AN ACTIVE DUMMY HEAD DRIVEN BY A MULTI-DEGREE-OF-FREEDOM ULTRASONIC ACTUATOR

S. Niwano[a], C.-H. Yun[a], J. Friend[a], K. Nakamura[a], S. Ueha[a] and T. Hirahara[b]
[a]Precision and Intelligence Laboratory, Tokyo Institute of Technology, Japan
[b]NTT Communication Science Laboratories, NTT Corporation, Japan
niwa34@sonic.pi.titech.ac.jp

Abstract

For researches on human hearing system, a quiet actuator is required to turn a dummy head around all three orthogonal axes in the same way as real human head. However, in the conventional system, many electromagnetic motors with gears or pulleys were used for multi-degree-of-freedom (MDOF) motion. A high level of audible noise is a trouble in the sound measurement as well as the complicated and heavy system. This study presents an application of the MDOF ultrasonic actuator for this purpose, considering the advantages of the ultrasonic actuator in noise radiation and output force. We introduced a new holding system composed of a Teflon plate and a ball bearing for the ball rotor, and succeeded in reducing the sound pressure level down to 10 dB in the frequency range of 100 Hz to 10 kHz, and a sufficient output torque to drive the dummy head. 2.5 kgf･cm for horizontal rotation and 5 kgf･cm for vertical rotation were achieved. Next, we tried to eliminate the inter-modal coupling by inserting inductors in the electrical port of the transducer, and finally we successfully reduced the coupling and achieved a high controllability.

1. Introduction

Multi-degree-of-freedom (MDOF) motion is required in many industrial applications such as robot arms, manipulators and optical measurement systems. The authors have proposed the ultrasonic actuator which is designed for MDOF motion of ball rotor. Three orthogonal vibrations, one longitudinal vibration and two bending vibrations, can be excited by one transducer [1-2]. For some researches on human hearing system, MDOF motion is required to turn a sound measuring dummy head. In the previous studies, the electromagnetic MDOF actuator has been used for driving the sound measuring dummy head [3]. Reduction gears or pulley system are required for the electromagnetic motors to drive the dummy head, and generate noise over 40 dBSPL. The noise radiation is a fatal problem for the study of human hearing system. The MDOF ultrasonic actuator does not need gears and it is operated at over 20 kHz. The ultrasonic system does not generate audible noise theoretically. However, in practice, friction noise generated in the rotor-transducer or rotor-holder contact surface will become a problem, and output force of the prototype was not sufficient to turn the dummy head. Although some studies have been performed with a preload by a permanent magnet [2], the preloading force was so weak that high torque characteristics could not be achieved. In the practical system, the controllability of the rotation direction of the rotor is lowered by unnecessary vibration caused by the coupling between the two vibration modes.

First, this study presents a new support mechanism, in order to gain the output force to drive the dummy head without losing its free MDOF motion. Second, the noise of the prototype actuator installed in a dummy head is measured and discussed. Next, we tried to eliminate the inter-modal coupling experimentally by separating the resonance frequency by inserting inductors in the electrical port.

2. Structure and the Operating Principle

Figure 1 shows the configuration of the MDOF ultrasonic actuator to be discussed in this paper. The actuator consists of a cylindrical stator and a spherical rotor [1]. The stator has two types of piezoelectric elements (PZTs) to excite the 1st longitudinal vibration and the 2nd bending vibration independently. The longitudinal vibration has displacement along the *z*-axis, while the bending vibrations have displacement in the *x*-*z* and *y*-*z* planes. By combining two of the three vibration modes, the actuator can generate the rotations about the *x*, *y* and *z*-axes. The ball rotor is put onto the stator surface to be driven through the friction force. When the longitudinal vibration and the bending vibration in *y*-*z* plane or *x*-*z* plane are exited with adequate phase difference, the ball rotor rotates about the *x* or *y*-axis. When the two bending vibrations are excited with the phase difference of 90 degrees,

