Novel Ultrasonic Motors and Their Applications

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***Abstract*—Ultrasonic motors have been expected as a leader of new actuators since 1980th when they were invented. Author has been conducted research on analysis of characteristics of ultrasonic motors, development of novel ultrasonic motors including multi-degree-of-freedom (DOF) ultrasonic motors, and application of ultrasonic motors for robotic field. In this paper, several results are described.**

Keywords: ultrasonic motor, multi DOF ultrasonic motor, vibration, robot hand

I. INTRODUCTION

Since an ultrasonic motor was invented in 1980th, variety of ultrasonic motors have been introduced by many researchers. Method for analyzing characteristics of the motor has also been introduced by many researchers in the world. As a result, it has a large market in the field of autofocus and zoom cameras as well as car applications. However, they still have rooms for analysis of motors and development of novel motors and applications. In the present paper, results of author's recent research are shown. First, a method for analyzing transient characteristics of ultrasonic motor is shown. It is shown that the calculated results by use of non-linear vibrator model agree well with the experimental ones. Then several novel ultrasonic motors developed by author are shown. Most of them are for multi-DOF movements. Finally, several applications of the ultrasonic motors in the robotic field are shown.

II. ANALYSIS OF DRIVING CHARACTERISTICS

Steady state characteristics of ultrasonic motors were analyzed by us in 1992 [1]. Steady state stands for the condition that vibration amplitude of the vibrator (stator) and the rotational speed of the rotor (or speed of linear slider) are constant. However, transient response, i.e. rotor/stator dynamics of starting and stopping condition, has not been clarified yet. Hence, authors have made the model taking into account the electrical-mechanical conversion by piezoelectric ceramics, non-linear vibration of the stator, and non-linear energy conversion at the contact surface between the rotor/stator. Calculated results are compared with the measured ones. Fig. 1 shows a calculated and measured frequency response of the vibrator of the bar-type ultrasonic motor when the input voltage is changed. Both of them agree well. Fig. 2 shows a comparison between calculated and measured transient response of ultrasonic motor when the driving frequency of the stator is changed. It is shown that both of them agree well.

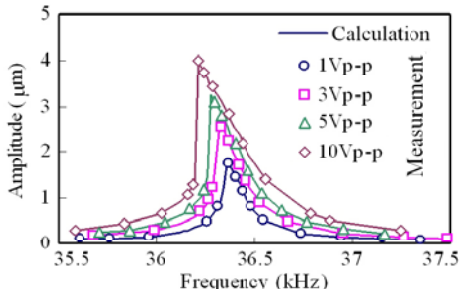


Fig. 1 Calculated and measured frequency response of the vibrator of the bar-type ultrasonic motor

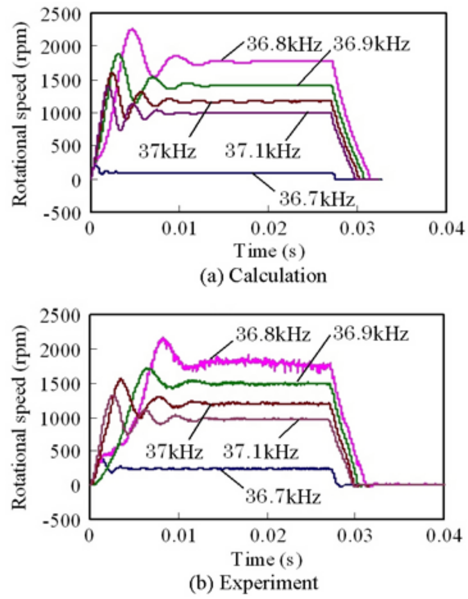


Fig. 2 Comparison between calculated and measured tangent response of ultrasonic motor

We can conclude that the proposed model is useful for clarifying the starting/stopping characteristics of the ultrasonic motors. It can be used to design the motor and to control the motors in optimum condition.

