Characteristics of an Ultrasonic Motor Capable of Generating a Multi-Degrees of Freedom Motion

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Abstract

The importance of generating a multi-degrees of freedom (DOF) motion is increasingly growing in order to develop dexterous robots. Authors developed a bar-shaped ultrasonic motor capable of generating a multi-DOF motion. The multi-DOF ultrasonic motor consists of a bar-shaped stator and a spherical rotor. The spherical rotor is rotated around three perpendicular axes by the three natural vibrations excited on the stator. In the present study, the driving and control characteristics around one driving axis, which is perpendicular to the stator's geometric axis, are measured in detail. Namely, the relationship between the frequency of the input signal and the rotational speed, the relationship between the torque and the rotational speed and the step response of the ultrasonic motor are measured. The maximum rotational speed and the maximum torque are 183 rpm and 5 mNm, respectively. The rotational speed is controlled successfully.

1. Introduction

Nowadays, the sphere of robotics is widely spreading to many fields, a medical field, an amusement field and so on. As growing such a tendency, the motion patterns of the robots are required to be more human-friendly. Namely, the dexterous-precise, multi-DOF motion is expected to the mechanisms. For designing the motion unit capable of generating a multi-DOF motion, the volume of each actuators have to be considered. If the general electromagnetic motors are used to construct the multi-DOF motion unit, the volume of the unit increases because reduction devices must be connected to the output axis to decrease the rotational speed while increasing the output torque. Additionally, the total number of motors required must be equal to the number of DOF of motion. Furthermore, such motors require electric power even when the rotor stops, in order to generate a holding torque to keep the rotor station. Thus, constructing a multi-DOF unit using general one-DOF actuators is difficult.

Because of these reasons, the actuators capable of generating the motions different from the ones of general electromagnetic motors are required to be developed to address the problems as mentioned above[1]. Some actuators meeting these requirements are proposed or developed [2][3][4], however, they are not practical at all.

On the other hand, the ultrasonic motors need no reduction device because of its characteristic of high torque at low rotational speed, and no electric power to keep the rotor station because of its characteristic of high stationary limiting torque. What is more, the ultrasonic motors offer the advantages of silence, simplicity of design, absence of electromagnetic waves, and high controllability. Because of such characteristics, the ultrasonic motors are thought to be suitable for arranging at the joints of robot arms or manipulators. However, most ultrasonic motors proposed have only one-DOF, i.e. rotational or linear motion [5][6][7]. So, if the ultrasonic motor that can generate the dexterous motion is developed, the robotics can become more widely applicable.

Because of the background as mentioned above, some multi-DOF ultrasonic motors are developed. Bansevisius [8] developed a piezoelectric multi-DOF actuator. It can generate a six-DOF motion by one stator. However, the construction of the stator (vibrator) is not simple enough for mass production. Toyama [9] developed a spherical ultrasonic motor in which three or four ring-shaped stators (vibrators) are arranged around a spherical rotor in order to generate a three- or two-DOF motion. However, the unused stators generate the excess load and heat when other stator in contact with the rotor is vibrating. Nakamura [10] proposed a bar-shaped ultrasonic motor capable of generating a three-DOF motion. It generates three-DOF actuation using only one stator, however, the structure of the stator and the contact points between the stator/rotor are not optimized. Authors [11] developed a bar-shaped ultrasonic motor capable of generating a multi-DOF motion using one stator, and confirmed its basic characteristics. However, the driving characteristics and the method to control the motor were not clear enough to make the motor practicable. So, we provide the rotational axes of the rotor around one axis that is perpendicular to the stator's geometrical axis, and study the driving characteristics and the method to control. The reason to choose the rotation around the axis as mentioned above is that its driving principle is a new idea in the history of ultrasonic motors. Furthermore, the rotation around the axis that is perpendicular to the stator's geometric axis, the elbow-shaped bend, is different from the motion patterns of general electromagnetic motors. It is profitable for the development of the robotics in itself.

In the present paper, the driving principle and the geometry of the ultrasonic motor are described in chapter 2 and 3, respectively. The driving characteristics and control characteristics of the motor are given in chapter 4 and 5, respectively. Then, in chapter 6, the conclusion and the application of the ultrasonic motor are shown.

2. Driving Principle

The ultrasonic motor is a frictionally driven motor. It usually consists of a stator and a rotor. The energy of the natural vibration of the stator is transmitted to the rotation of the rotor by the frictional force between the stator and the rotor.

