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Noncontact-stepping ultrasonic motor using radial array of rectangular vibrators

放射状矩形振動子アレイを用いた非接触型超音波ステッピングモータ

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1. Introduction

When the vibration amplitude difference is given during the near-field acoustic levitation by multiple ultrasonic vibration sources, a viscous force of acoustic streaming is generated between the vibration sources and the levitated object, and the object is transported without contact[1]. In addition, a noncontact stepping ultrasonic motor (NCS-USM) that uses bending vibration of fan-shaped vibrators arranged in a circle has been proposed[2], and a rotary noncontact synchronous ultrasonic motor has been realized[2].

The objective of this study is to increase the holding force of the rotor and realize stepping rotation with quick response. This paper reports simulation results on whether NCS-USM, which uses the stator with radially arranged rectangular vibrators, can achieve more accurate step angles than that with the conventional fan-shaped vibrators.

2. Operating principle

As shown in **Fig. 1**, in the state where the rotor with a fixed distance to the stator can rotate freely, one of the stators arranged in a plane is driven. A strong sound field is formed in the air gap, and the rotor moves to the driving stator side due to the bias of the acoustic viscous force acting on the bottom surface of the rotor[2]. If the driving stator is switched according to the position of the rotor, it is possible to realize step operation and continuous rotation.

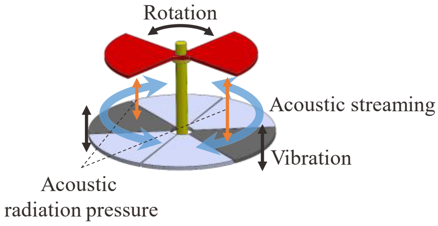

Fig. 1 Arrangement of stepping motor and operating principle of rotation by acoustic streaming[2].

3. Finite element analysis results

3.1 Rectangular vibrator

As shown in **Fig. 2**, the NCS-USM currently manufactured has six fan-shaped stators in a circular shape and a four-pole rotor with a central angle of about 60°. Stepping operation was possible by switching the three drive stators a, b, c, but only rough operation with a stepping angle of 30° was achieved. To increase the step angle resolution and the rotor stop position, a duralumin rectangular vibrator shown in **Fig. 3** was considered. The natural vibration mode and frequency of this vibrator was calculated by using a finite element analysis software (COMSOL Multiphysics 5.5). Two bending vibration modes, B_{50}-mode and B_{31}-mode, shown in **Fig. 4** were chosen. The rotational force of the rotor generated by these two modes was simulated by COMSOL. An acoustic-structure interaction analysis and fluid-structure interaction analysis were carried out with incorporating the necessary equations in COMSOL[2,3].

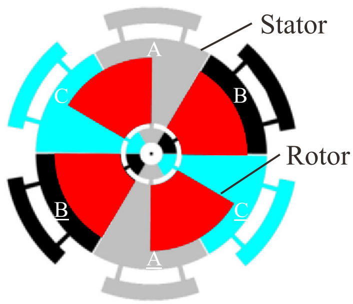

Fig. 2 Model of motor with 4-poles 60° rotor.

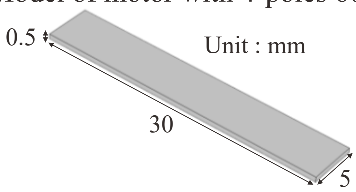

Fig. 3 Dimensions of vibrator.

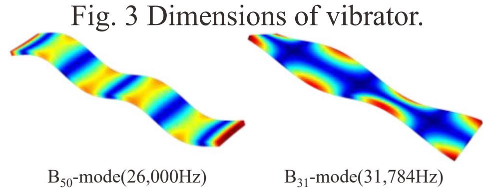

Fig. 4 Natural vibration modes and frequencies of rectangular vibrator.

Figure 5 shows the model of the analysis. The piezoelectric ceramic plate(PZT) for exciting the vibrator was attached to the stator. There was an air layer that considers viscosity between the stator and rotor, and the circumference was covered with air, and the absorption boundary was set on the outside. **Figure 6** shows the analysis range. The maximum stator amplitude was set to 1µm. The angle at which the vibrator and rotor match was set to θ=0°, and the analysis was performed in a counterclockwise rotated range from -5° to 5° with the interval of 0.5°.