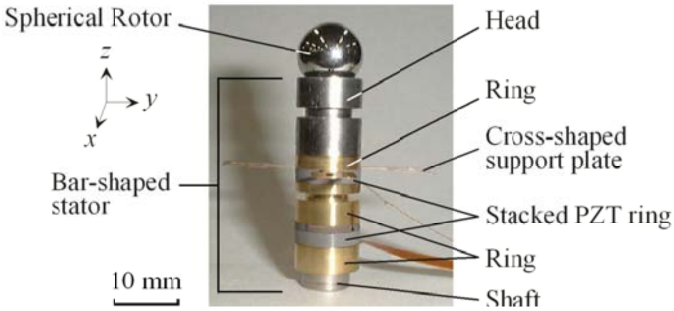


Fig. 3 Bar-type multi-DOF ultrasonic motor

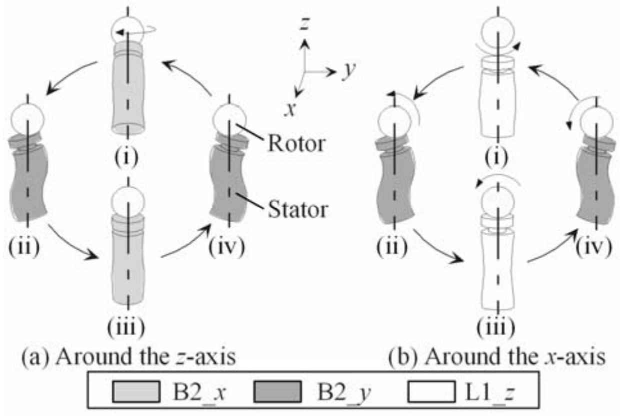


Fig. 4 Driving principle of the bar-type multi-DOF ultrasonic motor

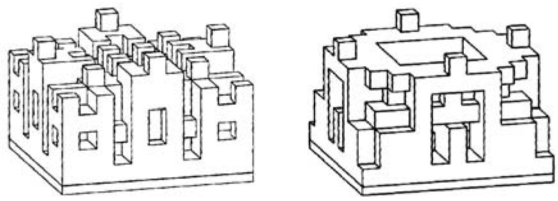
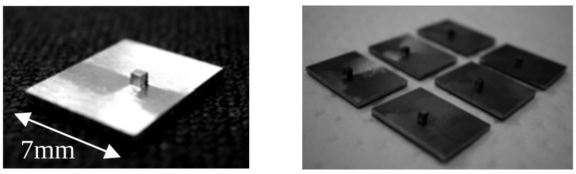


Fig. 5 Cubic multi-DOF ultrasonic motor designed by use of genetic algorithms



(a) Overview of a vibrator (b) Layouts of the vibrators

Fig. 6 Multi-vibrator-type miniature multi-DOF ultrasonic motor

III. DEVELOPMENT OF NOVEL ULTRASONIC MOTORS

Authors have suggested several types of new ultrasonic motors. One is a bar-type multi-degrees-of-freedom (multi-DOF) ultrasonic motor as shown in Fig. 3 [2].

Driving principles of the bar-type multi-DOF ultrasonic motors are shown in Fig. 4. Two second bending modes and a first longitudinal mode are made to have almost the same natural frequencies. As shown in Fig. 4 (a), when the two bending modes are excited, rotor rotates around the *z*-axis. When one of the bending modes and the longitudinal mode are excited simultaneously, rotation around *x*- or *y*- axis can be obtained as shown in Fig. 4 (b).

In the above motor, it was not difficult to select three natural modes because it is obvious that those three modes are perpendicular each other at the contact surface at the top of the stator. If we desire to design multi-DOF ultrasonic motors having arbitrary geometry, it is difficult to decide the geometry of the stator and to select adequate natural modes simultaneously.

