A micro ultrasonic motor using a micro-machined cylindrical bulk PZT transducer

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Abstract: In this paper, a micro ultrasonic motor using a micro-machined bulk piezoelectric transducer is introduced. The cylindrical shaped bulk piezoelectric transducer, a diameter of 0.8 mm and a height of 2.2 mm, was developed as stator transducer for traveling wave type ultrasonic motor. The transducer was made of PZT bulk ceramics, and formed by micro-machining, Ni plating and laser beam cutting process. Using this stator transducer, we have fabricated a cylindrical micro ultrasonic motor, a diameter of 2.0 mm and a height of 5.9 mm. We have also evaluated some characteristics and succeeded in driving the micro ultrasonic motor.

Cover Letter

A MICRO ULTRASONIC MOTOR USING A MICRO-MACHINED CYLINDRICAL BULK PZT TRANSDUCER

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Abstract

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Key Words: piezoelectric actuator, ultrasonic motor, micro motor, bulk piezoelectric material, micro machining

1. Introduction

Micro motors have been receiving increasing attention in realizing various types of micro mechanism applications, for example, micro robots, microsurgery equipments, and micro electro mechanical systems (MEMS). In this paper, micro ultrasonic motors utilizing micro-machined cylindrical bulk piezoelectric vibrators are introduced.

Ultrasonic motors have some merits for the miniaturization of motors. They have simple structure compared with other types of micro actuators, especially electromagnetic motors. In addition, ultrasonic motors need no deceleration mechanism because they have high torque output in low rotation speed. Hence, by using ultrasonic motors, we would realize micro mechanical systems driven by high power actuators.

Many types of micro ultrasonic motors have been reported [1-9]. Some of them used piezoelectric thin film for the acceleration [2-5]. However they could not realize enough high power output for the drive of micro mechanical systems. To realize high power output, we used bulk lead zirconate titanate (PZT) transducer [6, 10].

2. Structure and Principle

Figure 1 shows the schematic of the piezoelectric cylindrical transducer for the micro ultrasonic motor. Cylindrical shaped bulk piezoelectric vibrators were developed as stator transducers for traveling wave type ultrasonic motors.

Since the stator transducer was fixed at the end of the cylinder, it is easy to support the vibrator and the structure of the motor was not complicated. This is important for micro ultrasonic motor because it is difficult to support the vibrator when the vibrator was miniaturized. Four electrical sources were used for the oscillation of the vibrator [2, 3, 6]. The inner electrode works as an equivalent electrical ground. The rotate orientation can be changed by the phase shift between the electrical sources.

Figure 2 shows the analytical result of the vibrator deformation mode calculated by using the finite element method. One end of the cylinder was connected to the base, the cylindrical part which has larger diameter. As a result of modal analysis, another end of the cylinder was deformed.

Figure 3 shows a cross sectional view of micro ultrasonic motor and a photograph of fabricated micro motor. The diameter of the motor with pre-load mechanism was 2.0 mm, and the height was 5.9 mm. The micro ultrasonic motor consists of a rotor, the stator transducer, casing parts, spring and a bearing. The rotor, whose diameter was 0.8 mm, was pressed to the end of the stator transducer by using the spring whose diameter was 0.8 mm. The pre-load was given by the spring. The output shaft was united with the rotor, and the diameter of the shaft was 0.4 mm. The shaft and rotor was made of SUS630. The bearing was made of PTFE (poly tetra fluoro ethylene).

The finite element method (FEM) was used for the design of motor. The modal analysis by FEM gave the calculation results about the vibration mode. It is important that the stator transducer was fixed at one end and the motor case cannot be excited by the vibration of transducer. As shown in Fig.4, the dimensions of the vibrator, those of the case and their material properties gave suitable vibration mode.

3. Fabrication of Transducer

The stator transducers were fabricated by the micro machining of the bulk cylindrical piezoelectric ceramics.

The fabrication process of the stator transducer is shown in Fig.5. The bulk piezoelectric material was cylindrical shaped hard type PZT, C-218 (Fuji Ceramics Co., Japan). The cylindrical ceramics was formed to be a pipe and step like shape by micro machining process. In addition, nickel was plated as electrodes on the surface and inside of the pipe. After the polarization process, the nickel film was divided to four electrodes by the laser beam cutting. Each pitch between two electrodes is 0.1 mm.

Figure 6 displays the schematic view of the piezoelectric transducer. We fabricated two types of transducer. About those transducers, dimensions are shown in Table I. In both types of transducer, the dimensions of the pipe shaped part are an outer diameter of 0.8 mm, an inner diameter of 0.4 mm and a height of 2.2 mm. The transducer A and the transducer B have different dimensions of the base. The transducer A was for evaluating basic characteristics about transducer. This type transducer has larger base and the bending vibration can be excited at the pipe shaped part. The transducer B was built in micro motor as shown in Fig.3. Figure 7 shows photograph of transducer A and B. Divided electrodes are deposited on the PZT cylinder.

4. Evaluation of Transducer

Some characteristics of stator vibrator were evaluated. For the driving of the micro ultrasonic motor, bending vibration in two orthogonal orientations was used as illustrated in Fig.1. We evaluated the relationship between admittance and frequency about each orientation. The transducer A was used for the measurement. The experimental results are shown in Fig. 8. Each graph displays that the resonance frequency was approximately 70 kHz.

The vibration velocity at the end of the vibrator was also evaluated. The maximum vibration velocity at the resonance frequency was measured about the transducer A. The vibration velocity was measured with laser Doppler vibrometer. Figs 9 and 10 indicate the experimental results. Figure

9 displays the relationship between the vibration velocity and the frequency. As shown in this graph, the resonance frequency was 69 kHz. Figure 10 shows the relationship between the vibration velocity and the applied voltage. The measured relationship has linearity. When the applied voltage was 40 $V_{p\text{-}p}$, the resonance frequency was 69 kHz and the maximum vibration speed was 715 mm/s, causing the vibration displacement was 1.6 $\mu m_{o\text{-}p}$.

Some characteristics of motor were evaluated by using the transducer A and a rotor. The pre-load mechanism of the motor and transducer B were not used in this experiment. This is because it is difficult to change the pre-load value by using the pre-load mechanism built in the motor case. We evaluated the relationship between the rotation speed, applied voltage and the pre-load values. The relationship between the output torque of the motor, applied voltage and the pre-load values was also evaluated.

The experimental setup is displayed in Fig. 11. The transducer A, a rotor, a pre-load mechanism and a laser counter were used for the measurement. The pre-load was given by a spring through a needle. The rotor was pushed by the needle tip and has a contact with the end of the vibrator. The pre-load value was changed by the length of spring and the length was measured by using a gap sensor. The rotation speed of the rotor was measured by using the laser counter [6].

Figure 12 shows the relationship between the rotation speed and pre-load values. The frequency of the applied voltage was set at the first bending mode frequency of the stator transducer. The applied voltage was changed from 25 V_{p-p} to 40 V_{p-p}. The maximum revolution per minute was 3.85×10^3 at the applied voltage of 40 V_{p-p} and the pre-load of 0.5 mN. The experimental results show that the rotation speed was decreased suddenly when the pre-load increased.

