A cylindrical micro ultrasonic motor utilizing PZT thin film
(1.4 mm in diameter and 5.0 mm long stator transducer)

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Abstract

A cylindrical micro ultrasonic motor utilizing PZT thin film was fabricated and successfully operated. The dimensions of a stator transducer were 1.4 mm in outer diameter, 1.2 mm in inner diameter, and 5.0 mm in length. This volume is 17% compared to our previous motor 2.4 mm in diameter and 10 mm long stator transducer.

To deposit a PZT thin film, a hydrothermal method was adopted. In this study, we developed an ‘‘improved nucleation process’’, and succeeded in improving the performance of the deposited PZT thin film. The thickness of a PZT thin film was 12 μm, and the d31 factor was 25 pC/N.

The resonance frequency of the stator transducer was 227 kHz and the vibration amplitude was 58 nm at 4.0 V p-p driving voltage. The rotor was driven by frictional force and the revolving direction was reversible. The maximum revolution speed was 680 rpm and the maximum torque was 0.67 mN m. The experimental conditions were 20 V and 5.3 mN pre-load.

These results were investigated using an equivalent circuit from the point of a scale law. The performances of smaller ultrasonic motors were discussed. The output torque of the motor with 0.1 mm diameter was estimated at 27 nN m.

Keywords: Ultrasonic motor; Micro actuator; Hydrothermal method; PZT thin film; Cylindrical transducer; Equivalent circuit

1. Introduction

Ultrasonic motors offer many advantages, for example, in a simple construction, a direct drive, a brakeless mechanism and a bearingless mechanism. These advantages contribute to the miniaturization of ultrasonic motors. We have already reported a few types of micro ultrasonic motors.

The first type motor utilized a ceramic PZT as a stator transducer material [1]. The stator transducer was 2.4 mm in diameter and 10 mm long. This micro ultrasonic motor generated 0.22 mN m output torque with 100 V p-p input voltage. Maximum revolution speed was 650 rpm. As one of the applications, a micro robot hand was fabricated. This hand was composed of two motor units, and it had no bearing, no brake, and no gearbox. In spite of a simple construction, this hand succeeded in carrying a load up to 10 g.

The second type has the same size as the ceramic PZT motor, although it utilized a PZT thin film [2]. For miniaturization, a piezoelectric thin film is essential because the ceramic material is difficult to manufacture. To deposit PZT thin film, a hydrothermal method was adopted [3,4]. The maximum output torque and maximum revolution speed were 7 μN m and 880 rpm, respectively.

In this paper, we discuss the experimental results of a smaller ultrasonic motor and the calculation results for
smaller motors. The fabricated motor size was 1.4 mm in diameter and 5.0 mm long. This is one of the smallest ultrasonic motors, at this stage.

2. Structure and principle

The proposed micro ultrasonic motor was composed of a cylindrical stator transducer, a rotor and a pre-load mechanism, as shown in Fig. 1. The stator transducer has the following dimensions: outer diameter = 1.4 mm, inner diameter = 1.2 mm, length = 5 mm. The base metal of the stator transducer was titanium, and a PZT thin film was deposited on the sidewall by improved hydrothermal method. The thickness of PZT thin film was 12 µm and the poling direction was thickness direction. On the PZT thin film, four gold electrodes were deposited by gold evaporation with metal mask. The material of a rotor was stainless steel.

This ultrasonic motor is a mode-rotation type, which utilizes the first bending vibration mode. With four RF electrical sources to each electrode, the bending vibration is degenerated. The phase difference is 90° (of each other). Please note that a traveling wave is propagated at the end surface of the stator. The rotor loaded on the transducer turns around by a frictional force. The driving direction is reversible by changing electrical phase shift from 90° to −90°.

3. Hydrothermal method

The use of piezoelectric thin film in fabricating micro actuators is more convenient than to make small structures with ceramic materials. In this study, the hydrothermal method was used in depositing PZT thin film. The hydrothermal method utilizes the chemical reaction between a titanium base metal and high-temperature dissolved ions. To withstand high temperature and high pressure, an autoclave was used. The chemical reaction is carried out in solution, so the three-dimensional base metal is available. The other merits of hydrothermal method are thick deposited PZT film and the preclusion of the need for both poling and annealing processes [3].

The first reaction conditions were proposed by Shimo-mura et al. [3]. They mentioned that the piezoelectric factor $d_{31}$ of deposited PZT thin film was $-90 \text{ pC/N}$. However, we could not obtain the same PZT thin film under similar reaction conditions.