For example, authors have made a multi-DOF ultrasonic motor with the vibrator (stator) made of a rectangular plate [3]. However, the vibration modes have not been optimized, i.e., axes of the elliptical motion at the contact surface was not perpendicular each other. Hence, authors have proposed a method for designing a stator for a multi-DOF ultrasonic motor by using genetic algorithm (GA) [4]. Numbers of finite element model of the stator is made composed of cubic finite element having the same size. After judged if the models are adequate to be driven as multi-DOF ultrasonic motors, we conduct genetic operations including mutation, cross over and selection. By repeating this procedure, we finally obtain the optimum solution. Note that the emergent geometry that is not easy to come up in designers' mind can be obtained. Examples of stators of multi-DOF ultrasonic motors designed using GA are shown in Fig. 5. Geometries are still too complicated. So the detailed design is needed to make the stators easier to be produced.

Above mentioned multi-DOF ultrasonic motors are driven by use of elliptic motion of the contact surface of the stator. The elliptic motion is produced by selecting two natural modes out of three natural modes. Hence, we have to design the stator so that three natural frequencies agree. On the other hand, there exists another type of ultrasonic motor without using elliptic motion of the stator. They utilizes only one vibration mode. Contact point of the stator poke the rotor (slider) like a woodpecker. Fig. 6 is such a multi-DOF ultrasonic motor [5]. Four natural modes having different vibration direction at the projection are used. When one of the modes is selected, rotor (slider) can be driven in the desired direction. By switching the selected mode, we can rotate the rotor (slider) around arbitrary axis.

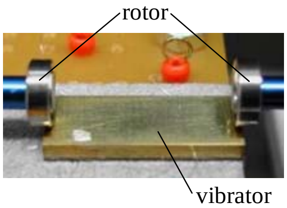


Fig. 7 Multi-DOF ultrasonic motor having twin-rotor

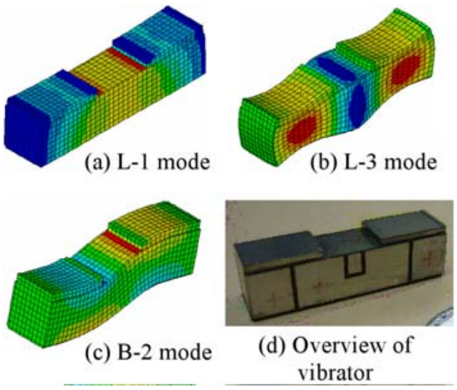


Fig. 8 Linear ultrasonic motor by use of rectangular wave

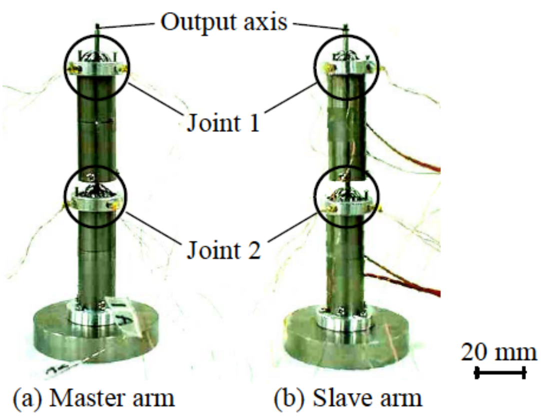


Fig. 9 Multi-DOF Master-slave system using Multi-DOF ultrasonic motors

Above mentioned multi-DOF ultrasonic motors are for driving a spherical rotor in arbitrary direction. We also designed a multi-DOF ultrasonic motor with which two rotors can be driven in arbitrary directions [6]. Fig. 7 shows a picture of multi-DOF ultrasonic motor having twin-rotor. Driving principle is as follows: Natural frequencies of a first bending mode and a first torsional mode of a plate-shaped vibrator are made to be the same. Also a natural frequency of a second torsional mode is made to be twice that of the first torsional mode. When the first bending mode and a first torsional mode are excited with a phase difference of 90 degrees, elliptic vibration in the opposite direction is made at the both end of the upper surface of the bar-shaped vibrator. Hence, the two rotors shown in Fig. 7 rotate in the opposite direction along the longitudinal axis of the bar-shaped vibrator. When the first bending mode and the second torsional mode are excited with a phase difference of 90 degrees, 8-shaped vibration in the same direction is made at the both end of the upper surface of the bar-shaped vibrator. Hence the two rotors rotate in the same direction. If the three modes are excited simultaneously, arbitrary ratio of speed between the two rotors can be obtained.