The static torque of the micro ultrasonic motor was also evaluated. The load cell was used for the measurement of the tension of thread pull by the rotor. Hence the measured torque values mean the static torque. Figure 13 shows the experimental results. This graph shows the relationship between the output torque and pre-load. The maximum output torque was 2.5×10^{-2} μNm when the pre-load was 5 mN and the applied voltage was 40 V_{p-p}. As shown in Fig.12, the rotation stopped when the applied voltage was 40 V_{p-p} and the pre-load was larger than 5 mN.

5. Micro Ultrasonic Motor

The transducer B was used as the stator vibrator as shown in Fig. 3. It was confirmed that the output shaft united with the rotor was driven by the vibrator. The direction of the rotation was changed by the polarity of the electrical sources

An analytical result of the deformation mode calculated by using the finite element method about the transducer B is shown in Fig.14. To miniaturize the motor, the base part of the stator transducer must be miniaturized. In this result, the figure shows the deformed shape when the diameter of the base part of the stator is 1.5 mm about the transducer B.

The structure of the micro ultrasonic motor using cylindrical bulk transducer and its parts are shown in Fig.13. The diameter of the motor with pre-load mechanism was 2.0 mm, and the height was 5.9 mm. A rotor, whose diameter was 0.8 mm, was pressed to the end of the stator vibrator by using a spring whose diameter was 0.8 mm. An output shaft was united with the rotor, and the diameter of the shaft was 0.4 mm.

Figure 15 shows the micro ultrasonic motor and the piezoelectric vibrator used for the micro ultrasonic motor. We have succeeded in driving this motor and controlling the rotating direction.

The revolution speed of shaft was measured with laser counter. Experimental result is shown in Fig.16. This graph displays the relationship between revolution speed of shaft and driving voltage. The vibrator was oscillated at the resonance frequency of this motor, 58 kHz, and the pre-load was 4.9×10^{-2} mN. This pre-load value means that the pre-load was only obtained by the load of rotor. When the driving voltage was 40 V_{p-p}, the revolution speed was 2.4×10^{3} rpm.

When the driving voltage 40V_{p-p}, the measured revolution speed generated by transducer B built in motor was 64% of maximum revolution speed generated by transducer A displayed in Fig. 12. This decrease of the revolution speed was thought to be due to the damping of vibration. Figure 17 shows the relationship between the admittance of transducer B built in the micro motor and the frequency. In comparison with Fig. 8, the admittance of transducer A, the value of admittance and Q factor are diminished in Fig. 17, those of transducer B.

6. Evaluation of Output Torque

The theoretical output torque value of this micro ultrasonic motor can be estimated by using equivalent circuit of transducer.

Figure 18 illustrates the equivalent circuit. In this figure, V, F, A, L_m, C_m, R_m mean applied voltage, output force, force factor, equivalent mass, equivalent compliance, and equivalent viscoelastic loss, respectively. The mechanical output force at the mechanical terminal in right side of equivalent circuit is obtained by the force factor, the conversion ratio between mechanical part and electrical part, and the applied voltage against the electrical terminal in left side of the circuit. The relationship can be expressed as

$$F = AV . \qquad (6\text{-}1)$$

The force factor A used in equation 6-1 is derived from the vibration mode and piezoelectric equations [3]. The vibrator used in the experiments is oscillated in its fundamental excitation mode. In addition, the vibrator has a fixed end and a free end. Under this boundary condition, vibration mode can be derived. When λ, l, R_o, R_i, and e_{31} are a constant equivalent to 1.875, the length of vibrator, the outer radius of vibrator, the inner radius of vibrator and the piezoelectric constant, the force factor A of transducer can be described as

$$A = \frac{1}{\sqrt{2}} \frac{\lambda}{l} \frac{(R_o + R_i) R_o e_{31}}{\cos\lambda \sinh\lambda - \sin\lambda \cosh\lambda} . \qquad (6\text{-}2)$$

From the summarized values in Table II and Eq. 2, the estimated force factor *A* of transducer is $3.85x10^{-4}$ N/V.

When the applied voltage is 40 $V_{p\text{-}p}$ and the radius of the rotor is 1.0 mm, the estimated output torque is 7.7 μNm. Experimentally, the static torque was 0.3% of this value. Mainly, this difference would be due to the damping of vibration as shown in section 5.

7. Conclusion

We have fabricated micro ultrasonic motor using micro-machined bulk piezoelectric transducer. Cylindrical shaped bulk piezoelectric vibrator, a diameter of 0.8 mm and a height of 2.2 mm, was developed as stator transducer for traveling wave type ultrasonic motor. We have succeeded in driving this motor and could measure some characteristics. The maximum revolution per minute was 3850 at the applied voltage of 40 $V_{p\text{-}p}$ and the pre-load of 0.5 mN. We have also evaluated the output torque of the motor. The maximum output torque was $2.5x10^{-2}$ μNm when the pre-load was 5 mN and the applied voltage was 40 $V_{p\text{-}p}$.

In the evaluation of this paper, the output torque of the micro ultrasonic motor was not enough to drive micro mechanism. The improvement of the pre-load mechanism and contact condition between the rotor and the stator vibrator is important to obtain high output micro ultrasonic motor.

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Biography

Takefumi Kanda was born in Fukuoka, Japan, on June 18, 1972. He received the B. Eng., the M. Eng. and the Dr. Eng. degrees in precision machinery engineering from The University of Tokyo, Japan in 1997, 1999 and 2002, respectively.

From 2002, he was a research associate at the Graduate School of National Science and Technology, Okayama University, Japan. Since 2003, he has been a lecturer at Okayama University. His research interests are micro sensors, micro actuators, micro systems and piezoelectric film.

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Akira Makino was born in Shizuoka, Japan, on January 16, 1982. He received the B. Eng. in systems engineering form Okayama University, Japan in 2004. Since 2005, he has been a graduate student at graduate school of information science, Nara Institute of Science and Technology.

His current research interest is in the artificial intelligence.

Tomohisa Ono was born on January 3, 1981. He received the B. Eng. in systems engineering from Okayama University, Japan in 2003 and the M. Sci. form Nara Institute of Science and Technology, Japan in 2005.

His current research interest is in the artificial intelligence.

Koichi SUZUMORI was born in 1959. He received the Doctor Degree from Yokohama National University in 1990. He had worked for Toshiba R&D Center from 1984 to 2001, and worked also for Micromachine Center, Tokyo from 1999 to 2001. He has been a professor at Okayama University, Japan since 2001.

He is a member of the Japan Society of Mechanical Engineers, the Robotics Society of Japan, IEEE and the Institute of Electrical Engineers of Japan.

Takeshi Morita was born in 1970. He received B. Eng., M. Eng. and Dr. Eng. degrees in precision machinery engineering from the University of Tokyo in 1994, 1996 and 1999 respectively.

After being a postdoctoral researcher at RIKEN (the Institute of Physical and Chemical Research) and at EPFL (Swiss federal institute of technology), he became a research associate at Tohoku University in 2002. Since June 2005, he has been an associate professor at The University of Tokyo.

His research interests are a hydrothermal method for ferroelectric thin films, piezoelectric actuators and its control systems.

Minoru Kuribayashi Kurosawa (formerly Kuribayashi) was born in Nagano, Japan, on April 24, 1959. He received the B. Eng. degree in electrical and electronic engineering, and the M. Eng. and Dr. Eng. degrees from Tokyo Institute of Technology, Tokyo, in 1982, 1984, and 1990, respectively.