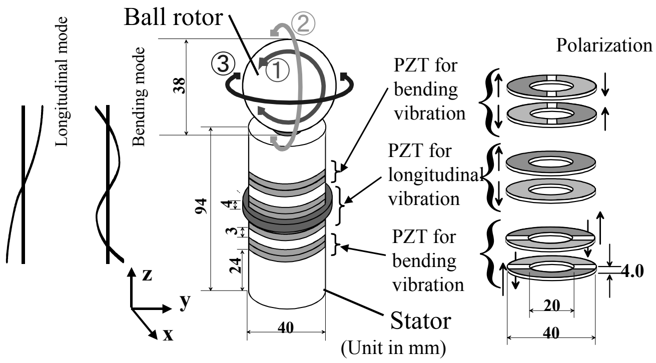


Figure 1: Motor configuration and the ball rotor rotation.

the ball rotor rotates about the *z*-axis. The longitudinal vibration is excited with the uniformly polarized PZT, and the bending vibrations are excited with the PZT whose polarization is reversed in the half portion. To drive the two bending vibrations independently at right angles, two sets of the PZT are installed at right angles to each other.

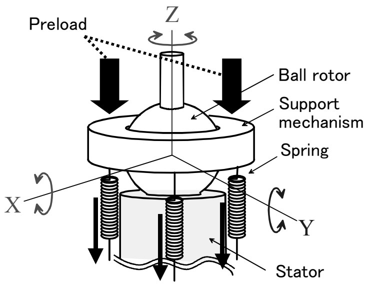
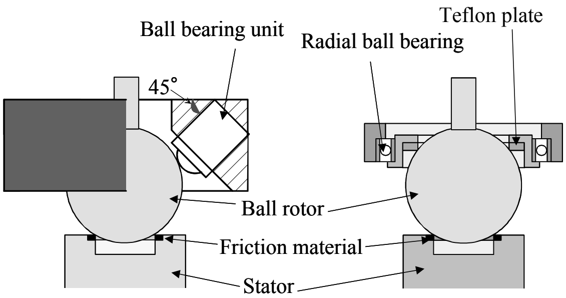


Figure 2: Holder for pre-loading.



(a) (b)

Figure 3: Support mechanism using:
(a), three ball bearing units; (b), a Teflon plate.

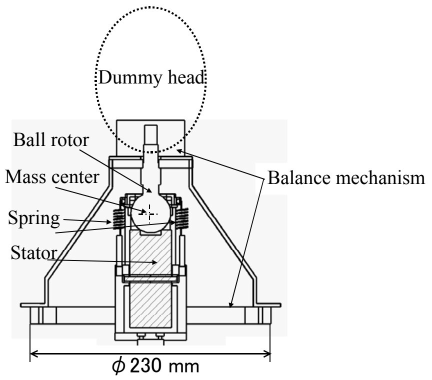


Figure 4: Dummy head system.

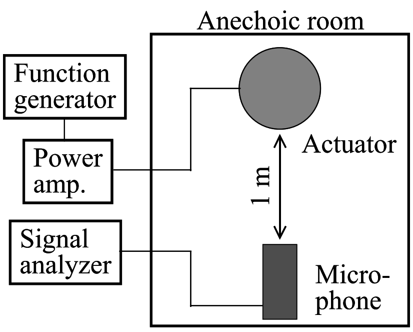


Figure 5: Sound pressure level measuring system.

3. Support Mechanism for the Ball Rotor

A ball rotor pressed onto the stator surface is driven by the frictional force between the ball rotor and the stator surface. To generate a larger output torque, new preloading systems illustrated Figs. 2 and 3 are examined.

Three coil tension springs pull down the support mechanism and a ball rotor to the stator surface with a large static force as shown in Fig. 2. In Fig. 3 (a), three ball bearing units allow the ball rotor to rotate in all directions. In Fig. 3 (b), while the *x* or *y*-axis rotations are possible by using slide contact between the Teflon plate and the ball rotor. To reduce the resistance to the *z*-axis rotation, we employed a radial ball bearing for the *z*-axis rotation.