Another research topic on the design of vibrator is to make a vibrator with less frictional loss, less wear and larger efficiency. One of the major subjects of ultrasonic motors that is expected to be solved is a velocity distribution of the contact point of the vibrator in contact duration with the rotor. As a contact point on the vibrator draws an elliptic locus, tangential velocity of the vibrator changes as a sinusoidal wave. When the velocity of the vibrator is smaller than that of the rotor surface point, dynamic friction force opposite to the direction of the rotor movement is produced at the surface of the vibrator. When the velocity of the vibrator is larger than that of the rotor surface point, direction of the dynamic friction force and the rotor movement becomes the same. In the both case frictional power loss proportional to the friction force times the relative velocity between the rotor and the vibrator is produced. It becomes the reason of wear and low efficiency.

Hence, we have suggested a linear ultrasonic motor whose wave shape in tangential direction is trapezoidal instead of sinusoidal, because the trapezoid has constant velocity [7]. Fig. 8 shows vibration modes to produce the trapezoidal wave. If we add the first longitudinal mode (L-1) and the third longitudinal mode (L-3), we can obtain approximately trapezoidal wave in tangential direction. The second bending wave (B-2) is for sinusoidal wave in normal direction. Now we are trying to measure the efficiency of the constructed motor to prove that the designed vibrator is adequate.

IV. APPLICATIONS FOR ROBOTS

We are not only suggesting novel ultrasonic motors but also suggesting several applications in robotic field. We developed a master-slave system for active endoscope using multi-DOF ultrasonic Motors [8] as shown in Fig. 9. By using two ultrasonic motors described in Fig. 3 and Fig. 4, we made a six-DOF master-slave system. It is for use in active endoscope.

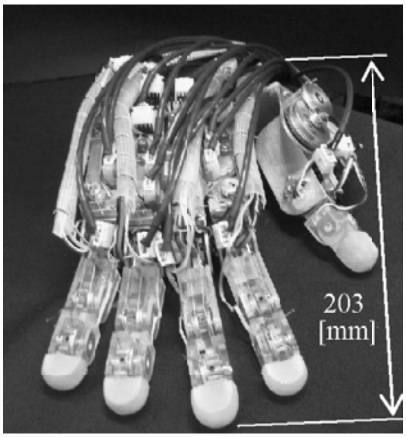


Fig. 10 Five-fingered robot hand using 20 ultrasonic motors

Fig. 10 shows a five fingered robot hand driven by 20 ultrasonic motors. Each finger has five degrees of freedom. The size is about the same as that of human hands. As ultrasonic motor has characteristics such as rapid response, large torque and silence, it is adequate for robot hand. Speed of fingers is faster than that of humans. So this hand is adequate for use in master-slave system for remote control in the medical and extreme environment. We are planning to construct a master-slave system to show the applicability of our hand to dexterous manipulation.

V. CONCLUSIONS

In the present paper, author's recent researches were shown. First, a method for analyzing transient characteristics of ultrasonic motor was shown. It was shown that the calculated results by use of non-linear vibrator model agree well with the experimental results. Then, several novel ultrasonic motors developed by author were shown. Most of them are for multi-DOF movements. Finally, several applications of the ultrasonic motors for robots were shown. I believe that analysis of ultrasonic motor, development of novel ultrasonic motors and development of novel applications of the ultrasonic motor are important for progress of the ultrasonic motors.

ACKNOWLEDGMENT

This research is supported-in-part by the grant-in-aid for scientific research on priority areas, No. 438, “Next-generation actuators leading breakthroughs”.

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