He was a Research Associate at the Precision and Intelligence Laboratory, Tokyo Institute of Technology, Yokohama, Japan, from 1984, and an Associate Professor at the Graduate School of Engineering, The University of Tokyo, Tokyo, Japan, from 1992. Since 1999, he has been an Associate Professor at the Interdisciplinary Graduate School of Science and Engineering, The Tokyo Institute of Technology, Yokohama, Japan. His current research interests include ultrasonic motor, micro actuator, PZT thin film, SAW sensor and actuator, and single bit digital signal processing and its application to control systems.

Dr. Kurosawa is a member of the Institute of Electronics Information and Communication Engineers, the Acoustical Society of Japan, IEEE, the Institute of Electrical Engineers of Japan and the Japan Society for Precision Engineering.

Fig. 1 Schematic of the piezoelectric cylindrical transducer for the micro ultrasonic motor

Fig. 2 Analytical result of the Vibrator deformation mode by the finite element method

Fig. 3 Cross-sectional view Structure of the micro ultrasonic motor using cylindrical bulk transducer and its parts

Fig. 4 Analytical result of the deformation mode about the type 2 transducer the using the finite element method

Fig. 5 Fabrication process of the piezoelectric transducer

Fig. 6 Schematic show of the cylindrical bulk piezoelectric transducer

Fig. 7 Photograph of the cylindrical bulk piezoelectric transducer

Fig. 8 Relationship between admittance of the vibrator and frequency

Fig.9 Relationship between the vibration velocity at the tip of the transducer A and the frequency

Fig. 10 Relationship between the vibration velocity and driving voltage about the transducer A

Fig. 11 Experimental setup for the measurement of the relationship between the revolution speed, pre-load, and applied voltage

Fig. 12 Relationship between the revolution speed of rotor and pre-load against the rotor

Fig. 13 Relationship between the static torque and the pre-load against the rotor

Fig.14 Deformation of transducer B at the resonance frequency; Calculation result of the modal analysis by FEM

Fig.15 Photograph of the micro ultrasonic motor and piezoelectric vibrator, transducer B on US one cent coin

Fig.16 Relationship between the revolution speed and the driving voltage of micro ultrasonic motor

Fig.17 Equivalent circuit of piezoelectric transducer

Table I Dimensions of the cylindrical bulk piezoelectric transducers

Table II Parameters of transducer

Table(s)

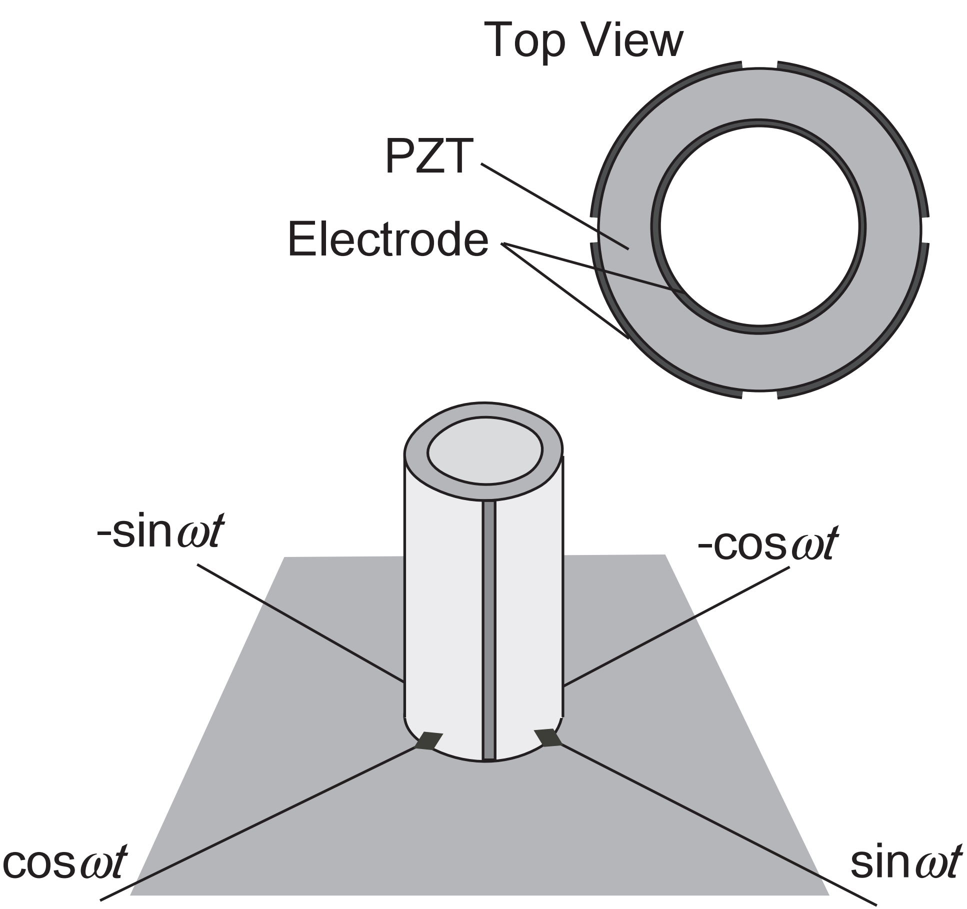
Table I Dimensions of the cylindrical bulk piezoelectric transducers

	Transducer A	Transducer B
a (mm)	0.8	
b (mm)	0.4	
c (mm)	2.2	
d (mm)	2.8	1.0
e (mm)	4.0	1.5

Table II Parameters of transducer

λ		1.875
l	length of vibrator [mm]	2.2
Ro	outer radius of vibrator [mm]	0.4
Ri	inner radius of vibrator [mm]	0.2
e31	piezoelectric constant [N/Vm]	-11

Figure(s)


