Characteristics Analysis of a New Spherical Actuator Employing 3-D FEM

Shuhei Maeda, Katsuhiro Hirata
Osaka University
2-1Yamadaoka, Suita, Osaka, 565-0871, Japan
shuhei.maeda@ams.eng.osaka-u.ac.jp, k-hirata@ams.eng.osaka-u.ac.jp

Abstract — We have been developing different kinds of 3 degrees of freedom electromagnetic spherical actuators. However, these actuators only have a small tilt direction rotation angle. In order to apply these actuators to various applications such as robot joints, we present an improved model with a wide rotation angle. In this paper, the basic structure and operating principle of the new model of this actuator are described. The static and dynamic performances of this wide-angle model are then analyzed using 3D-FEM and the effectiveness of this actuator is verified.

I. INTRODUCTION

Conventionally, a multi degree of freedom drive mechanism is typically achieved by combining more than one motor. However, this mechanism has some difficulties, such as deterioration of efficiency, increase of weight and size. Therefore, multi-degree-of-freedom actuators are expected to become a key technology for the solution of these defects [1]. Particularly, spherical actuators [2]-[3] have attracted attention and are being extensively studied since they can be applied to the joints and eyeballs of robots, because they can be freely rotated in every axis direction.

The current challenges of spherical actuator design include low torque, narrow rotation angle, low-precision positioning, sensing method, supporting the mover etc. We have been studying various kinds of spherical actuators, and the torque characteristics of the actuator were analyzed using 3-D FEM [4]-[5]. It was found that the tilt direction rotation angle of these actuators was too small for robot joints.

In this paper, we propose a wide-angle model of the actuator for expanding its application, and show the results of the static and dynamic characteristic analysis using 3D-FEM.

II. DESCRIPTION OF THE ACTUATOR

A. Basic structure

The basic structure of a new model of the actuator with tilt direction rotation angle enhancement is represented in Fig. 1. This actuator is mainly composed of a mover with four interior magnets (Br = 1.4T) and two sets of stators with six magnetic poles (500 turns) arranged along the Z-axis. The mover rotates three-dimensionally around a spherical bearing. The gap is kept constant (0.7mm) during the motion. The outer diameter of the stator is 100mm and the outer diameter of the mover is 60mm.

B. Operating principle

Fig. 2 shows the operating principle of the actuator around the X-axis. The N and S poles appear alternately on the mover due to the arrangement of the magnets. When the four coils are excited, the mover rotates in the direction of the arrow. The mover rotates in the counter direction when these coils are conversely excited.

Fig. 3 shows the operating principle around the Y-axis. When eight coils are excited as shown in Fig. 3, the mover rotates around the Y-axis according to the net torque produced in the cross-section B and C.

Fig. 4 shows the operating principle around the Z-axis. The mover rotates when the eight coils are excited. In addition to this principle, when all coils are connected as shown in Fig. 4(right), and excited by a three-phase AC supply, the mover can continue rotating around the Z-axis as a synchronous motor.

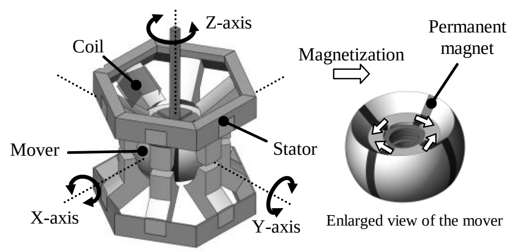

Fig. 1. Basic structure of the actuator

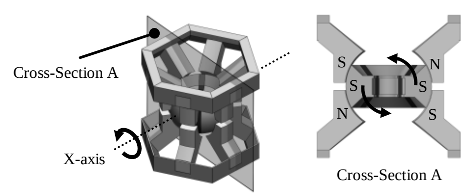

Fig. 2. Operating principle around X-axis

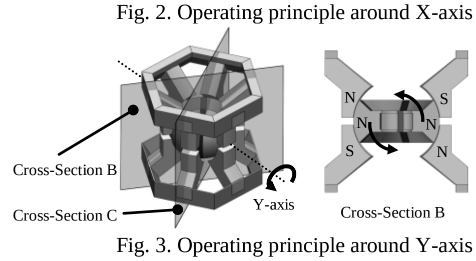

Fig. 3. Operating principle around Y-axis

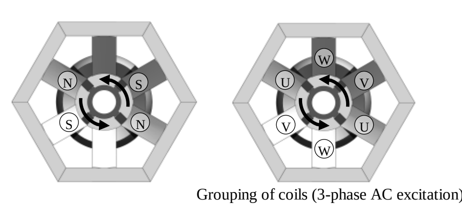

Fig. 4. Operating principle around Z-axis

III. CHARACTERISTIC ANALYSIS

A. Analysis method

An electromagnetic field analysis using the 3-D finite element method (FEM) is conducted to show the static torque characteristics and the dynamic operating characteristics of the wide-angle model. In order to compute the characteristics of the actuator, T-Ω method is employed. In T-Ω method, (1) (2) is satisfied.

$$\mathrm{div}\{\mu(T_m + T_e + T_0 - \mathrm{grad}\,\Omega)\} = 0 \tag{1}$$

$$J = \mathrm{rot}\,(T_m + T_e + T_0) \tag{2}$$

Where T_m, T_e and T_0 are current vector potentials of equivalent magnetizing current density, eddy current density and forced current density respectively, Ω is magnetic scalar potential, μ is the permeability. The motion equation is given as follows.

$$I_i \frac{d^2\theta_i}{dt_i^{\,2}} + D_i \frac{d\theta_i}{dt_i} \pm T_{s\,i} = T_{m\,i} \qquad (i = x, y, z) \tag{3}$$

Where I_i is the moment of inertia of the armature, D_i is the viscous damping coefficient, θ_i is the rotation angle of mover, T_{si} and T_{mi} are the friction torque and the torque acting on the mover, and *i* is the rotation axis of the mover.