The multi-DOF ultrasonic motor we developed consists of a bar-shaped stator and a spherical rotor as shown in Figure 1. Three axes shown in Fig. 1 are common by use in this paper. The multi-DOF ultrasonic motor can generate the rotations of the spherical rotor around *x*-, *y*- and *z*-axis. The driving principle is shown in Figure 2. Fig. 2 (a) shows the natural vibrating modes of the stator used when the rotor rotates around *z*-axis. Figures (i) and (iii) show the second bending mode of the stator in *z*-*x* plane (mode A), and figures (ii) and (iv) show the second bending mode of the stator in *y*-*z* plane (mode B). When these two natural vibrating modes, A and B, are combined with the phase difference of 90 degrees, the tip of the stator rotates around *z*-axis. Then, the spherical rotor in contact with the stator's head also rotates around *z*-axis by the frictional force. Fig. 2 (b) shows the natural vibrating modes of the stator used when the rotor rotates around *x*-axis. Figures (i) and (iii) show the first longitudinal mode of the stator along *z*-axis (mode C), and figures (ii) and (iv) shows the second bending mode of the stator in *y*-*z* plane (mode B). When these two natural vibrating modes, B and C, are combined with the phase difference of 90 degrees, the tip of the stator rotates around *x*-axis. Then, the spherical rotor in contact with the stator's head also rotates around *x*-axis by the frictional force, as well. The rotor rotates around *y*-axis, when mode A and mode C are combined in the same way as Fig. 2 (b).

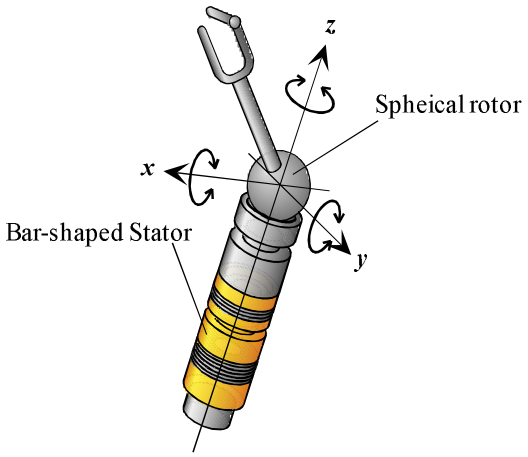
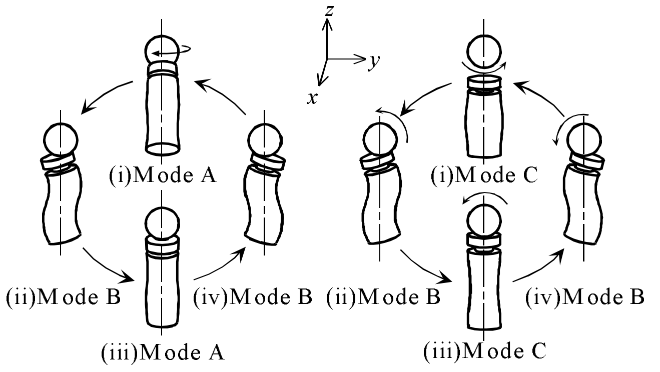


Figure 1 : Entire view of the ultrasonic motor capable of generating a multi-DOF motion



(a)When two 2nd bending modes are used (b)When a 2nd bending mode and a 1st longitudinal mode are used

Mode A : Bending mode in *z*-*x* plane
Mode B : Bending mode in *y*-*z* plane
Mode C : Longitudinal mode along *z* axis

Figure 2 : Driving principle of the ultrasonic motor capable of generating a multi-DOF motion

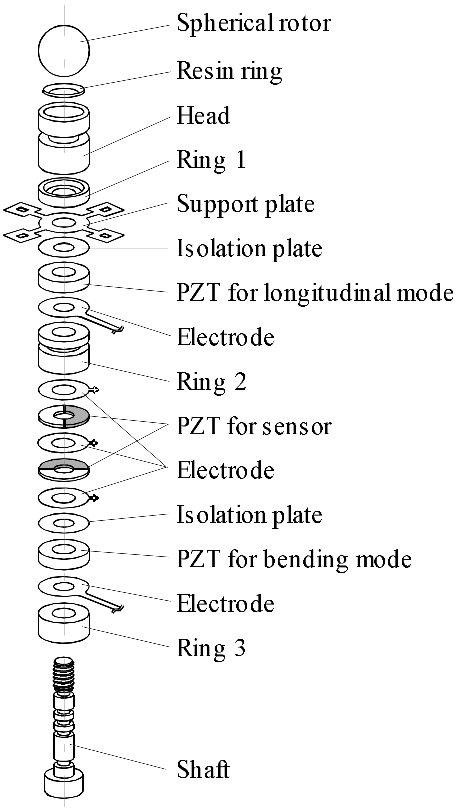


Figure 3 : Configuration of the ultrasonic motor capable of generating a multi-DOF motion

The point to notice is that the natural frequencies of these three natural vibrating modes, A, B and C, should correspond.