Top View
PZT
Electrode
-sinωt
-cosωt
cosωt
sinωt

Figure(s)
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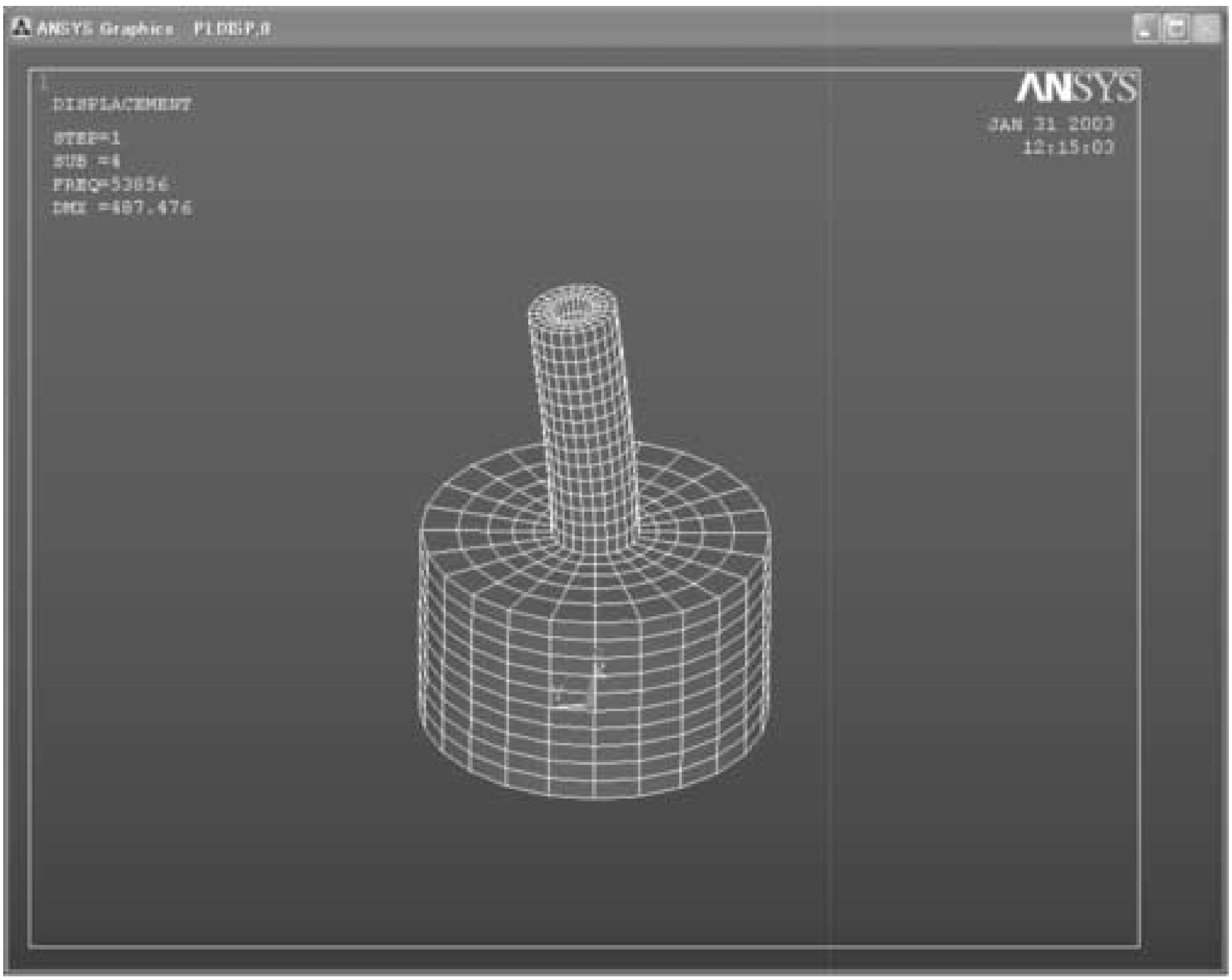

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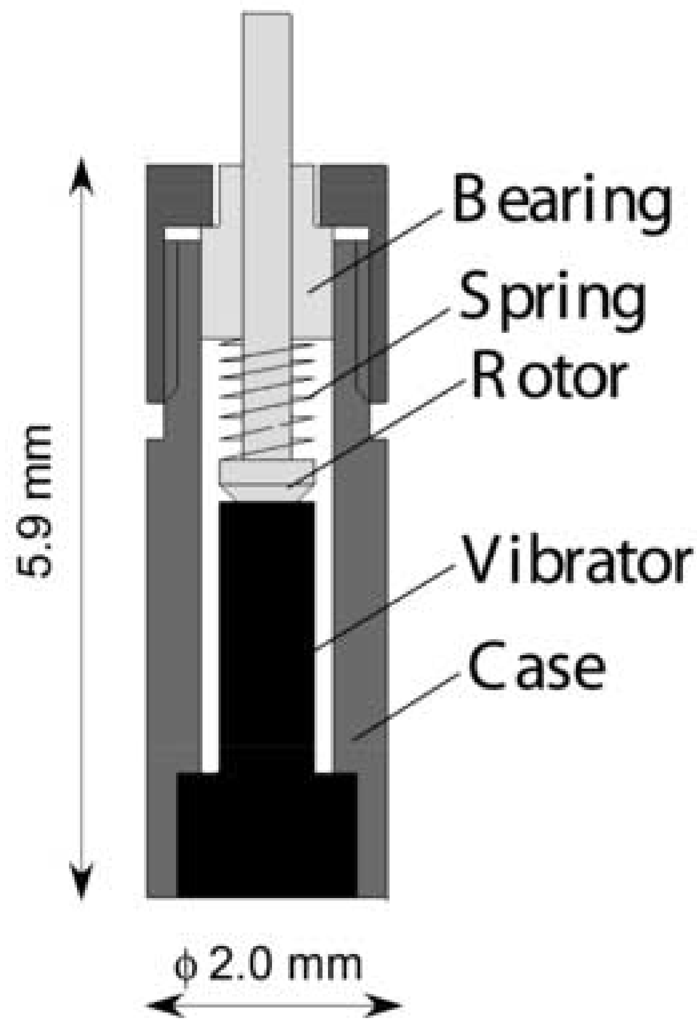

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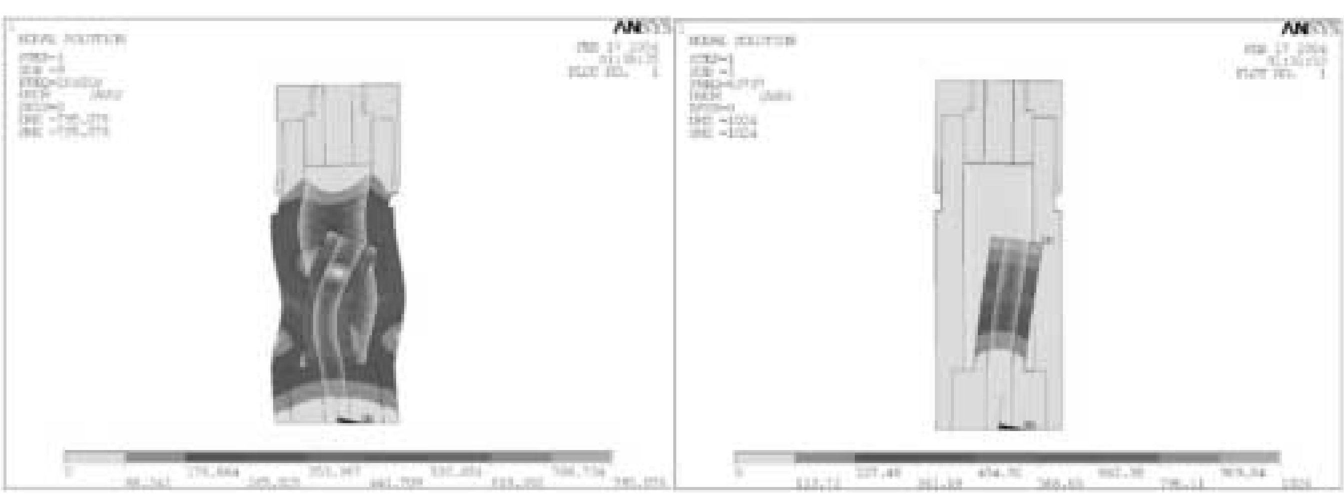

