because the quality of photograph depends on them. A miniaturized actuator is needed to operate AF and/or the optical zooming function, which is limited in size for mounting in mobile phones [1]. The actuator used for optical zoom is primarily the stepping motor or DC motor, but their problem is in their size and performance. The minimum size of a stepping motor is 4 mm in diameter and its torque is inadequate to move the lens. Also, the conventional electro-magnetic motor has to use the reduction gear to decrease its fast speed and it is hard to control precisely due to its backlash [2]. The ultrasonic motor (USM) can overcome these problems in the electro-magnetic motor. Compared to typical electromagnetic motors, the USM has various advantages [3, 4]. It may be manufactured in a wide range of sizes, from a few micrometers to several centimeters in motor diameter. No gears are necessary to reduce the speed of rotation. It is solid-state in nature and windings, magnets or brushes are unnecessary. Highly accurate speed and position control are relatively easy to obtain with the motor using standard feedback control systems, unlike electro-magnetic motors that require complex sensors and controllers to ensure accuracy, particularly with position control. It is capable of delivering high torque for its size at low speed, which is excellent for low-speed applications. Unaffected by magnetic fields, it provides a unique capability to deliver motion in electro-magnetic environments. With little rotor inertia and large torque, it is exceptionally responsive with a response time as little as a few milliseconds. Finally, it possesses an inherent braking action when power is removed, making it useful for robot and step motor applications [5, 6]. The USM is newly designed for the optical zoom function of a camera phone and its vibration mode is analyzed by FEM (Finite Element Method) in this paper. Based on simulation results, a prototype USM is fabricated and its characteristics are measured.

2. Operation principle of motor and simulation of vibration

In general, the ultrasonic motor is driven by mechanical vibration such as the traveling wave and a combination of two vibration modes. The structure of the ultrasonic motor by the traveling wave is very complex. Its driving circuit is

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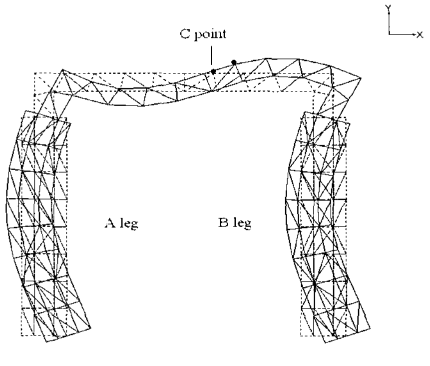
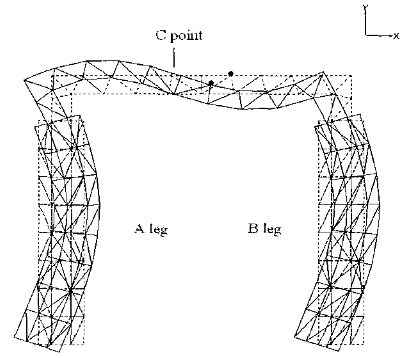
also complex and expensive because of the driving method of input voltage with two phases. Accordingly, in this paper, we focus on the design motor driven by a single phase input voltage with simple structure. The stator structure of the newly proposed ultrasonic motor is shown in Fig. 5. The stator is composed of rectangular π-shaped piezoelectric ceramic plates and a π-shaped elastic body. The piezoelectric plates are bonded onto both sides of the elastic legs in parallel. The motion principle of the proposed ultrasonic motor is presented in Fig. 1. The commercial finite elements analysis software (Atila, Magsoft Co.) is used to analyze its vibration mode. In principle, it is important as to how to generate an elliptical motion of a given point mass on the surface of the stator, which is contacted with the surface of the rotor in the ultrasonic motor [2-4]. A motion of the point "C" on the center arm of the π-shaped stator as a point mass during a period of input voltage is investigated as follows. If voltage is applied to the piezoelectric ceramics in A-leg, the elastic body is bended and the standing wave is generated at the whole elastic body because it is finite. The point "C" on the elastic body moves to +X direction during the positive half cycle of applied voltage and –X direction during the negative half cycle due to the bending vibration of A-leg. That is, the bending vibration by the piezoelectric ceramic is converted to the displacement of X direction because of the π-shaped elastic body. Simultaneously, the point "C" on the elastic body also is displaced from +Y direction to –Y direction, as shown in Fig. 1. As the vibration to X and Y direction is combined, the point "C" moves in elliptical trajectory counterclockwise by means of application of only a single phase voltage, not two phase voltage driving, which is common in the conventional ultrasonic motor [2, 3, 4]. If the rotating cylindrical rod as a rotor is contacted with the point "C" and impressed by spring as indicated in Fig. 5, the rod can be rotated in a clockwise direction. If the voltage is applied to B-leg, the point "C" moves in elliptical trajectory clockwise, and the rod will be rotated in a counterclockwise direction. The rotation direction of the rotor (rod) can be easily altered by changing the leg which has the applied voltage. We have worked on the π-shaped ultrasonic motor previously as shown in Fig. 1 [7]. In the figure, piezoelectric ceramic is bonded to an elastic body with bimorph type, however its fabrication process is complex and the cost becomes expensive. In order to reduce the cost, bimorph type is changed to unimorph type. The unimorph type means that the piezoelectric ceramic plate is bonded onto one face of a leg in the π-shaped stator, but on the other hand the piezoelectric plates are bonded onto both faces of a leg in bimorph type. A simulation result on displacement in the unimorph type stator is shown in Fig. 2. The displacement of the unimorph type ultrasonic motor is relatively small but its vibration pattern is almost similar to the bimorph type so that it can be also realized as an ultrasonic motor.



