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Development of a spherical motor driven by electro-magnets[†]

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Abstract

This paper presents a spherical motor driven by electro-magnets that can rotate omnidirectionally with some degrees of rotation angle error independent of rotation direction. The spherical motor is composed of a spherical rotor, a semi-spherical stator, a control PC, a control circuit, and a DC power supply. The rotor has 92 neodymium magnets. On the other hand, 84 electro-magnets are arranged on the stator. Each electro-magnet can be excited to north or south magnetic pole. The control PC calculates the posture of the rotor after a small time interval and generates the pattern of excitation of electro-magnets in order to rotate the rotor to its calculated posture. The results of the performance of the developed spherical motor show that the maximum torque is 0.24 (N・m), the maximum rotation speed is 2.5 (rad/s), and the average error of rotation angle is several degrees.

Keywords: Spherical motor; Omnidirection; Electro-magnet; Computer simulation

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1. Introduction

A spherical motor has the advantage that it can rotate omnidirectionally in a simple mechanism. Up to now, several spherical motors such as ultrasonic spherical motor [1], spherical stepping motor [2], spherical induction motor [3], and spherical motor [4] driven by electro-magnets have been studied. In the ultrasonic spherical motor [1], a rotor is rotated by some ultrasonic wave motor, but the motor has a limitation of low durability. The spherical stepping motor [2] realizes omnidirectional rotation by combining two stepping motors. However, the rotation angle of the motor is restricted. The spherical induction motor [3] changes the torque depending on the rotation direction, and the spherical motor [4] changes the rotation angle error depending on the rotation direction.

We developed a spherical motor driven by electro-magnets [5] that is composed of a spherical rotor with 32 neodymium magnets and a stator with 84 electro-magnets, a control PC, a control circuit, and a DC power supply. A simulation code was also developed to examine the control method of the motor and the performance improvement by increasing the number of neodymium magnets on the rotor and/or that of electro-magnets on the stator. The maximum torque of the developed spherical motor was 0.06 (N・m) and the maximum rotation speed was 6.5 (rad/s). The maximum torque was predicted to improve by increasing the number of electro-magnets by the simulation code.

This study develops an improved spherical motor to increase the maximum torque. It also examines the effect of decreasing the gap size between the rotor and stator on the performance improvement by using the improved spherical motor and applying the simulation code.

The composition of the improved spherical motor and the rotation control method of the motor are described in Section 2. Section 3 briefly introduces the simulation code for the spherical motor. Section 4 shows the experimental and simulation results of the rotation performance of the improved motor and discusses the effect on the rotation performance by increasing the number of neodymium magnets and decreasing the gap size between the rotor and the stator. The results of this study and future problems are summarized in the conclusions.

2. Structure of spherical motor and its control method

2.1 Structure

The main components of the improved spherical motor are shown in Fig. 1. The improved motor is composed of a spherical rotor, a semi-spherical stator, a control PC, a control circuit, and a DC power supply. The rotor has 92 neodymium magnets on its inner surface. This study utilizes a slightly stronger neodymium magnet than that of the previous study

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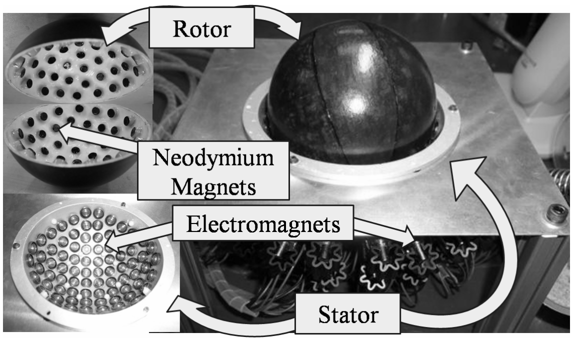

Fig. 1. Appearance of the main components of the improved spherical motor.

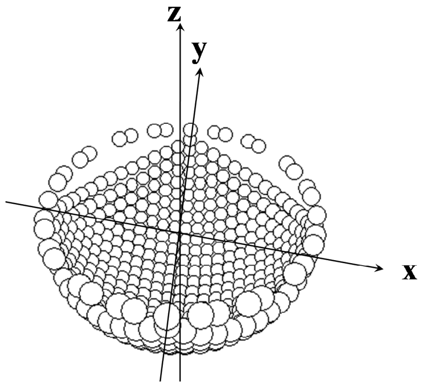

Fig. 2. Arrangement of electro-magnets in stator.