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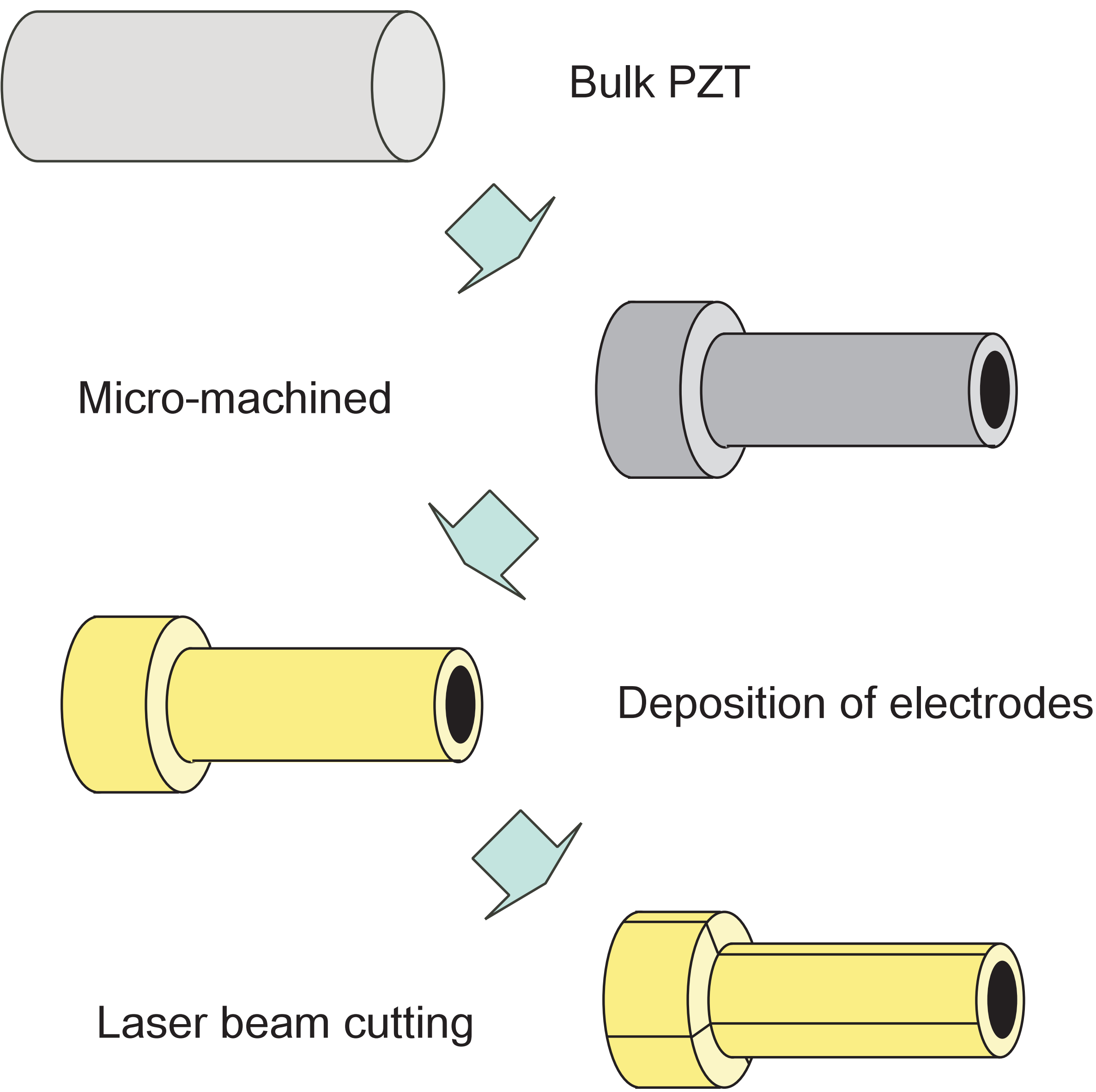
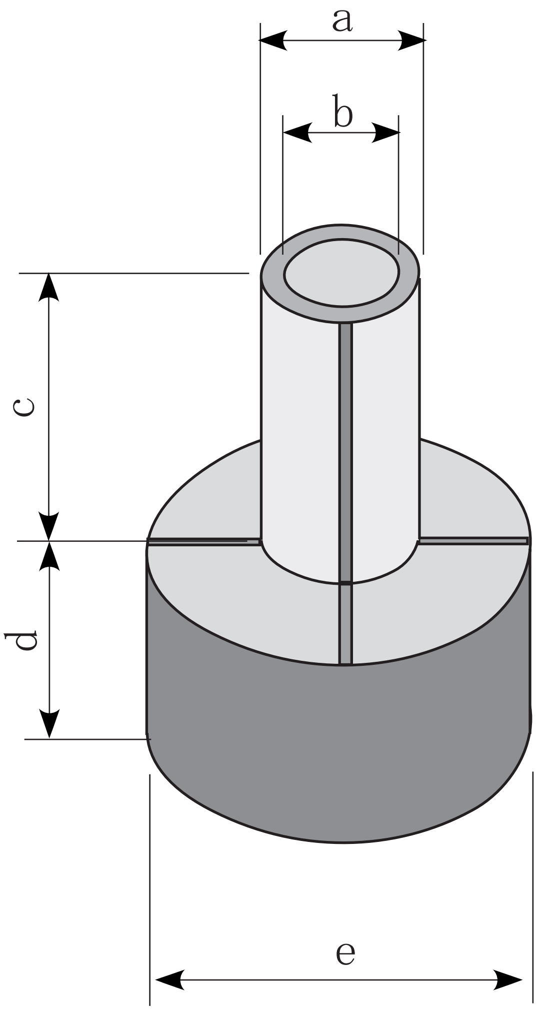

Bulk PZT
Micro-machined
Deposition of electrodes
Laser beam cutting

Figure(s)



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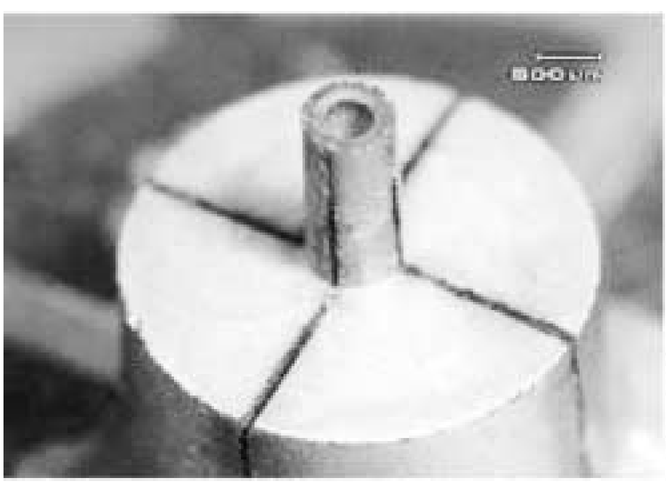 