(a) Positive half cycle



(b) Negative half cycle

Fig. 1 The motion principle of the proposed ultrasonic motor

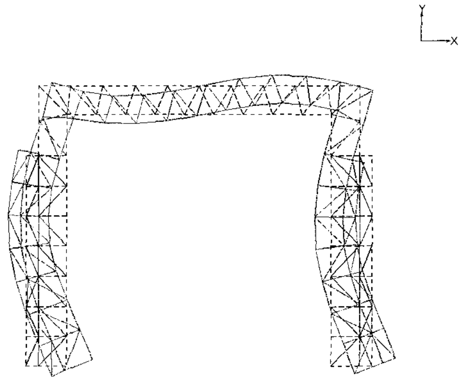


Fig. 2 The displacement pattern of the unimorph type ultrasonic motor

In Fig. 1 and Fig. 2, the thickness of the elastic body is 0.6 and 0.8 mm, respectively. As the size of the mobile phone becomes small and slim, the size of the actuator must be minimized. So, as the thickness of the elastic body is changed from 0.3 to 0.8 mm, the displacement pattern is simulated. The result on the elastic body of 0.3 mm in thickness is indicated in Fig. 3. Its pattern is different from

Fig. 1 and Fig. 2 and there is no displacement to X direction. The reason can be explained as follows. As the thickness of the elastic body thins out, the displacement generated by the piezoelectric ceramic can't transfer to the edge of the elastic body and as such there is no displacement to X direction. Accordingly, the thickness of the elastic body must be more than 0.3 mm.

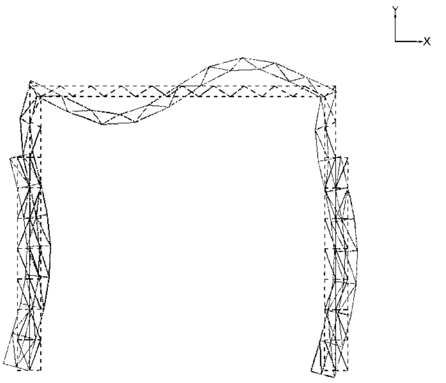


Fig. 3 The displacement pattern of the elastic body of 0.3 mm in thickness

Fig. 4 illustrates the simulation result in the case that the length of the center arm is reduced to 4 mm. As shown in Fig. 4, its pattern is similar to Fig. 1 and Fig. 2 and it can be realized as an ultrasonic motor.