In this paper, the “improved nucleation process” is proposed. The reaction conditions, which were adopted for

<table>
<thead>
<tr>
<th>Material</th>
<th>Reaction Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZrOCl$_2$·8H$_2$O</td>
<td>1.078 g/2 ml pure water</td>
</tr>
<tr>
<td>TiCl$_4$</td>
<td>0.0433 ml (1.95 mol/l)</td>
</tr>
<tr>
<td>Pb(NO$_3$)$_2$</td>
<td>2.317 g/7 ml pure water</td>
</tr>
<tr>
<td>KOH</td>
<td>5.47 g/12 ml pure water</td>
</tr>
<tr>
<td>Temperature</td>
<td>160°C</td>
</tr>
<tr>
<td>Reaction Time</td>
<td>12 h</td>
</tr>
</tbody>
</table>

Fig. 3. Relationship between vibration amplitude and driving frequency.
transducer fabrication, are shown in Table 1. They are almost similar to a previous hydrothermal method. The difference between previous “nucleation process” and “improved nucleation process” is the amount of titanium ions present in the reaction solution. A very small quantity of titanium ions was very useful in increasing the piezoelectric factor. After the “improved nucleation process”, a “crystal growth process” was carried out for four times to make the film thicker. In this paper, the detailed comparison with previous processes is not mentioned. The piezoelectric factor of $d_{33}$ was $25 \text{ pC/N}$ and PZT thickness was 12 $\mu\text{m}$. The SEM photograph of PZT thin film deposited by our process is shown in Fig. 2.

4. Experiments

4.1. Vibration characteristics

The relationship between driving frequency and vibration amplitude was measured by a laser Doppler velocimeter. The input voltage to facing electrodes was 4 $V_{p-p}$. The stator transducer has two pairs of electrodes; thus, another pair of electrode was opened. The rotor was not placed on the stator transducer during this experiment. The result is shown in Fig. 3. From this result and admittance measurement, all parameters of an equivalent circuit were calculated.

4.2. Driving operation

The operation test of the motor was carried out. The revolution speed was measured by another laser Doppler velocimeter. This velocimeter can measure the tangential velocity of the subject that is moving across the laser. The laser was irradiated to the sidewall of the rotor. The revolution speed and starting torque was calculated from the result of the transient response.

The rotation speed is increased linearly with the input voltage, as shown in Fig. 4. Larger pre-load decreased the revolution speed with the same input voltage, although the starting torque increased in proportion to the pre-load, as shown in Fig. 5. The maximum torque was 0.67 $\text{mN}\cdot\text{m}$ with 5.3 $\text{mN}$ pre-load and 20 $V_{p-p}$ input voltage. Under the same conditions, the convergent revolution speed was 680 rpm. With larger input voltage, 30 $V_{p-p}$ concretely, the PZT thin film was broken down, so further experiments could not be carried out.

5. Estimations for smaller motor

The equivalent circuit is very useful in estimating the performance of ultrasonic motors. Force factor $A$ is very important because the output force is proportional to the force factor. In this section, the relationship between the stator transducer and the input voltage was measured.

<table>
<thead>
<tr>
<th>Type</th>
<th>$D$ (mm)</th>
<th>$D'$ (mm)</th>
<th>$L$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>1.4</td>
<td>1.2</td>
<td>5.0</td>
</tr>
<tr>
<td>Type 2</td>
<td>2.4</td>
<td>1.9</td>
<td>10</td>
</tr>
<tr>
<td>Type 3</td>
<td>1.4</td>
<td>1.2</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 2
Three types of a stator transducer
$D$: outer diameter, $D'$: inner diameter, $L$: length.

<table>
<thead>
<tr>
<th>fr</th>
<th>$Q_m$</th>
<th>Amp</th>
<th>$V$</th>
<th>$A$</th>
<th>$e_{33}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>227</td>
<td>160</td>
<td>58</td>
<td>4</td>
<td>0.61</td>
</tr>
<tr>
<td>Type 2</td>
<td>110</td>
<td>235</td>
<td>90</td>
<td>4</td>
<td>1.1</td>
</tr>
<tr>
<td>Type 3</td>
<td>72</td>
<td>124</td>
<td>205</td>
<td>4</td>
<td>0.44</td>
</tr>
</tbody>
</table>

Table 3
The parameters for each stator transducer
$fr$: Resonance frequency (kHz), $Q_m$: quality factor, Amp: Amplitude ($\text{nm}_{p-p}$), $V$: input voltage ($V_{p-p}$), $A$: force factor ($\text{mN}/V$), $e_{33}$: piezoelectric factor ($\text{C/m}^2$).
force factor and stator dimensions is examined. From the piezoelectric equations, the force factor is expressed as

$$A = 4\sqrt{2} \left( \frac{\lambda}{l} \right) \left( \frac{R_o + R_i}{2} \right) R_o e_{31} \sinh \left( \frac{\lambda}{2} \right) \sin \left( \frac{\lambda}{2} \right)$$

(5-1)

where $\lambda$ is a constant equivalent to 4.730; $R_o$, outer radius of piezoelectric material; $R_i$, inner radius of piezoelectric material; $l$, length; and $e_{31}$, piezoelectric coefficient. About the calculation of the force factor, please refer to Appendix A. The constant value $\lambda$ depends on the vibration mode. For the stator transducer that uses PZT thin film, $R_o$ is almost equal to $R_i$. The force factor was proportional to the radius squared and was inversely proportional to the length. If the longer stator transducer was fabricated, the maximum output force of stator transducer was decreased while the vibration amplitude was increased on the other hand.