3. Geometry

The natural frequencies of the second bending modes and the first longitudinal mode of the bar-shaped stator should correspond, as mentioned above. So, we designed the stator by calculating the natural vibrating modes and the natural frequencies using a finite element analysis. Figure 3 is the configuration of the ultrasonic motor we developed. The stator consists of the metal rings, ring-shaped piezoelectric ceramics and shaft. The piezoelectric ceramics are used to excite the natural vibrations of the stator. The shaft is screwed up into the head. The tip of the cross-shaped support plate is fixed to hold the stator. The diameter and the height of the stator are 10 mm and 32.12 mm, respectively. The diameter of the spherical rotor is 10 mm, as well.

In order to measure the characteristics of the multi-DOF ultrasonic motor precisely, we provide the rotational axis of the spherical rotor around one axis that is perpendicular to the stator's axis. Figure 4 is the structure of the device to measure the characteristics of the multi-DOF ultrasonic motor around x-axis. The normal load between the stator and the rotor is gained by the coil spring arranged under the pedestal. The normal load is adjusted by turning the screw shown in Fig. 4. The rotational speed is measured using an optical encoder connected to the rotational axis. The output torque is measured by a weight attached to a string that is reeled to a pulley.

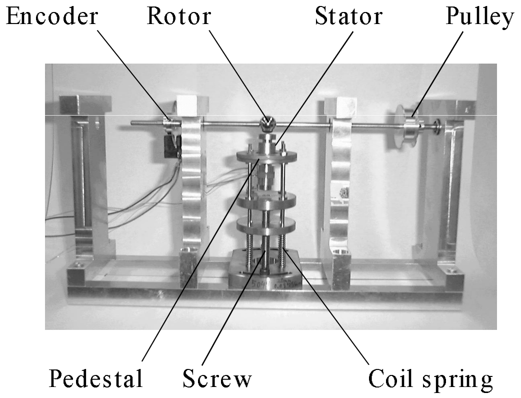


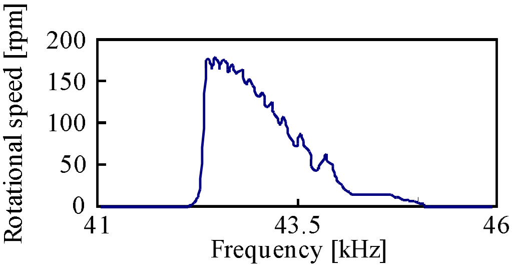
Figure 4 : Device to provide the rotational axis of the spherical rotor around x-axis

4. Driving Characteristics

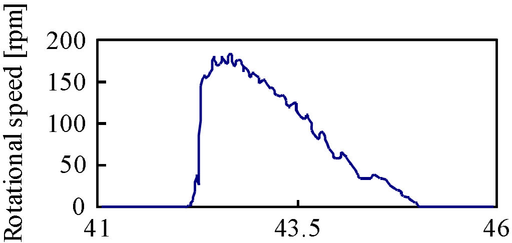
Driving characteristics of the multi-DOF ultrasonic motor around x-axis are measured using the device shown in Fig. 4. The experimental results of the driving characteristics of the ultrasonic motor are described as follows.