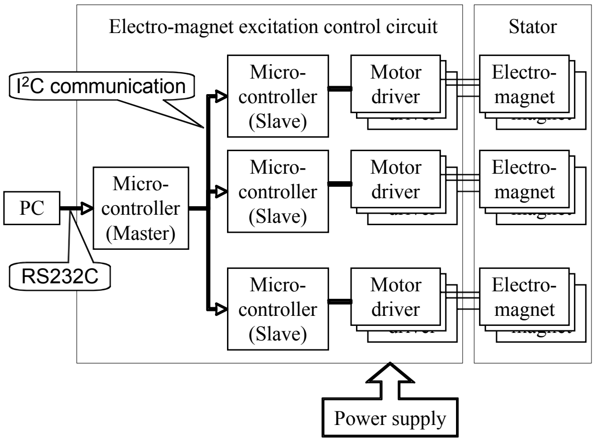

Fig. 3. Composition of electric circuits for excitation of electro-magnets.

[5]. The surface magnetic flux density of each magnet is 470 (mT). Thirty-two magnets are placed at the points of the vertices of the body combining with a regular dodecahedron and a regular icosahedron. The north magnetic poles of the magnets face outside. The remaining 60 magnets are placed at the cross-sections of the inner surface of rotor sphere and the semi-line connecting from the center of the rotor and the gravity center of the neighboring three vertices of the body combining with a regular dodecahedron and a regular icosahedron. The south magnetic poles of the magnets face outside. By this arrangement, the magnets are arranged in almost spherical symmetry.

On the other hand, the stator has 84 electro-magnets as shown in Fig. 1. The stator also has 12 ball plungers to support the rotor with small friction force. The position of the top of each electro-magnet is given by the coordinate system shown in Fig. 2 as

$$x = Rsin\left(\frac{\pi}{12}i\right), \tag{1}$$

$$y = Rsin\left(\frac{\pi}{12}j\right), \tag{2}$$

$$z = -\sqrt{R^2 - (x^2 + y^2)}\,, \tag{3}$$

where R is the inner radius of the stator, and i and j are integers that satisfy the following equations.

$$-\frac{\pi}{2} \le \frac{\pi}{12}i \le \frac{\pi}{2}, \tag{4}$$

$$-\frac{\pi}{2} \le \frac{\pi}{12}j \le \frac{\pi}{2}, \tag{5}$$

$$R^2 - (x^2 + y^2) \ge 0 \tag{6}$$

A switching DC power supply of 12 (V) output voltage and 600 (W) maximum output power is used to excite the electro-magnets in the stator. As shown in Fig. 3, the excitation control signals are transmitted hierarchically in a compact electro-magnet excitation control circuit from the control PC to 84 electro-magnets through RS232C connection between the PC and the control circuit and I^2C communication among a master micro-controller and 8 slave micro-controllers in the circuit.

2.2 Control method

The electro-magnets on the stator are excited to be north or south magnetic pole so as to rotate the rotor in a desired angle velocity. First, the desired posture of the rotor after a short time interval Δt is specified based on the rotor posture at time t, desired rotational direction and desired rotation speed. Then, the positions of all magnets in the rotor at $t + \Delta t$ are calculated. The electro-magnets in the area near the expected positions of magnets in the rotor within a predetermined radius are excited to generate the attractive forces to the magnets as shown in Fig. 4. On the other hand, the electro-magnets outside the area are excited to generate the repulsive forces.

3. Simulation code of spherical motor

A simulation code of the spherical motor was developed to examine the excitation method of electro-magnets and to design a spherical motor [5]. The magnets and electro-magnets are approximated as point uni-poles, and the forces for all combinations between a magnet and an electro-magnet are calculated by the Coulomb equation. The rotational moment working to the rotor is calculated by summing the Coulomb

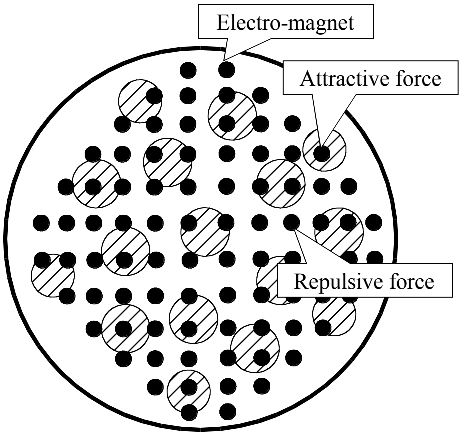

Fig. 4. Excitation method of electro-magnets in the stator.