Maximum output force $F_{\text{max}}$ is expressed as $AV$ and the maximum output torque is proportional to $F_{\text{max}}R_o$. Thus, the maximum output torque is proportional to the radius squared under the condition that the ratio of radius and the length is fixed.

The piezoelectric coefficient $e_{31}$ is important parameter to determine the force factor. To measure the value of $e_{31}$, three types of stator transducer were fabricated. In this section, we refer to these stator transducers as types 1, 2, and 3, as indicated in Table 2. Using each type stator transducer, the vibration amplitude as a function of driving frequency was measured. From these results and an admittance measurement, all parameters of equivalent circuit were calculated. With gained force factor and Eq. (5-1), the piezoelectric coefficient $e_{31}$ was measured for each stator transducers as shown in Table 3.

To estimate the performances of a smaller ultrasonic motor, the piezoelectric coefficient $e_{31}$ was used as $-0.57 \ \text{C/m}^2$, which is an average of each result for three stator transducers. With this value, the smaller ultrasonic motor performance was estimated. The force factor and maximum output torque vs. a diameter was calculated as shown in Figs. 6 and 7. The numerical results are shown in Table 4. The output torque of 27 nNm with a 100-\(\mu\)m diameter motor is sufficient as a micro actuator. For example, the output torque of electrostatic micro motor or previous disk type micro ultrasonic motor was pN m order. Thus, the calculated value indicates that the ultrasonic motor is a promising actuator for micro mechanical systems.

### 6. Conclusions

The micro ultrasonic motor was fabricated by hydrothermal method and successfully operated. The stator transducer is 1.4 mm in diameter and 5 mm long. The revolution direction was reversible and the maximum output torque was 0.67 \(\mu\)N m.

The piezoelectric coefficient $e_{31}$ of deposited film was measured as $-0.57 \ \text{C/m}^2$. The $e_{31}$ value of bulk PZT was $-4.1 \ \text{C/m}^2$. Thus, there is plenty of room for improving the chemical reaction conditions of the hydrothermal method. If the property of thin films would be increased to that of a ceramic PZT, the output torque or revolution speed would be increased seven times with the same input voltage.

### Acknowledgements

The authors would like to thank Mr. T. Kanda and Mr. H. Yasui of Tokyo University for assistance on the hydrothermal method of the PZT thin film. This work has...
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Appendix A

Generally, ultrasonic motors utilize the piezoelectric materials to convert electrical energy to vibration energy. To estimate the output torque or vibration velocity of a stator transducer, an equivalent circuit is indispensable. The force factor indicates the output mechanical force per unit input voltage, and vibration velocity per unit displacement current.

Here, the force factor (Eq. (5-1)) of cylindrical shaped transducer is calculated. The cylindrical coordinate \((r, \theta, z)\) is used. The stator dimensions are \(-1/2 < z < 1/2\), \(R'_s < r < R_s\), and the considered electrode dimension are \(-\pi/4 < \theta < \pi/4\), \(-1/2 < z < 1/2\). Parameter \(R'_s\) is the inner radius of the stator transducer and \(R_s\), which will appear later, is the inner radius of the piezoelectric material. In case of a PZT thin film type motor, \(R_s\) exceeds \(R'_s\).

The fundamental equation for piezoelectric phenomenon is expressed as

\[
T_z = e_{31}S_z - e_{31}E_z, \quad D_z = e_{31}S_z + e_{33}E_z, \quad \text{(A-1)}
\]

where \(T_z, e_{31}, S_z, e_{31}, E_z, D_z, e_{33}\) are stress, stiffness, strain, piezoelectric coefficient, electrical field, charge density, and dielectric constant, respectively. The vibration mode is bending mode, so the relationship between \(S_z\), and vibration displacement \(u\) is expressed as

\[
S_z = -r \sin \theta \frac{\partial^2 u}{\partial z^2}. \quad \text{(A-2)}
\]

Taking into account the equation

\[
\frac{\partial D_z}{\partial r} = 0, \quad \text{(A-3)}
\]

a piezoelectric equation is simplified to

\[
e_{31} \sin \theta \frac{\partial^2 u}{\partial z^2} = e_{31} \frac{\partial E_z}{\partial r}. \quad \text{(A-4)}
\]