4.1. *f-N* Curve

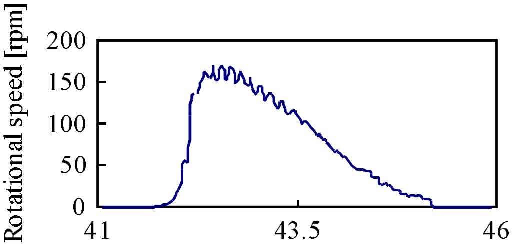
Here shows the relationship between the frequency of an input signal and the rotational speed of the rotor around x-axis (*f-N* curve). Amplitude of the input signal to excite the second bending mode is 40 Vp-p, and one to excite the first longitudinal mode is 20 Vp-p. A phase difference between these two input signals is 90 degrees. The rotational speed of the rotor is measured continuously, while the frequencies of the input signals are swept from 46 kHz to 41 kHz in 10 s. The measured *f-N* curves are shown in Figure 5. Fig. 5 (a)-(e) are when the normal load between the stator and the rotor is 10 N, 8 N, 6 N, 4 N and 2 N, respectively. The vibrations of curves depend on the



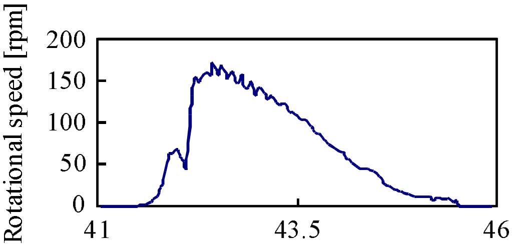
(a) Load = 10



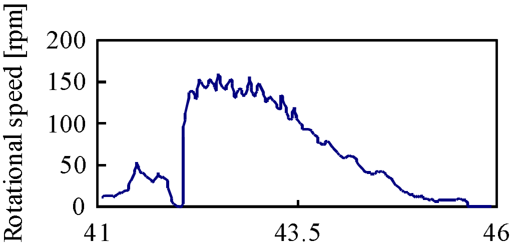
(b) Load = 8N



(c) Load = 6N



(d) Load = 4N



(e) Load = 2N

Figure 5 : *f*-*N* curve of the ultrasonic motor around *x*-axis

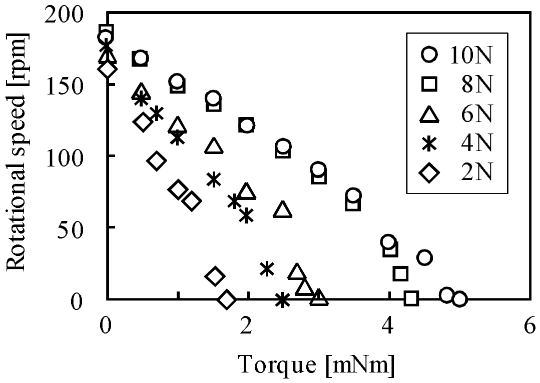


Figure 6 : *T*-*N* curve of the ultrasonic motor around *x*-axis

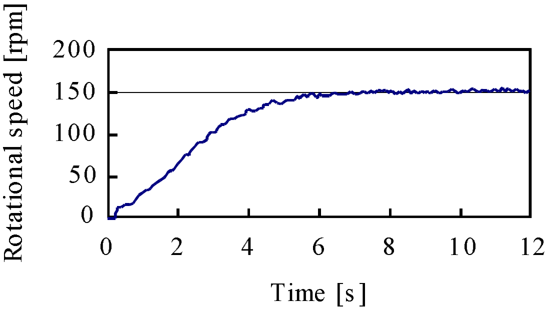
error of processing. It is seen from Fig. 5 that the maximum values of the rotational speed do not change a lot while the normal load between the stator and the rotor is changed from 10 N to 4 N. It is also seen that the range of the frequency where the motor can be driven stably is wide when the load is small.

4.2. *T-N* Curve

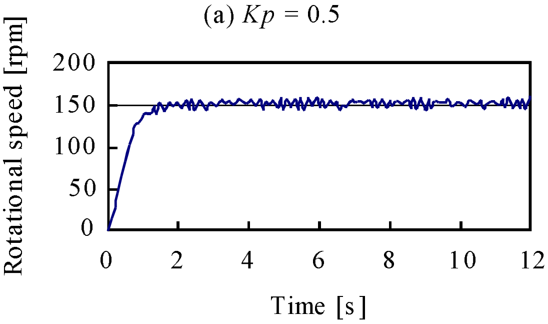
Here shows the relationship between the torque and the rotational speed of the rotor around *x*-axis (*T*-*N* curve). Amplitude of the input signal to excite the second bending mode is 40 Vp-p and one to excite first longitudinal mode is 20 Vp-p. The phase difference between these two input signals is 90 degrees, the same condition as that for measuring the *f*-*N* curve. The torque is measured using the weights attached to the pulley shown in Fig. 4. The frequencies of the input signals are equal to the natural frequencies of the second bending mode and the first longitudinal mode of the stator. The measured *T*-*N* curve is shown in Figure 6. It is seen form Fig. 6 that the rotational speed decreases when the torque increases, and that the maximum torque increases when the normal load between the stator and the rotor increases. The maximum values of the rotational speed and the torque under the present condition are 183 rpm and 5 mNm, respectively.