To turn a dummy head effectively by the present actuator, we adjusted the center of gravity of the dummy head to the center of the ball rotor by attaching a counter weight as shown in Fig. 4.

4. Noise Characteristics

Though the ultrasonic transducer itself generates no audible sound, the friction at the rotor-transducer or rotor-holder contact surface generates audible noise in practice. We measured the sound pressure level (SPL) and evaluated the two kinds of support mechanisms.

The SPL with preload by the two kinds of support mechanisms were measured. Figure 5 shows the composition of the noise measurement system. The actuator was operated in an anechoic room, and the instruments such as amplifier were placed exterior of the room. The SPL was measured by using a microphone (NL32, Rion) which located 1 m away from the actuator. Output of the microphone was analyzed by a frequency analysis machine (SA-01A, Rion). These measurements were performed over the frequency range from 20 Hz to 20 kHz.

Figures 6 (a) and (b) show the FFT analysis results and 1/3-octave band analysis results. The noise floor level of the anechoic room is also plotted in the figures. These are the results when the actuator rotated about the *x*-axis. The results of other rotations, *y* and *z*-axes, were almost the same as this result. Driving frequency was 22.45 kHz and the input voltage was 100 $V_{0\text{-}P}$. The ball rotor was preloaded with 15 kgf. The SPL for the support mechanism with three ball bearing units was about 40 dB in the range of 0.1 to 10 kHz because of the noises of rotating ball bearings, while less than 10 dB for the support mechanism with the Teflon plate radiates.

Figures 7 (a) and (b) show the torque characteristics. We achieved an enough output torque to drive the dummy head, 5 kgf･cm for the *x* or *y*-axis rotation (Fig. 7 (a)) and 2.5 kgf･cm for the *z*-axis rotation (Fig. 7 (b)) by using the present support mechanism.

5. Improvement of the Controllability by Eliminating the Inter-Modal Coupling

In the practical system, the unnecessary vibration caused by the coupling between the two vibration modes affects the rotation direction of the ball rotor. This phenomenon spoils the controllability of the ball rotor. The method for changing the resonance frequency of a piezo-electric transducer by inserting an inductor in the electrical port has been reported [4-5], and the technique has been utilized to suppress the unnecessary vibration in the same-phase drive-type ultrasonic motor [6]. In this section, let us discuss the experimental elimination of the inter-modal coupling in the MDOF actuator being based on the same method.

5.1 Eliminating the inter-modal coupling by inserting inductor

The actuator is designed so that the resonance frequencies of the three vibration modes may become almost equal, and all the modes can be excited at the same frequency. This design causes undesirable excitation of the mode to be cut off, and the rotation axis of the ball rotor is deviated from the required direction. We call this phenomenon ‘inter-modal coupling’, and examined the use of inductor for the PZT of the vibration which is unnecessary, and reduced the coupling by shifting the resonance frequency temporarily.

5.2 Experimental Result

Figure 8 shows the shift of the resonance frequency of the transducer by changing the inductance of the inductor. Both the results calculated by the circuit simulator PSpice (Cadence Inc.), and the measured results by an impedance analyzer (HP 4192A, Hewlett Packard) are plotted in the figure. The equivalent circuit of the transducer and its constants are shown in Fig. 9 and Table 1, respectively. The resonance frequency becomes low as the inductance increases. On the other hand, as the inductance increases the resonance frequency of the higher order mode is approaching the resonance frequency of the 2nd bending vibration. 6 mH is suitable for this purpose, since the separation of the 2nd bending mode is sufficient, and the higher mode is also apart enough.

To confirm the effect of the inductor, we excited the PZT for *y*-*z* plane bending vibration alone and measured the vertical vibration velocity at the stator surface as shown in Fig. 10. A laser Doppler vibrometor CLV 1000 (PI Polytec Corp.) was used for this measurement. We measured two phases; one is at 0 degrees and the other is at 90 degrees on the stator surface. In the *y*-*z* plane bending vibration, the vibration becomes its maximum at 0 degrees phase and the null at 90 degrees phase theoretically. The measured results are shown in Fig. 11.