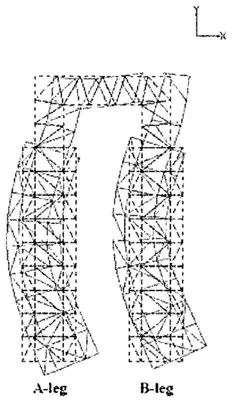


Fig. 4 The displacement pattern of the elastic body with center arm of 4 mm in length

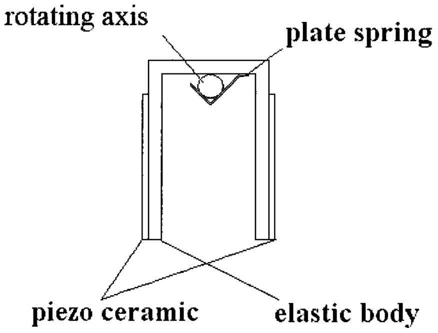
3. Fabrication of ultrasonic motor

Piezoelectric ceramic for the newly proposed motor is fabricated with a composition; $0.9(Pb(Zr_{0.51}Ti_{0.49})O_3) - 0.1(Pb(Mn_{1/3}Nb_{1/3}Sb_{1/3})O_3$. The fabricated piezoelectric ceramic plate is stacked to seven layers and its physical dimension is 6*2*0.35 mm^3 (length*width*thickness). Its piezoelectric and dielectric properties are listed in Table 1.

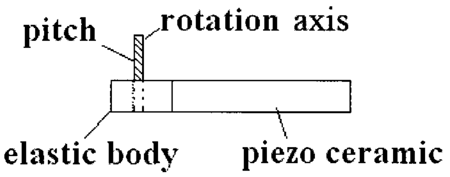
Table 1. Piezoelectric and dielectric properties of fabricated piezoelectric ceramic

Electro-mechanical coupling factor, k_{31}	0.32
Mechanical quality factor, Q_m	1500
Piezoelectric constant, d_{33}	340 pC/N
Resonance frequency, fr	275 kHz
Free capacitance	10 nF

The elastic body makes from SUS 304, stainless steel, its dimension is 8*4*2 mm^3 (length*width*height) and its thickness is varied from 0.3 to 0.8 mm, respectively. The piezoelectric ceramic plate is bonded onto the outer face of each leg of the elastic body in parallel by epoxy, as shown in Fig. 5. A rotating cylindrical stainless steel rod of 2 mm in diameter as a rotor is contacted with the inner surface of the center arm of the π-shaped elastic body and impressed with a plate spring. The rotor is divided into two parts in length, in which a part contacting with the stator is coated with lining materials and the other part is machined to a screw with 0.35 mm in pitch for operating optical zooming function. Resonance frequency of the stator is measured by impedance analyzer (HP 4194A, Agilent), compared with simulation results by FEM.



(a) Top view



(b) Cross section

Fig. 5 The structure of the proposed ultrasonic motor

The driving system of the ultrasonic motor is shown in Fig. 6. A function generator (HP 33120A, Agilent) and a power amplifier (HAS 4012, NF) are used to drive the test ultrasonic motor. A series inductor is also utilized to make resonance with capacitance of the piezoelectric ceramic. The rotation direction of the ultrasonic motor is changed by a mechanical switch. The rotation speed is measured by tachometer (M 3632, Yokogawa). Power consumption of the ultrasonic motor is calculated by the product of the voltage and the current, which is measured by current probe (P6022, Tektronix) and oscilloscope.

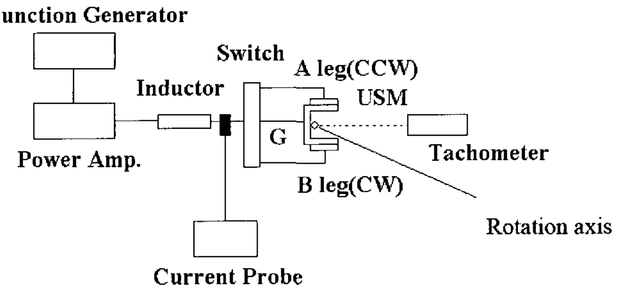


Fig. 6. The driving system of an ultrasonic motor

4. Results and discussion

The change of resonance frequency as a function of the thickness of elastic body is indicated in Fig. 7. The dimension of piezoelectric ceramics is fixed. As shown in Fig. 7, as the thickness of the elastic body increases, resonance frequency also increases linearly.