Figures 7 and **8** show the analysis results of the sound pressure generated in the air layer and rotational torque acting on the rotor. As shown in **Fig. 8**, the rotational torques generated by two bending vibration modes acts in the direction to hold the rotor on the vibrator. As shown in **Figs. 7** and **8**, in B_{31}-mode, the sound pressure increased, and the rotation torque increased accordingly. It was considered that the vibration displacement was not distributed in the circumferential direction in the B_{50}-mode, so that the sound field suitable to generate the acoustic streaming in the rotation direction was not well formed. Therefore, it seems that B_{31}-mode was better to use for the stator.

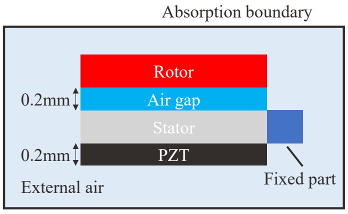

Fig. 5 Model of finite element analysis.

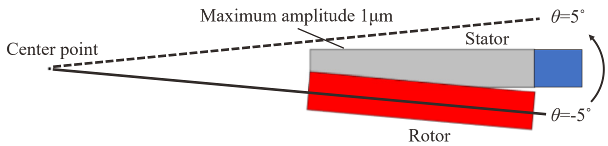

Fig.6 Analysis range.

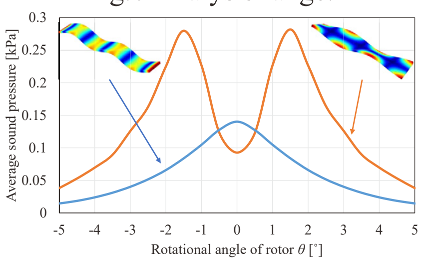

Fig.7 Simulated average sound pressure vs. rotor rotational angle θ.

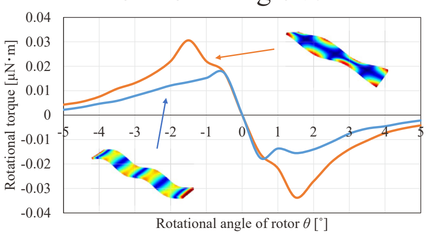

Fig.8 Simulated rotational torque vs. rotor rotational angle θ.

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3.2 Radial arrangement of rectangular vibrators

Figure 9 shows the novel model of NCS-USM. 36 vibrators and 24 rotor blades are arranged in a radial pattern. One phase is made up of 12 vibrators, and the rotor can be rotated by switching between the three phases. **Figure 10** shows the simulated rotational torque with the rotational angle when switching the drive vibrator. It is considered that this motor was able to step with an accuracy of 5° in simulation, as shown in **Fig. 10**. The rotor located in A-phase at the state shown in **Fig. 9** was able to rotate counterclockwise by switching the drive vibrators in the order of B-phase, C-phase, and A-phase. It is also possible to rotate clockwise by reversing the order of driving the vibrators.

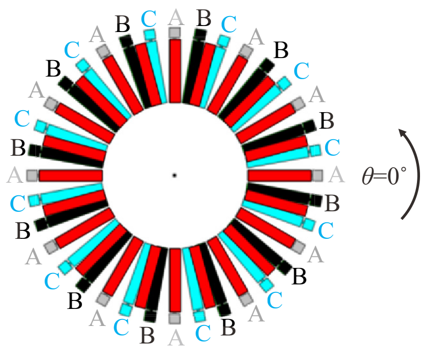

Fig. 9 Novel model of NCS-USM using radial array of rectangular vibrators.

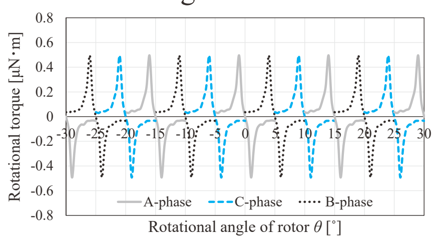

Fig.10 Simulated rotational torque generated by switching phases.

4. Summary

The NCS-USM, which uses the radial array of rectangular vibrators with more stationary positions, was devised, and a step angle of 5° was obtained in simulation. Hereafter, it is necessary to actually manufacture the NCS-USM and examine the optimal control method for the stepping motor.

References

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