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Study on spherical stator for multi-degree-of-freedom ultrasonic motor

多自由度超音波モータ用球状ステータの研究

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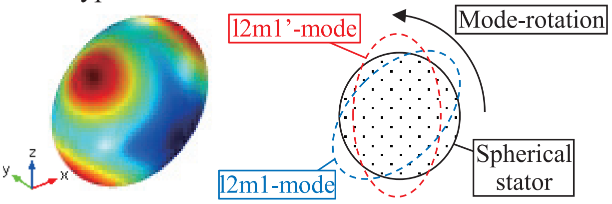
1. Introduction

A multi-degree-of-freedom spherical actuator can realize the rotation around the axes of rotation, and it is effective for downsizing and light-weighting of multi-dimensional system[1,2]. Among them, a multi-degree-of-freedom ultrasonic motor (MDOF-USM) has characteristics of high torque at low speed and self-holding power. MDOF-USMs using a spherical rotor have been mainly studied[1-4]. There is limitations of the design of the stator for design of multiple vibration modes.

In this paper, the MDOF-USM using a spherical stator is proposed, and the analytical and experimental results of the spherical stator are reported. The advantages of the ultrasonic motor using the spherical stator are that (1) the shape of a rotor can be easily designed and (2) the rotational axis can be arbitrarily selected. As for the application of the MDOF-USM, a spacecraft where light-weighting is pursued is expected.

2. Operating principle

The vibration modes of a sphere can be expressed like the earth. The vibration mode shown in **Fig. 1(a)** is called l2m1-mode here. l and m indicate the number of nodal lines and meridian, respectively. Hence l2m1-mode has two nodal lines. One of them is meridian. Its orthogonal mode is expressed with l2m1'-mode. By giving the phase difference of 90 degrees to the excitation of those modes, a mode-rotation shown in **Fig. 1(b)** is obtained on the spherical stator like the traveling-wave type ultrasonic motor.



(a) l2m1-mode. (b) Mode-rotation on xz-plane.
Fig. 1 Operating principle of MDOF-USM using spherical stator.

3. Vibration mode of sphere

The vibration mode of a sphere is analyzed by finite element analysis software (COMSOL Multiphysics). A principal displacement distribution of l2m1-mode is shown in **Fig. 2**. This modes can be excited by applying appropriate stress to the strain distribution on the spherical surface. Two types of an excitation method are considered. One is method using lateral effect of piezoceramic plates stuck on the sphere. The other is method using longitudinal effect of multilayered piezoelectric actuator(MPA) embedded on the sphere.

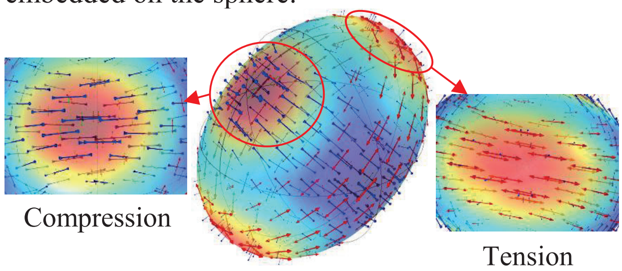


Fig. 2 Principal strain distribution on l2m1-mode.

4. Excitation using piezoceramic plate

Figure 3 shows a prototype spherical stator which was fabricated based on a stainless steel SUS304 sphere 50.8 mm in diameter. Planes were provided by shaving the surface of the sphere, and piezoceramic plates ($16\times11\times2$ mm^3) polarized in the thickness direction were stuck on there. Two resonance points were observed at approximately 51 kHz by measuring the input admittance characteristics of the stator. The excitations of l2m1-mode and l2m1'-mode were observed from the distribution of normal displacements of the stator measured by a laser Doppler vibrometer (LDV). When both modes were excited with a phase difference, the mode-rotation was confirmed by the rotation of the bearing in contact with the stator. However, the rotation and vibration were weak.

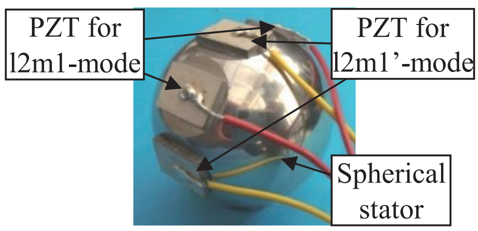


Fig. 3 Prototype stator using piezoceramic plates.