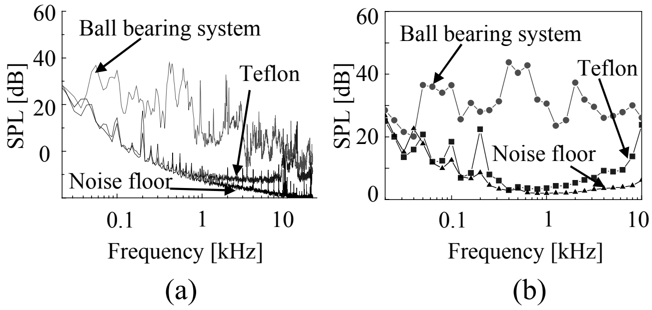


Figure 6: Frequency characteristics of sound pressure level measured for the different support mechanisms: (a), FFT analysis; (b), 1/3oct. band analysis.

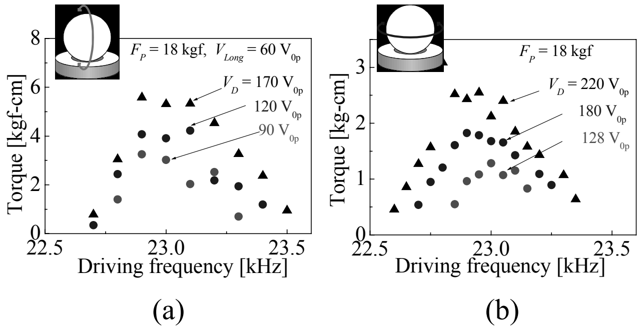


Figure 7: Torque characteristics: (a), *x* or *y*-axis; (b), *z*-axis.

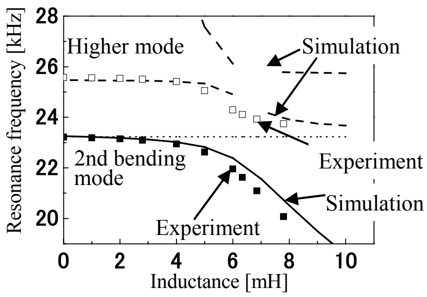


Figure 8: Resonance frequencies vs. the inductance.

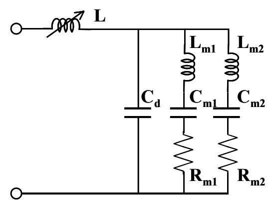


Figure 9: Equivalent circuit.

Table 1: Equivalent circuit constants.

	bending vibration mode	
	Mode 1	Mode 2
C_d	7.03 nF	
L_m	492 mH	1.77 H
C_m	95.2 pF	21.9 pF
R_m	80.95 Ω	2.71 kΩ

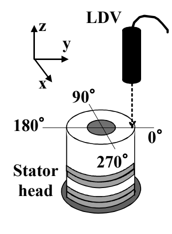


Figure 10: Experimental setup.

At the 0 degrees phase, the vibration velocity was independent of the inductance and about 1.0 m/s, while at the 90 degrees phase, it was depend on the inductor and became its minimum at 6 mH. If we increased the inductance beyond 6 mH, the vibration at 90 degrees phase became larger gradually due to the effect of the higher vibration mode.

Next, we excited the longitudinal vibration alone or *y*-*z* plane bending vibration alone, and measured the vertical vibration velocity along with the stator surface as same way to Fig. 10. Figures 12 (a) and (b) show the experimental results of when generated the longitudinal vibration and when generated the *y*-*z* plane bending vibration, respectively. As shown in Fig. 12 (a), when the inductor was not inserted and generated the longitudinal vibration alone, the vibration velocity of the stator surface was uneven.