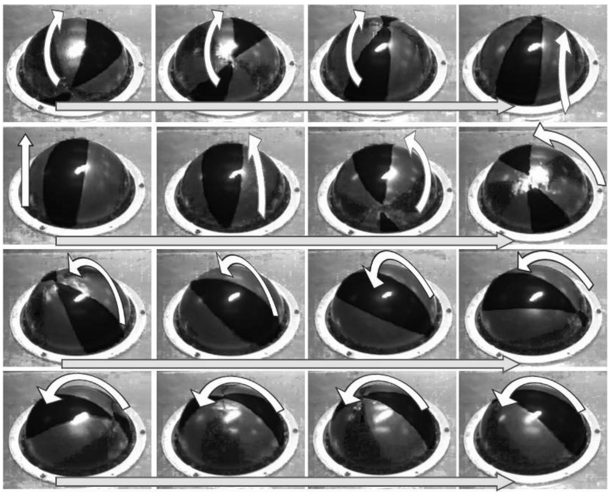

Fig. 5. Sequential images of rotor rotation.

forces and subtracting the friction force between the rotor and the stator. Although the rotor is supported by 12 ball plungers, the rotor is assumed to be supported at a point in the simulation code. By considering the inertia of the rotor, the angle acceleration of the rotor is calculated. From the current posture of the rotor and the angle acceleration, the posture of the rotor at time $t + \Delta t$ is calculated by integrating numerically.

4. Evaluation of rotation performance

The rotation performance of the improved spherical motor is evaluated. First, the authors confirm that the improved motor can rotate omnidirectionally. For example, sequential images of rotor rotation are shown in Fig. 5.

Fig. 6 shows the relations between torque and rotation speed for the spherical motors in the previous study [5] and in this study. The figure also shows the prediction results by the simulation code. The gap size between the rotor and the stator is 5 (mm) as it was in the previous study. By increasing the number of magnets in the rotor, the maximum torque greatly increases although the maximum rotation speed decreases due to the increase of mass of the rotor resulting in increasing its inertia.

Table. 1. Comparison of rotation angle error between the previous spherical motor [5] and the improved one.

	Average (rad)	Maximum (rad)
Improved motor	0.034	0.076
Previous motor	0.040	0.102

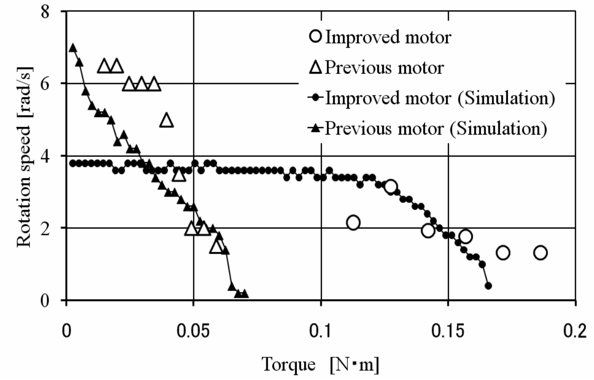

Fig. 6. Comparison of rotation performance between the previous spherical motor [5] and the improved one.

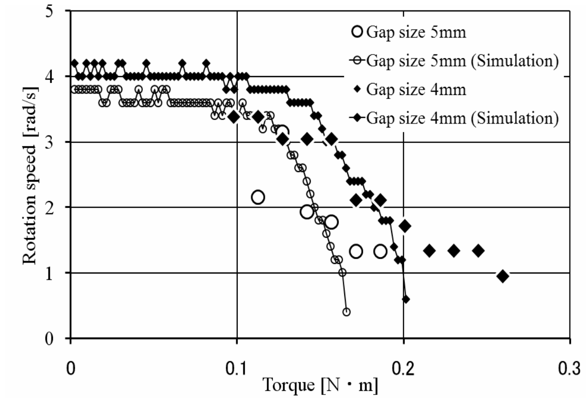

Fig. 7. Comparison of rotation performance by changing the gap size between the rotor and the stator.

Table 1 compares the rotation angle errors between the previous spherical motor and the improved motor. The rotation angle error decreases by increasing the number of magnets in the rotor.

The performance change of spherical motor by changing the gap size between the rotor and the stator is shown in Fig. 7. The figure also shows the prediction results by the simulation code. The prediction results almost coincide with the experimental results. As shown in the figure, the performance is better for the motor of 4 (mm) gap size than that of 5 (mm) gap size. One of future problems is to decrease the gap size by improving the manufacturing precision.

5. Conclusions

This study develops an improved spherical motor driven by electro-magnets. The improved spherical motor is confirmed to have better rotation performance than that developed in the previous study from the results of rotation performance evaluation. This study also examines quantitatively the performance increase by decreasing the gap size between the rotor and the stator. A simple simulation code of the spherical motor is confirmed to have good prediction capability for the design of the type of spherical motor studied in this study.

Future work includes the improvement of rotation angle velocity and the development of a small spherical motor for real applications.

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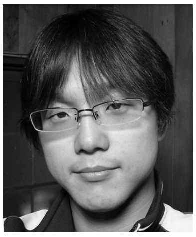

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