5. Control Characteristics

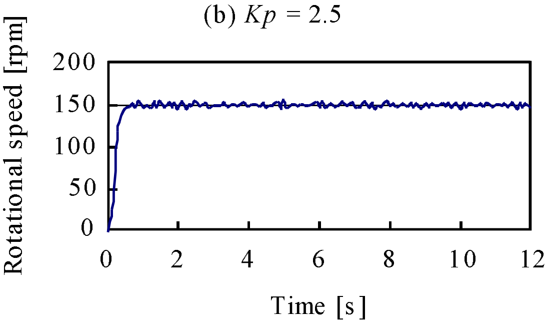
It is seen from Fig. 5 that the rotational speed of the rotor can be controlled by changing the frequency of the input signal. So, we control the rotational speed of the rotor by changing the frequency of the input signal. The frequency of the input signal are changed as,



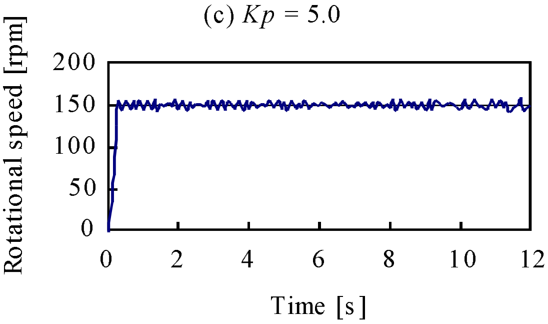
(a) *Kp* = 0.5



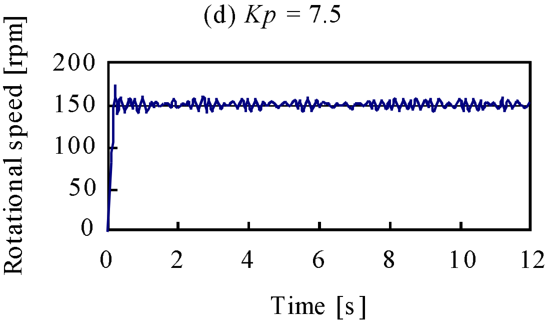
(b) *Kp* = 2.5



(c) *Kp* = 5.0



(d) *Kp* = 7.5



(e) *Kp* = 10.0

Figure 7 : Control characteristics of the ultrasonic motor around *x*-axis

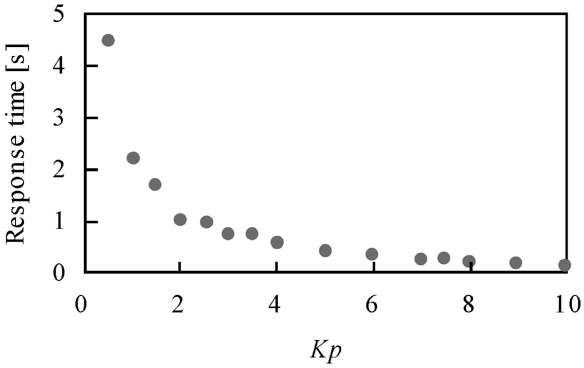


Figure 8 : Relationship between K_p and the response time

$$f_{next} = f_{now} + K_p\left(N_{now} - N_{target}\right) \qquad (1)$$

where, f_{next} is a frequency of an input signal in the next step, f_{now} is a present frequency of an input signal, K_p is a proportional gain, N_{now} is a present rotational speed and N_{target} is a target rotational speed. The amplitude of the input signals to excite the second bending mode and the first longitudinal mode are 40 Vp-p and 20 Vp-p, respectively. The phase difference between these two input signals is 90 degrees. The normal load between the stator and the rotor is 8 N. The target rotational speed is 150 rpm.

The experimental results of the step response are shown in Figure 7. Fig. 7 (a)-(e) show results when K_p is equal to 0.5, 2.5, 5.0, 7.5 and 10.0, respectively. Fig. 7 shows that the rotational speeds converge to the steady state, 150 rpm, after a sufficient time. The response time is improved as K_p increases. Figure 8 is the measured response time when K_p is varied. The response time decreases sharply as K_p increases. However, the overshoot is seen when K_p is equal to 10.0 as shown in Fig. 7 (e). In the future study, the derivative component must be added to the equation (1) to reduce the overshoot. In Fig. 7, the steady-state error does not take place. However, there remains the vibration around 150 rpm. It is due to the steady-state vibration and the eccentricity of the rotor.