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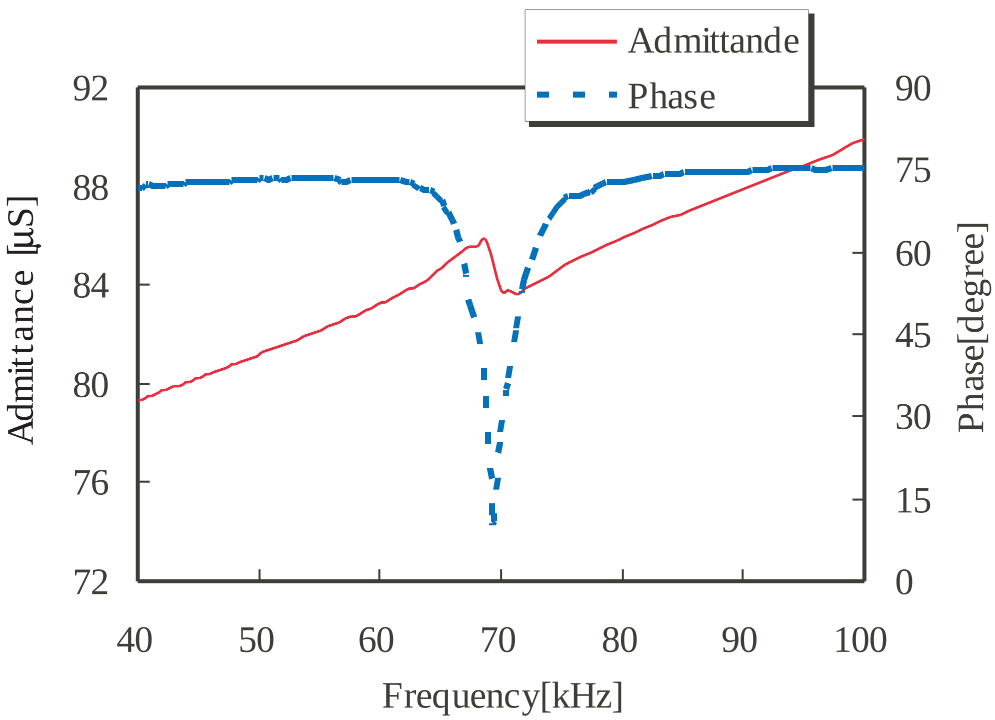
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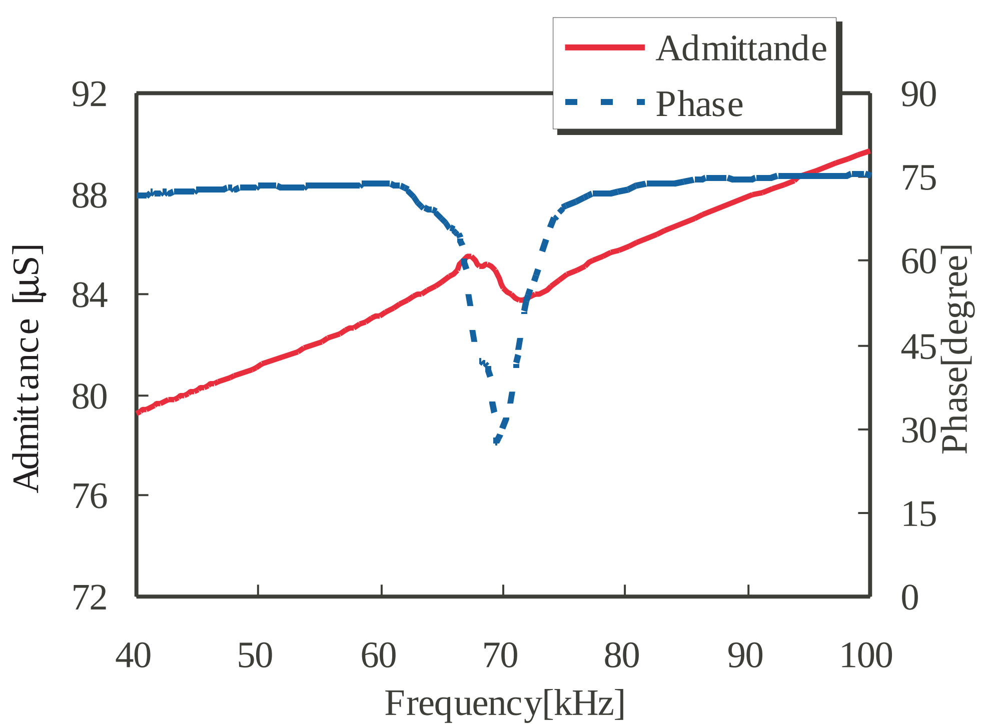
Phase[degree]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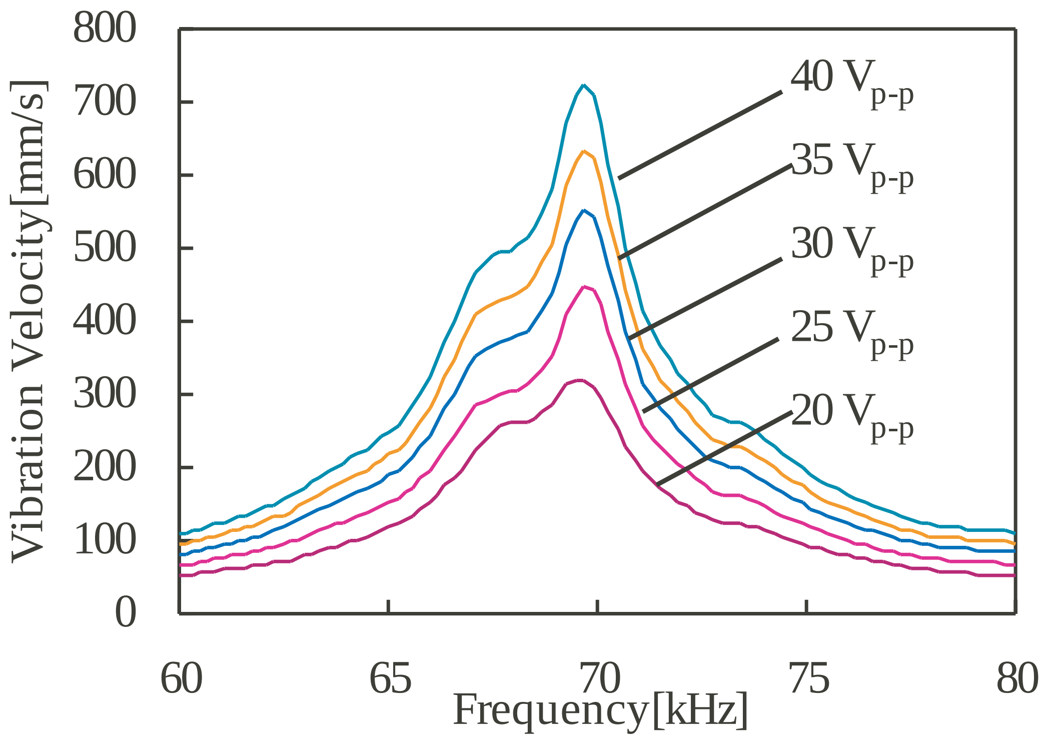
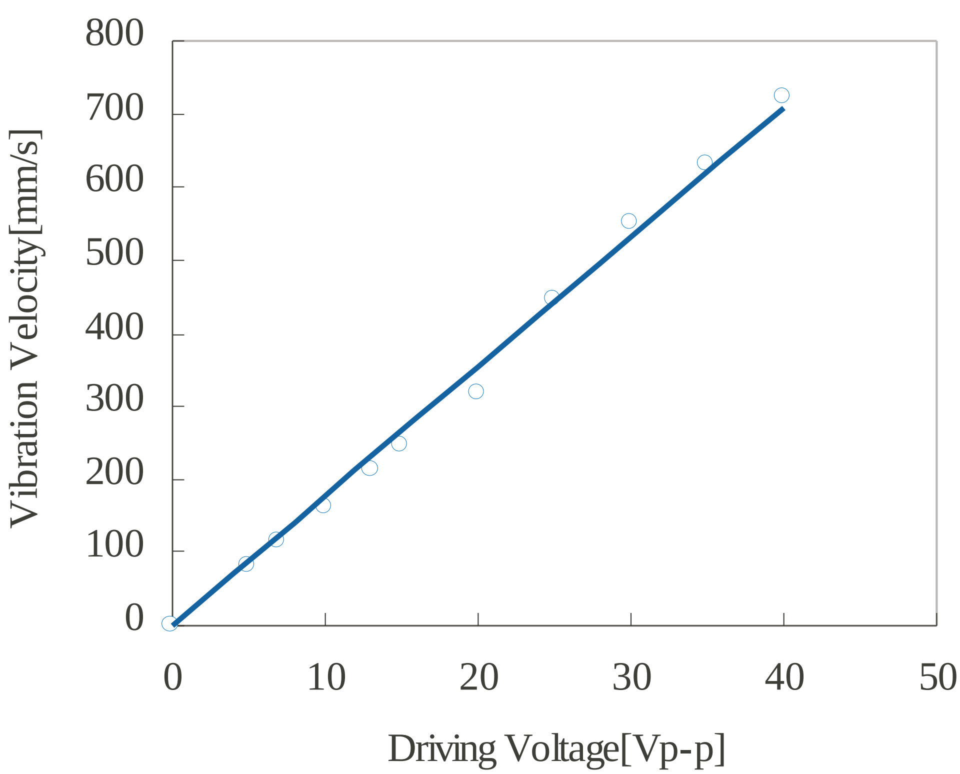