5. Excitation using MPA

An MPA has high electro-mechanical conversion efficiency and can generate large force and large displacement at low voltage. To obtain strong vibration, the structure of the stator embedding MPAs for the excitation was considered. The heat generation from MPAs using hard piezoelectric material can be suppressed. To excite vibration modes for the rotations around three axes, 24 MPAs were placed at regular interval on circumferences around 3 axes. From the results of finite element analysis, the excitations of l2m1-mode and l2m1'-mode were confirmed.

The prototype stator using MPAs is shown in **Fig. 4**. Square holes were formed on the surface of the stainless steel SUS304 sphere 50.8 mm in diameter. MPAs (6×6×5 mm^3) were embedded in the holes to obtain the strain of the y-direction, and fixed by stainless steel wedges and adhesion. In this trial, for the generation of mode-rotation around only a single axis, as the minimum construction, at least 4 MPAs had to be embedded in the large strain positions. Resonance frequencies measured from Port A and Port B took a slightly different value at approximately 51.4 kHz. **Fig. 5** shows measured vibration displacement distribution, I to IV, in the case of driving the stator from both electrical ports with applied voltage of 10 Vp-p at each resonance frequency. Displacement distributions perpendicular to the surface of stator were measured by LDV. In this figure, the surface of the stator is expressed as zero displacement. The peaks of vibration displacement were confirmed on modes of I and III. It can be considered that they were desired vibration modes, l2m1-mode and l2m1'-mode. On the other hand, vibration displacement distributions, II and IV, might be spurious modes which had an indistinct peak and were distorted.

Excited vibration modes were able to be checked by the rotation direction of a ball bearing contacting the spherical stator. In the case of modes of I and III, the rotation direction of the ball bearing changed near nodes. This means that an independent vibration mode, l2m1-mode, was strongly excited. On the other hand, in the case of modes of II and IV, the ball bearing rotated in the same direction on whole circumference of the stator. It means that a mode-rotation in single phase might occur as single-phase ultrasonic motor, because degenerate resonance modes are divided by an external perturbation such as machining the sphere[5].

When the stator was excited by applied voltages with phase difference of 90 degrees between both ports, at a proper driving frequency of 51.39 kHz, the ball bearing uniformly rotated in the same direction in whole circumference. In addition, the inversion of the bearing rotation was confirmed by reversing phase of applied voltage for either one mode. Hence the mode-rotation was confirmed.

6. Conclusion

It was found that the excitation method using piezoceramic plates cannot strongly excite the sphere. The excitation method of MPAs embedding in the sphere showed the feasibility of mode-rotations around 3 axes. Further, from the experiment of the prototype stator, it was possible to excite l2m1-mode and l2m1'-mode, and to obtain the mode-rotation by combining them. In addition, the frequency to obtain mode-rotation was found. The MDOF-USM using spherical stator was realized.

Acknowledgment

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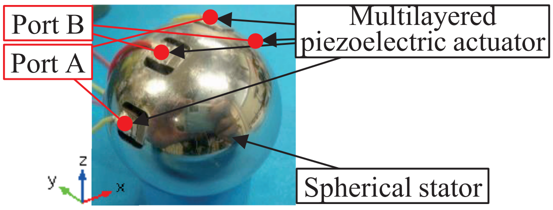
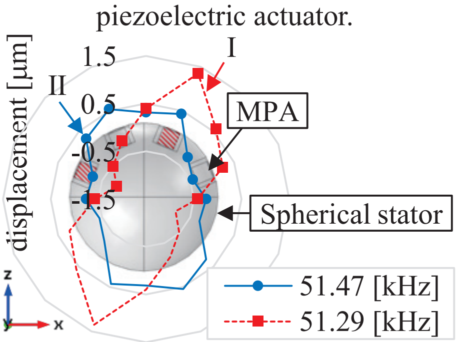
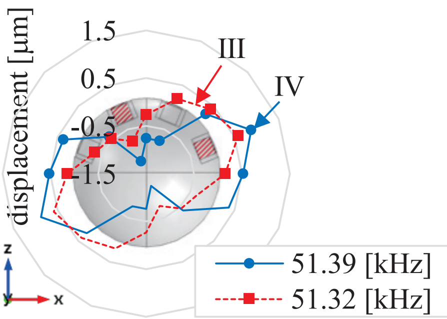


Fig. 4 Prototype stator using multilayered piezoelectric actuator.



(a) Excitation from Port A.



(b) Excitation from Port B.

Fig. 5 Measured vibration displacement distributions which were perpendicular to the surface of stator.