6. Conclusion

In the present study, the characteristics of the multi-DOF ultrasonic motor are measured precisely. First, we made a measuring device that provides the rotational axis of the spherical rotor around *x*-axis, in order to measure the characteristics of the spherical rotor around *x*-axis. Next, the driving and control characteristics of the spherical rotor around *x*-axis are measured using the

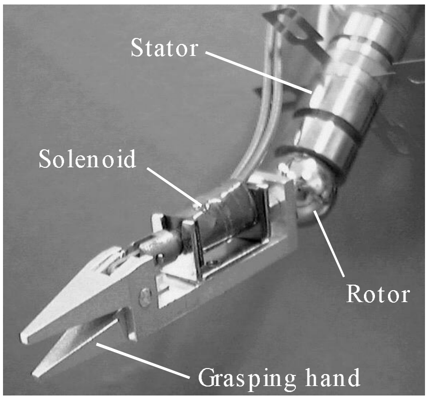


Figure 9 : Image figure of a multi-DOF forceps

device mentioned above. The result of the present study should be extended to the multi-DOF drive of the motor in our future studies.

After achieving the multi-DOF position control of the spherical rotor, we will apply the multi-DOF ultrasonic motor to the forceps for a laparoscopic surgery. The image figure of the multi-DOF forceps we propose is shown in Figure 9. The multi-DOF forceps can generate the motion similar to that of human wrists by using the multi-DOF ultrasonic motor and can generate the grasping motion by using a solenoid shown in Fig. 9. Then the dexterous manipulation under the laparoscopic surgery can be achieved, consequently.

References

[1] T. Yano, Multi-DOF Actuators, J. Robotics Society of Japan, vol. 15, no.3, pp. 300-333, 1997. (in Japanese)

[2] T. Yano, An Actuator With Multi Degree of Freedom Having an Identical Center of Rotation (10th Report) Real Time Control of the 3D stepping motor withjoystick, Proc. 17th Annual Conf. Robotics Society of Japan, vol. 3, pp.971-972, 1999. (in Japanese)

[3] R. Roth and Kok-Meng Lee, Design Optimization of a Three Degrees-of-Freedom Variable-Reluctance Spherical Wrist Motor, Trans. ASME, vol. 117, pp. 378-388, 1995.

[4] K. Sasae, *et al*, Development of a Small Actuator with Three Degrees of Rotational Freedom (2nd report) -Simulation and Experiment of a Friction Drive-, J. Japan Society of Precision Engineering, vol.61. no.4, 1995. (in Japanese)

[5] I. Okumura, A Design Method of a Bar-Type Ultrasonic Motor for Autofocus Lenses, Proc. IFToMM-jc Intl. Symp. on Theory of Machines and Mechanisms, pp. 75-80, 1992.

[6] K. Nakamura *et al.*, Ultrasonic Motor Using Free Bending Vibration of a Short Cylinder, Journal of the Acoustical Society of Japan, pp. 795-796, 1988. (in Japanese)

[7] T. Funakubo *et al.*, Ultrasonic Linear Motor Using Multilayer Piezoelectric Actuators, Japanese Journal of Applied Physics, vol.34, part 1, no. 5B, pp. 2756-2759, 1995.

[8] R. Bansevicius, Piezoelectric Multi-degree of Freedom Actuators/Sensors, Proc. 3rd International Conference on Motion and Vibration Control, pp. K9-K15, 1996.

[9] S. Toyama *et al.*, Development of an Actuator for a Robotic Manipulator with Ultrasonic Motor –2nd Development of Prototypal Spherical Ultrasonic Motor-, Journal of the Robotics Society of Japan, Vol. 13, No. 2, pp. 235-241, 1995. (in Japanese)

[10] K. Nakamura *et al.*, Designs of an Ultrasonic Actuator with Multi-degree of freedom using Bending and Longitudinal Vibrations (II), Journal of the Acoustical Society of Japan, pp. 376-377, 1998 (in Japanese)

[11] K. Takemura, N. Kojima and T. Maeno, Development of a Bar-Shaped Ultrasonic Motor for Three Degrees-of-Freedom Motion, Proc. 4th International Conference on Motion and Vibration Control, pp. 195-200, 1998.