800
700
600
500
400
300
200
100
0
Vibration Velocity[mm/s]
40 Vp-p
35 Vp-p
30 Vp-p
25 Vp-p
20 Vp-p
60
65
70
75
80
Frequency[kHz]

Figure(s)



Vibration Velocity[mm/s]
800
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Driving Voltage[Vp-p]

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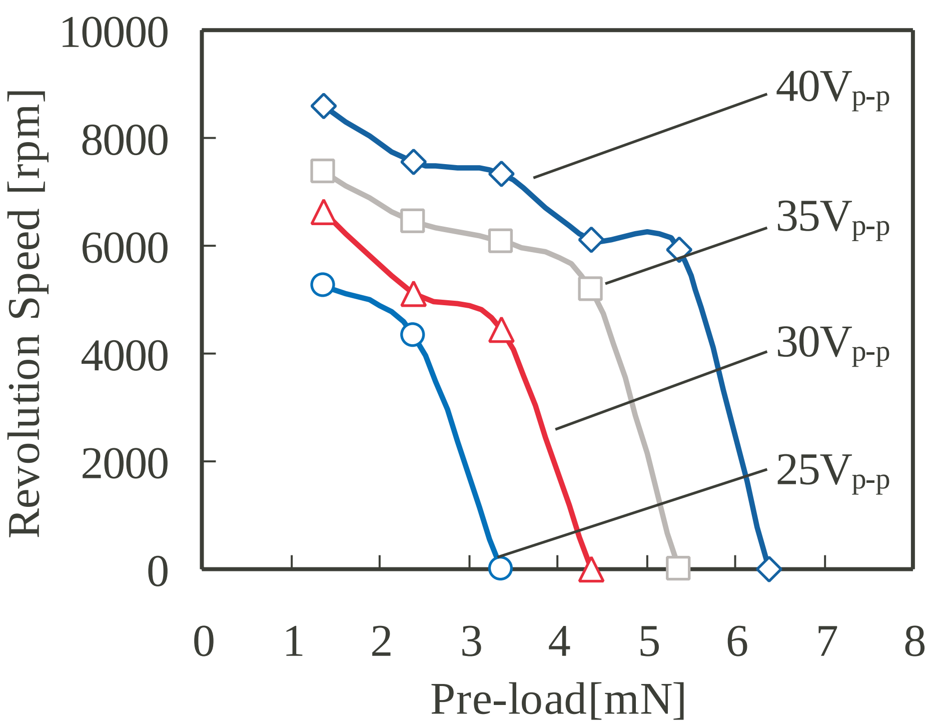
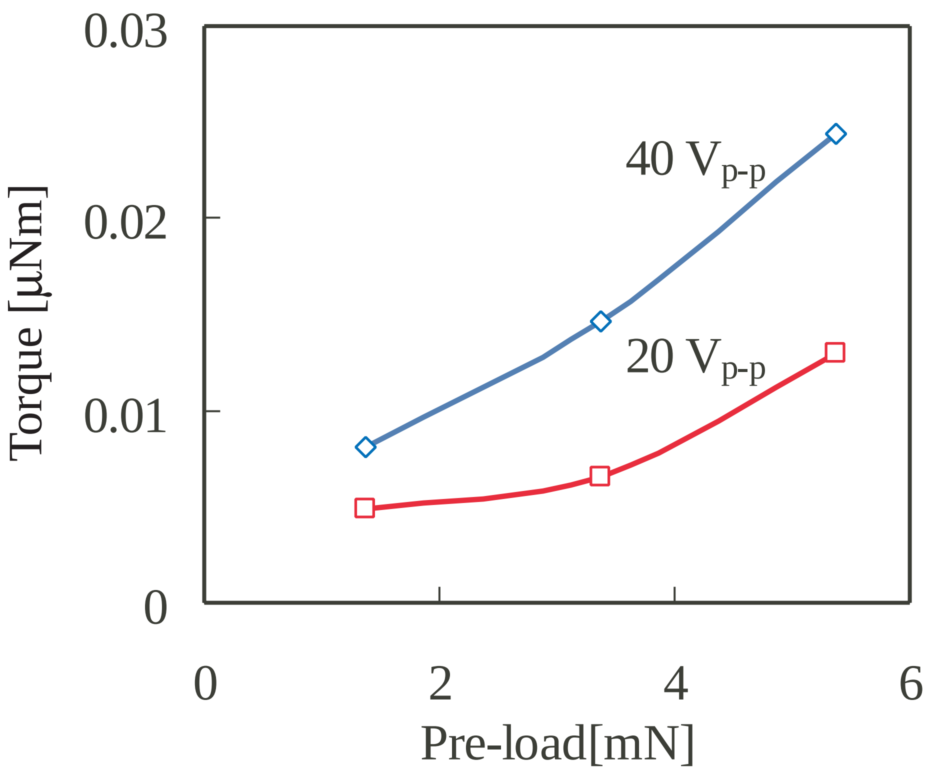


10000
8000
6000
4000
2000
0
Revolution Speed [rpm]
0
1
2
3
4
5
6
7
8
Pre-load[mN]
40Vp-p
35Vp-p
30Vp-p
25Vp-p

Figure(s)