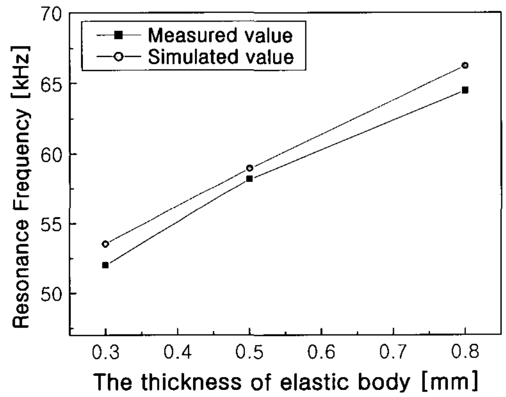


Fig. 7 The change of resonance frequency as a function of the thickness of elastic body

This reason can be explained as follows. If we consider the elastic body as a cantilevered beam, its fundamental natural frequency ν is given by

$$\nu = 0.163\frac{h}{l^2}\sqrt{\frac{E}{\rho}} \qquad (1)$$

where, E is Young's modulus, ρ the density, l the length, and h the thickness [5]. Accordingly, resonance frequency has direct proportion with the thickness of elastic body.

Fig. 8 indicates the rotation speed and current as a function of applied voltage. Where the thickness of elastic body is only 0.8 mm because the 0.3 mm-thick ultrasonic motor does not rotate, and the 0.5mm-thick motor rotates at more than 30 Vpp of applied voltage, but unstably. As the thickness of the elastic body thins out, the flexural wave may be hard to induce. Also, when applied voltage is more than 30 Vpp, rotation speed is saturated because mechanic-cal dissipation increased due to the heat generation in the piezoelectric ceramic. The prototype of the motor is fabricated and its outer size is 8*4*2 mm^3 including the cylindrical steel rod of 2 mm in diameter as the rotor. The motor exhibits a maximum speed of 500 rpm and a power consumption of 0.3 W when driven at 20 Vpp and 64 kHz.

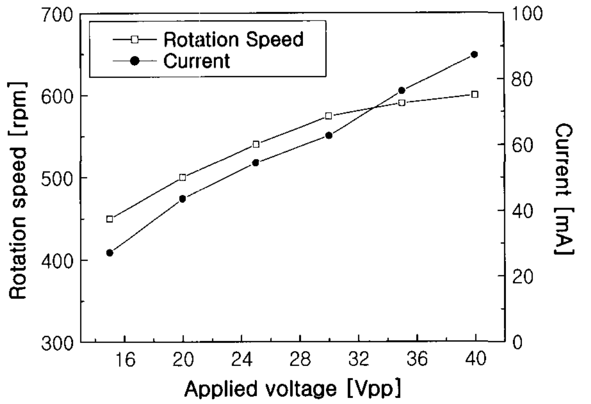


Fig. 8 Rotation speed and current as a function of applied voltage

5. Conclusion

A π-shaped ultrasonic motor for an optical zooming system for mobile phones is newly designed using FEM commercial software and the performances of the test motor are discussed in this paper. As the FEM analysis results, a combination of two vibration modes is induced at the center arm of the π-shaped elastic body, when driven at only a single phase voltage. It is also shown that an elliptical motion of a given point mass on the surface of the arm is generated, which is contacted with the surface of the rotor in the ultrasonic motor. Based on the simulation results, the prototype of the motor is fabricated and its outer size is 8*4*2 mm^3 including the cylindrical steel rod of 2 mm in diameter as the rotor. The piezoelectric ceramic plate stacked in seven layers is bonded onto a face of each leg of the unimorph type. To drive the ultrasonic motor, the voltage is applied to one piezoelectric ceramic plate. To change the rotation direction, the applied voltage can be altered to the other piezoelectric ceramic plate. The motor exhibits a maximum speed of 500 rpm and a power consumption of 0.3 W when driven at 20 Vpp and 64 kHz. It is concluded that the π-shaped ultrasonic motor proposed in this study has a very simple structure and is small in size

Furthermore, the performances of the motor including power consumption, rotation speed, output torque, and efficiency are satisfactory for application of optical zooming and the automatic focusing actuator. However, the driving voltage must be reduced.

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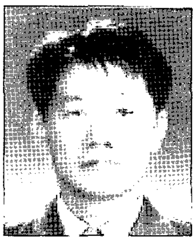

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