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Study on spherical shell-like stator for weight reduction of spherical ultrasonic motor

球面超音波モータの軽量化のための球殻ステータの検討

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1. Introduction

Multi-degree-of-freedom (MDOF) actuators using various operating principles have been researched. Among them, an MDOF ultrasonic motor has some characteristics; noiseless, high torque at low speed, and self-holding power without electric power. The authors developed the MDOF spherical ultrasonic motor (MDOF-SUSM) using the spherical stator. This motor has advantages that any rotation axes can be formed, and that there are no restrictions on the shape and material of a rotor. In previous research, the spherical stator has realized 3-DOF drive.[1)]

This paper proposes the weight reduction of the MDOF-SUSM using the spherical stator. A use of a spherical shell-like stator for the weight reduction was attempted. Two prototype models were devised and verified experimentally.

2. Operating principle

The MDOF-SUSM treated in this study is categorized a kind of the mode-rotation type motor. **Figure 1** shows the contact mechanism in the case of the mode-rotation generated on the spherical stator using piezoelectric (PZT) plates. The mode-rotation forms an elliptical displacement motion on the spherical surface. Hence the friction drive force is generated between the stator and rotor. The rotor can rotate in any directions by changing the direction of the mode-rotation.

The mode-rotations can be generated by several resonance vibration modes giving 90-degree time phase difference. Resonance vibration modes are excited by giving suitable stress for each mode[2)].

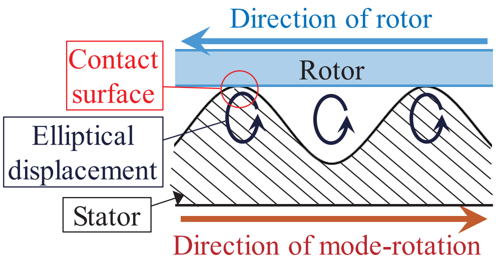

Fig.1 Contact mechanism.

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3. Spherical shell-like stator

3.1 Vibration mode and SUSM structure

An SUSM using the precessional mode-rotation around three orthogonal axes was considered. **Figure 2** shows the l2m1-mode of spherical shell stator used for mode-rotations. The l2m1-mode can be excited by two opposing PZT rings with four electrodes which are polarized in thickness direction, as shown in **Fig. 3**. When other opposing PZTs are excited with 90-degree time phase difference, the mode is rotated. **Figure 4** shows the SUSM using the spherical shell stator mode of stainless steel. The diameter and thickness of the spherical shell are 50 mm and 0.8 mm, respectively. Holes 4mm diameter are bored on the spherical shell to take electric wires out. The PZT ring and that divided in two are adhered inside the spherical shell. The spherical shell stator weighted 256 g, which was 71.2% lighter than the spherical stator 889 g in weight and 50.8 mm in diameter.[2)] The magnet was used as a rotor and pre-load adjustable by the number of thin plastic board.

3.2 Measurement and examination results

Figure 5 shows an example of measuring the vibration displacement of l2m1-mode of the stator. Electrodes used for the excitation, and measurement line are shown in **Fig. 5(a)**. The displacement in radial direction was measured by Laser Doppler Vibrometer (LDV). As a result, the maximum displacement of about 0.05 μm was obtained when input voltage was $60V_{p\text{-}p}$, and the measured displacement distribution indicated as l2m1-mode, as shown in **Fig. 5(b)**. In the examination, a slight rotation of x(y)-axis was observed at the exciting frequency of 21,550Hz, and applied voltage of $100V_{p\text{-}p}$. The z-axis rotation could not be observed.

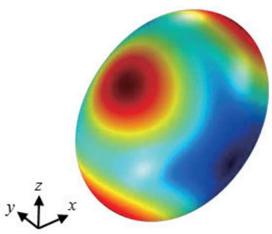


Fig.2 l2m1-mode of sphere.

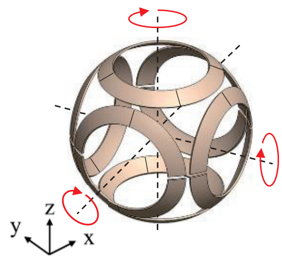


Fig.3 Rotation direction and PZTs arrangement.

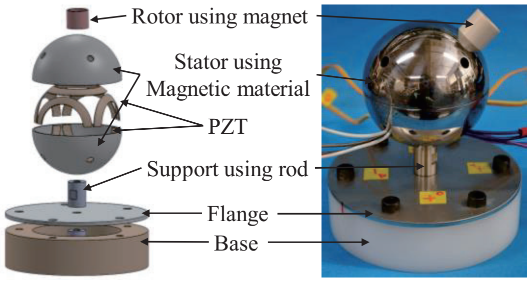
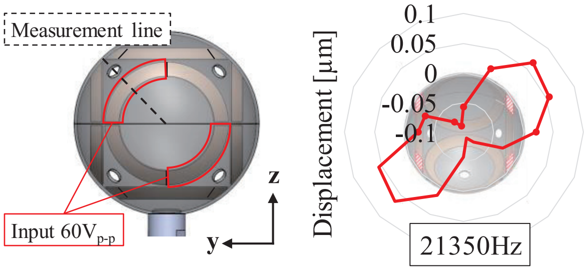


Fig.4 MDOF-SUSM using spherical shell stator.