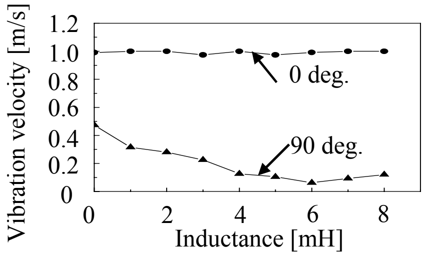


Figure 11: Vibration velocity vs. the inductance.

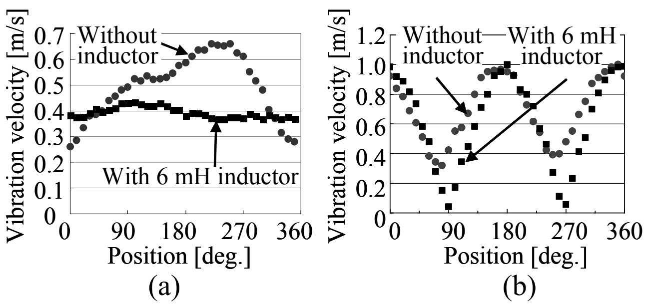


Figure 12: Vibration velocity vs. the angular position: (a), longitudinal vibration; (b), bending vibration.

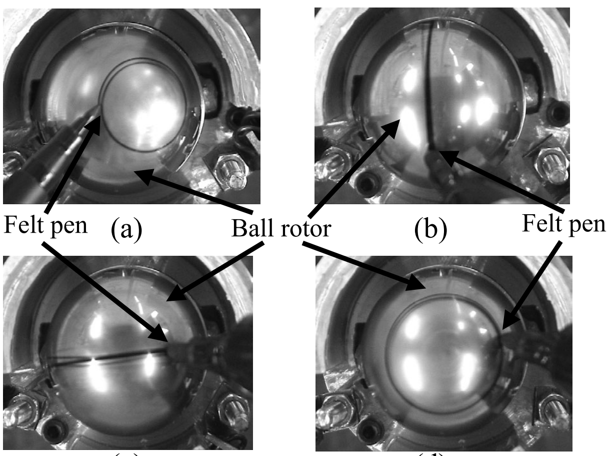


Figure 13: Pictures of the ball rotor orbit: (a), about the *y*-axis with coupling; (b), about the *y*-axis; (c), *x*-axis; (d), *z*-axis.

This is considered that the unwanted vibration mode was excited. When the 6 mH inductor was inserted in the electrical ports of the two bending vibrations, the vibration velocity became uniform. As shown in Fig. 12 (b), when the inductor was not inserted and generated the *y*-*z* plane bending vibration alone, 90 and 270 degrees phase generated vibration almost 30% of 0 and 180 degrees phase. When the 6mH inductor was inserted in the electrical port of the *x*-*z* plane bending vibration, the vibration velocity of 90, 270 degrees phase downed to almost 0. By reducing the unwanted vibration, we obtained precise three axes rotation of the ball rotor.

To visualize the rotation of direction of the ball rotor, a felt pen was put on the revolving rotor. The results are shown in Figs. 13. These are the pictures from upside of the rotor. If we operate ball rotor about the *y*-axis without the inductor, the rotation is not about the axis as shown in Fig. 13(a). With the inductor, the rotor rotates exactly about the axes, as shown in Figs. 13 (b), (c) and (d).

6. Conclusion

To achieve a quiet and high torque MDOF motion with high controllability for an active dummy head, an ultrasonic actuator has been introduced. We developed a new support mechanism in this report, and measured the radiated noise. Low sound pressure level of 10 dB in the range of 0.1 to 10 kHz has been achieved when the ball rotor was preloaded by the Teflon plate. Enough output torque to drive the dummy head, 2.5 kgf・cm for *z*-axis rotation and 5 kgf・cm for *x* or *y*-axis rotation, was obtained. Also, we tried to eliminate the inter-modal coupling by inserting inductors in the electrical ports of the transducer, and finally we successfully reduced the coupling and achieved a high controllability.

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