The differential equation for input voltage vs. \(r\) is obtained as

\[
\frac{\partial V}{\partial r} = -E_z = \left( \frac{e_{31} \sin \theta}{e_{31} \frac{\partial^2 u}{\partial z^2}} \right) r. \quad \text{(A-5)}
\]

This differential equation (A-5) with the boundary conditions

\[
V = V_0 \ (r = R_s) \quad \text{and} \quad V = 0 \ (r = R_i), \quad \text{(A-6)}
\]

is resolved as

\[
V = \left( -\frac{1}{2} \left( \frac{e_{31} \sin \theta}{e_{31} \frac{\partial^2 u}{\partial z^2}} \right) r^2 + \left( \frac{e_{31} \sin \theta}{e_{31} \frac{\partial^2 u}{\partial z^2}} \right) \frac{R_o + R_i}{2} \right) + \frac{V_0}{R_o - R_i} \left( \frac{e_{31} \sin \theta}{e_{31} \frac{\partial^2 u}{\partial z^2}} \right) \frac{R_o + R_i}{2} - \frac{V_0 R_o}{R_o - R_i}. \quad \text{(A-7)}
\]

From this equation, the charge density \(D_z\) is calculated to

\[
D_z = -e_{31} \sin \theta \frac{\partial u}{\partial z^2} \left( \frac{R_o + R_i}{2} \right) - \frac{e_{31} S_z V_0}{R_o - R_i}. \quad \text{(A-8)}
\]

The second term of the right side shows the damped capacitance. To calculate the force factor, the displacement current \(I_m\) is essential, so here, \(I_m'\) is defined as

\[
I_m' = -e_{31} \sin \theta \frac{\partial u}{\partial z^2} \left( \frac{R_o + R_i}{2} \right). \quad \text{(A-9)}
\]

The displacement current is calculated as

\[
I_m = -j \omega \int_S D_z dS_i
\]

\[
= -4 \sqrt{2} j \omega C \left( \frac{\Lambda}{l} \right) \left( \frac{R_o + R_i}{2} \right) R_o e_{31} \sinh \left( \frac{\Lambda}{2} \right) \sin \left( \frac{\Lambda}{l} \right). \quad \text{(A-10)}
\]

using the first bending vibration mode expressed as

\[
u = \left[ \sin \left( \frac{\Lambda}{2} \right) \cosh \left( \frac{\Lambda}{l} \right) \right] - \sinh \left( \frac{\Lambda}{2} \right) \cos \left( \frac{\Lambda}{l} \right) \]. \quad \text{(A-11)}
\]

where \(C\) and \(\Lambda\) are constants.

On the other hand, the vibration velocity at the top of the stator transducer \((z = l/2)\) is

\[
u = \frac{\partial u}{\partial t} \left. \right|_{z = l/2} = j \omega C \left[ \sin \left( \frac{\Lambda}{2} \right) \cosh \left( \frac{\Lambda}{l} \right) \right] - \sinh \left( \frac{\Lambda}{2} \right) \cos \left( \frac{\Lambda}{l} \right). \quad \text{(A-12)}
\]

Force factor \(A\) is expressed as \(|I_m' / v|\), so

\[
A = \left( \frac{4 \sqrt{2}}{l} \right) \left( \frac{R_o + R_i}{2} \right) R_o e_{31} \sinh \left( \frac{\Lambda}{2} \right) \sin \left( \frac{\Lambda}{2} \right) \sin \left( \frac{\Lambda}{2} \right) \cosh \left( \frac{\Lambda}{l} \right) - \sinh \left( \frac{\Lambda}{2} \right) \cos \left( \frac{\Lambda}{2} \right) \right]. \quad \text{(A-13)}
\]

is obtained.

References


Biographies

Takeshi Morita was born in 1970. He received his B. Eng., M. Eng., and Dr. Eng. degrees in Precision Machinery Engineering from the University of Tokyo, Japan in 1994, 1996, and 1999, respectively. Since 1999, he has been a postdoctoral researcher for the Division of Fundamental Technology Development, at the Institute of Physical and Chemical Research (RIKEN). His research interests include micro-ultrasonic motor, PZT thin film, extreme condition mechatronics, and micro-manipulation system.

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Toshiro Higuchi was born in 1950. He received his BS, MS, and Dr. Eng. degrees in Precision Machinery Engineering from the University of Tokyo, Japan, in 1972, 1974, and 1977, respectively. He was a lecturer at the Institute of Industrial Science, University of Tokyo, from 1977 to 1978, and an Associate Professor from 1978 to 1991. Since 1991, he has been a Professor in the Department of Precision Engineering, University of Tokyo. His research interests include mechatronics, magnetic bearing, electrostatic actuator, stepping motors robotics and manufacturing.