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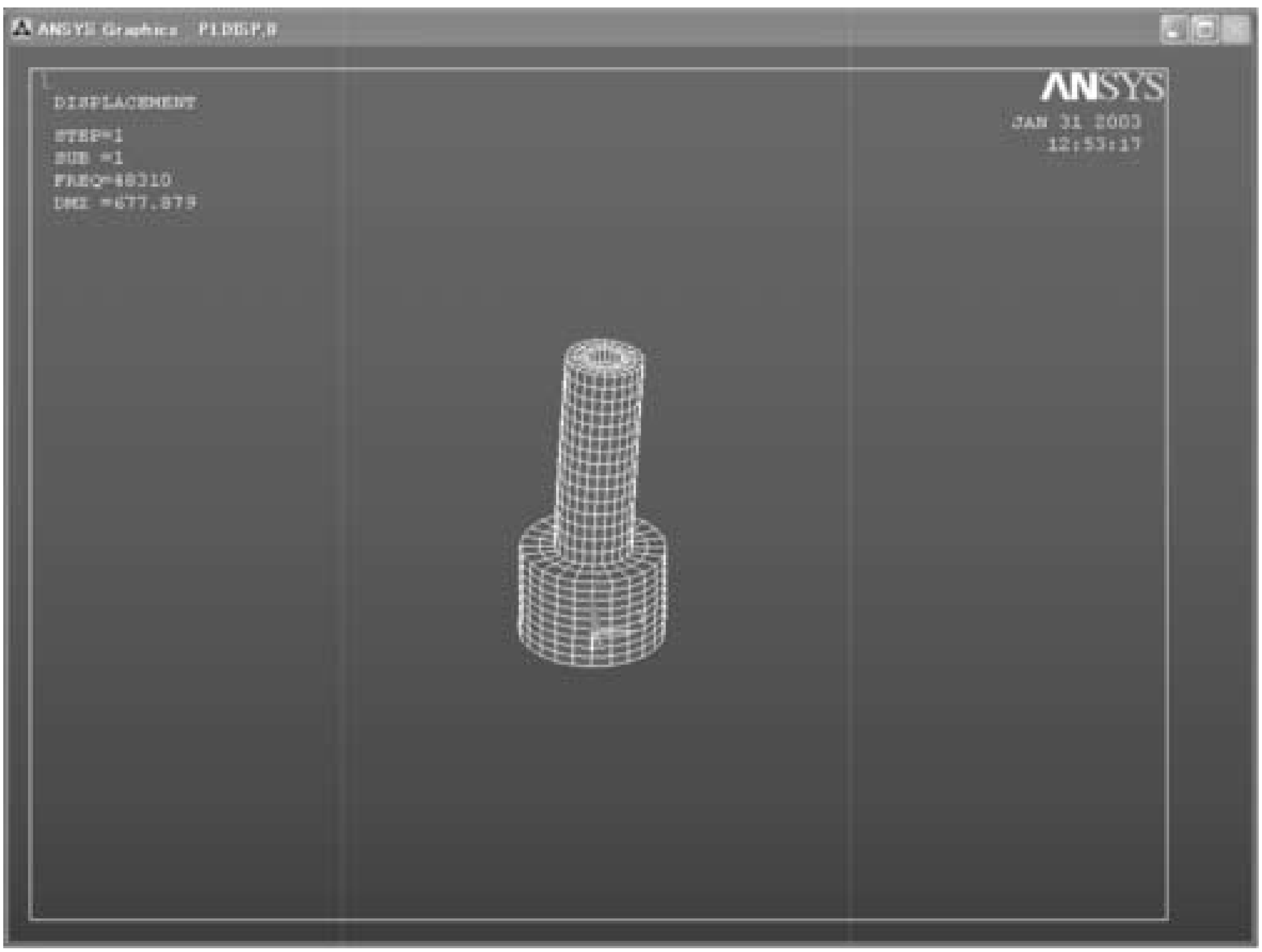

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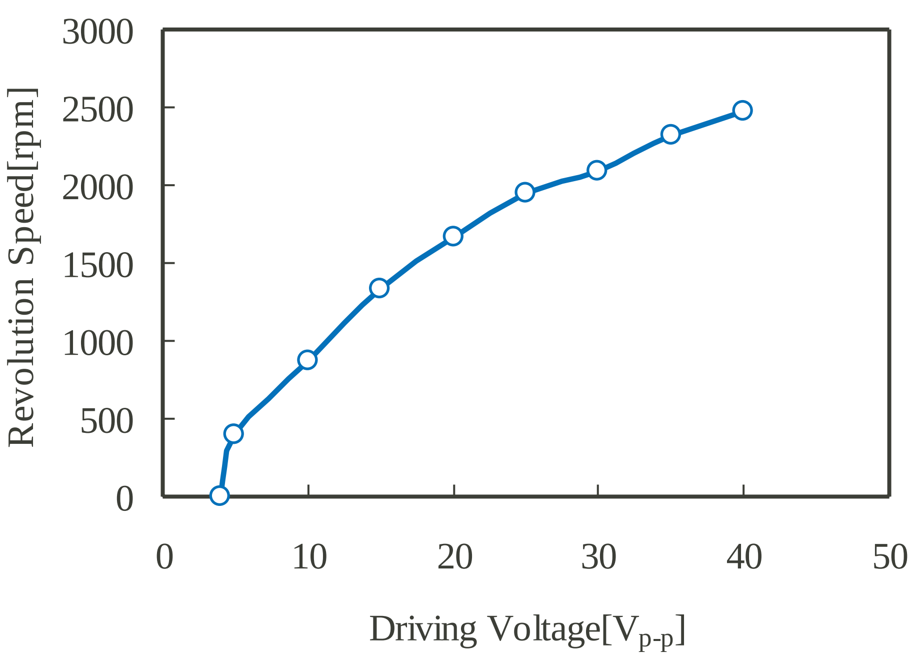

3000
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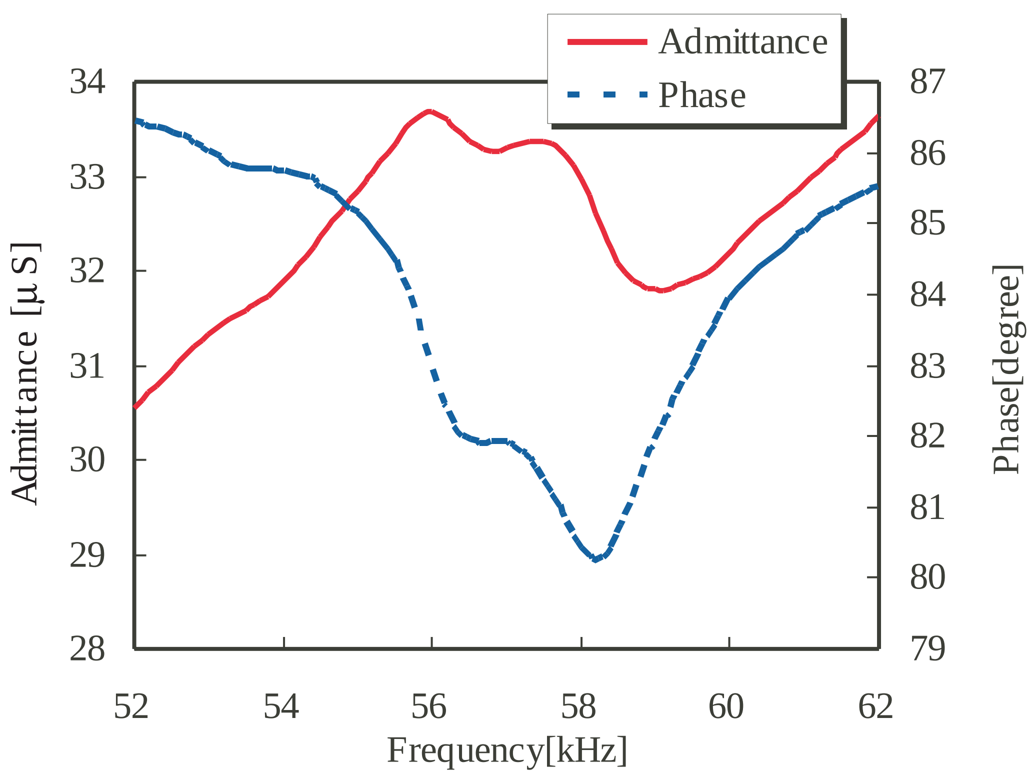
Revolution Speed[rpm]
Driving Voltage[Vp-p]

Figure(s)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Frequency[kHz]
Admittance [μS]
Phase[degree]

Figure(s)