(a)Condition. (b)Result.
Fig.5 Vibration displacement measurement.

4. Hemispherical shell-like stator

4.1 Vibration mode and SUSM structure

Since the spherical shell stator was too weak, the MDOF-SUSM using the hemispherical shell stator was considered to increase the rotation force. The stator uses l2m1-mode and l1m0-mode shown in **Fig. 6**. The x(y)-axis rotation is generated by combining both modes. On the other hand, the z-axis rotation is generated by precessional rotation excited by l2m1-mode and its orthogonal mode.

Figure 7 shows the prototype of hemispherical shell stator made of stainless steel. The diameter and thickness of the stator are 50mm and 3mm, respectively. Support parts are designed not to affect the vibration of the stator. Four arc-shaped PZTs bonded to the stator opening excites each vibration mode. The stator weighted 306 g, which was 65.6% lighter than the spherical stator.

4.2 Measurement and examination results

Vibration displacements of each vibration mode of the hemispherical shell stator were also measured by LDV. Input voltage was 60V$_{p-p}$. In-phase voltage was applied into all electrodes for measuring displacement of l1m0-mode, and the out-of-phase voltage was applied into two electrodes facing each other for l2m1-mode. Excitations of l1m0-mode and l2m1-mode were confirmed at 28,250 Hz and 29,640 Hz, respectively, as shown in **Fig. 8**.

A rotation around the z-axis was confirmed at approximately 29,500 Hz and 100V$_{p-p}$, and the reverse rotation was observed by changing phase relation of input voltage. However, the rotation was confirmed at only top of the spherical surface. A rotation around the x(y)-axis was also observed at approximately 28,500 Hz. However, there was a big difference between the forward and reverse rotational forces. The l1m0-mode excitation appeared to be too small than l2m1-mode excitation.

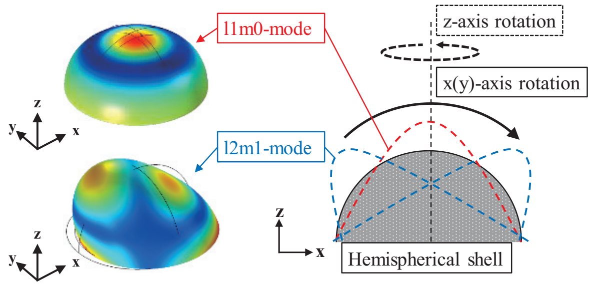


Fig.6 Vibration modes of hemisphere, and rotation direction.

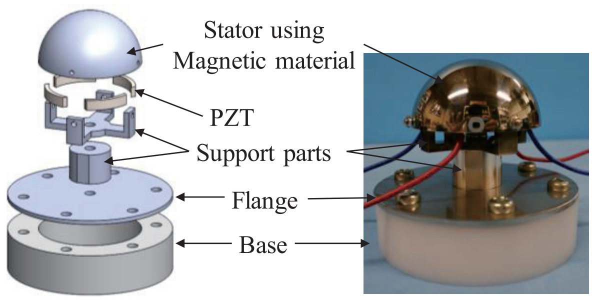
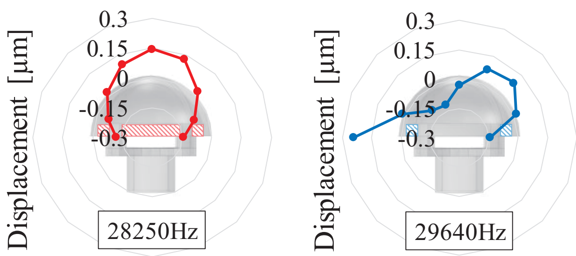


Fig.7 MDOF-SUSM using hemispherical shell stator.



(a)l1m0-mode. (b)l2m1-mode.
Fig.8 Measured vibration displacement.

5. Summary

Two prototypes of MDOF-SUSM for weight reduction were experimentally considered. Both motors were lighter than MDOF-SUSM using spherical stator. The spherical shell stator could not move the rotor strongly. On the other hand, the hemispherical shell stator was observed to rotate the rotor around three axes. However, each rotation was too weak to be stable. The problem is how to increase and stabilize the rotational force.

References

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2. S. Nakajima ,H.Kajiwara, M.Aoyagi, H.Tamura and T.Takano: Jpn. J. Appl. Phys. **55** (2016) 07KE18.