B. Analysis condition and analyzed results

As an example, analyses around the X-axis are shown in this chapter. Table I shows the discretization data. The torque characteristics of the mover between -25 and 25 degrees were analyzed. The operating characteristics under the conditions shown in Fig. 7 were also analyzed. Coils A1 and A2 are the coils that actively contribute to the rotation of the mover, and coils B are other coils excited by DC current to fix the mover position around the Z-axis. The inertia of the mover around the X-axis is 1.47×10^{-4} kg·m^2. The 3-D mesh model is shown in Fig. 5. and the results of these analyses are shown in Fig. 6, and Fig. 8.

The static analysis results show that the cogging torque of this model is relatively small and changes smoothly. From the operating characteristic analysis results, it can be seen that the mover moves in a reciprocating motion, as was intended.

TABLE I
DISCRETIZATION DATA OF ANALYSIS AROUND X-AXIS

	Static torque	Dynamic characteristic
Number of elements	731,050	
Number of nodes	126,368	
Number of steps	11	400
Total CPU time	1 [hour]	48 [hours]

(Coils and air layers not shown)

Fig. 5. 3-D mesh model

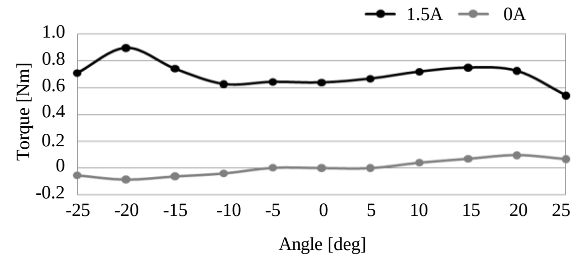

Fig. 6. Torque characteristic around X-axis

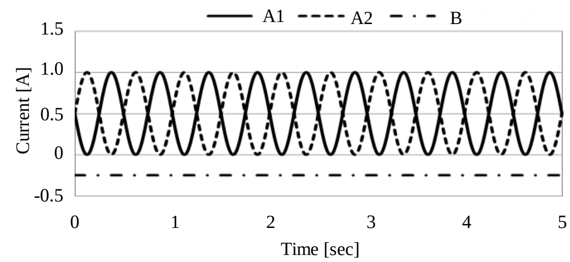

Fig. 7. Excitation current

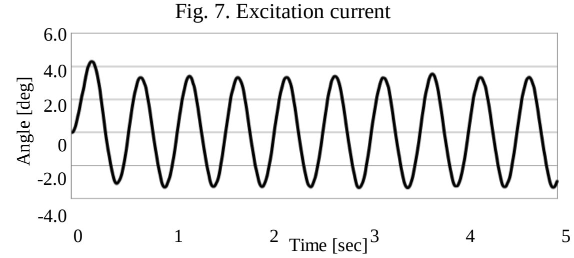

Fig. 8. Operating characteristic of the mover around X-axis

IV. CONCLUSION

In this paper, a wide-angle spherical actuator was proposed and its characteristics were investigated through electromagnetic field analysis using 3-D finite element method. From the analyzed results, the suitability of this actuator to apply to the joints of robots was verified.

In the future, we are planning to install sensors to measure the rotation angle of the mover and to control it through position feedback control.

V. REFERENCES

[1] Investigating R&D Committee on Systematize technology of multi degrees of freedom motors, "Systematize technology of multi degrees of freedom motors," *Technical Report of IEEJ*, No.1140, pp.1-47, 2008.

[2] Liang Yan, I-Ming Chen, Guilin Yang, Kok-Meng Lee, "Analytical and experimental investigation on the magnetic field and torque of a permanent magnet spherical actuator," Mechatronics, IEEE/ASME Transactions, vol.11, no.4, pp.409-419, 2006.

[3] Dehez, B., Grenier, D., Raucent, B., "Two-degree-of-freedom spherical actuator for Omnimobile ROBOT," *Robotics and Automation, 2002. Proceedings*. ICRA '02. IEEE International Conference, vol.3, pp.2381-2386, 2002.

[4] Yuya Hasegawa, Katsuhiro Hirata, Yoshio Mitsutake, Tomohiro Ota and Manabu, Nakata, "Torque, Characteristics of A New Spherical Resonant Actuator," *Proceedings of the 13th Biennial IEEE CEFC*, PA5-1, p.74, 2008.

[5] Shohei Ikejiri, Katsuhiro Hirata, Byungjin Yoo and Mingyu Tong, "Proposal of Electromagnetic Spherical Actuator with Three-Degree-of-Freedom," *Proceedings of the 14 International Symposium on Electromagnetic Fields in Mechatronics*, Electrical and Electronic Engineering, Arras, France, pp117-118, 2009.