Analysis of 3-DOF Outer Rotor Spherical Actuator Employing 3-D FEM

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We have been developing various kinds of 3-DOF electromagnetic spherical actuators. Some problems such as low torque, large size and narrow rotation angle remain to apply these actuators to robot joints. In this paper, we present a new 3-DOF spherical actuator whose rotor is on the outside to solve these problems. The basic structure and operating principle of this actuator are described. The static and dynamic performances are analyzed using 3D-FEM, in which two types of control methods are taken into account.

***Index Terms*— Spherical Actuator, outer rotor, 3-DOF, control method, 3-D FEM**

I. INTRODUCTION

CONVENTIONALLY, many single-degree-of-freedom actuators were used to realize devices with multi degrees of freedom. However, this makes the structure larger, heavier and more complicated due to the large number of actuators. To remove these drawbacks, the development of a spherical actuator with multi degrees of freedom is necessary, and various spherical actuators have been developed [1]-[4], including our own [5]. However some problems such as low torque, large size and narrow rotation range remain. To solve these problems, the employment of an outer rotor structure is one of the solutions.

In this paper, we propose a new 3-DOF outer rotor spherical actuator and its control method. The basic construction and operating principle are described. The static torque characteristics and dynamic characteristics are computed employing 3-D FEM, in which two types of control methods are taken into account.

II. DESCRIPTION OF THE ACTUATOR

A. *Basic structure*

The proposed outer rotor spherical actuator consists of a stator and a rotor as shown in Fig. 1. This actuator can realize high torque because of the large radius of the outer rotor. The rotor has small spherical shell-shaped permanent magnets and back yoke (Fig. 2). The permanent magnets are arranged all over the inner surface of the rotor, the N and S poles appear alternately. The stator has 32 teeth with concentrated windings, which are arrayed around the Z-axis at even intervals (Fig. 3).

B. *Operating principle*

We propose two types of control methods for this 3-DOF actuator, Stronger field control, which is open loop control and Torque control, which is closed loop control.

Stronger field control is that all coils produce current patterns in accordance with the rotor's reference position. In this control method, coils generate stronger field, so the rotor is always locked (Fig. 4). By moving current patterns (① in Fig. 4), the rotor track the given trajectory (② in Fig. 4).

Torque control is that all coils produce current patterns which generate a target output torque. An output torque of this actuator is given by (1).

$$\mathrm{T}_{\mathrm{target}} = \mathrm{K}\vec{I} + \mathrm{T}_{\mathrm{cogging}} \tag{1}$$

$$\mathrm{T}'_{\mathrm{current}} = \mathrm{T}_{\mathrm{target}} - \mathrm{T}_{\mathrm{cogging}} \tag{2}$$

Where $\mathrm{T}_{\mathrm{target}}$ is a target output torque calculated by the difference between the rotor's target position and present position, K is a torque constant which is decided on the rotor's present position, $\vec{I}$ is the control current, $\mathrm{T}_{\mathrm{cogging}}$ is a cogging torque, and $\mathrm{T'}_{\mathrm{current}}$ is a current torque. K and $\mathrm{T}_{\mathrm{cogging}}$ are derived from superposition of the current torque and cogging torque generated by single magnetic pole (Fig. 5). We assume that the sum of a torque generated by one magnetic pole equals to a overall torque generated by all magnetic poles. Equation(3) is calculated by (1) and (2).

$$\mathrm{T}'_{\mathrm{current}} = \mathrm{K}\vec{I} \tag{3}$$

$$\mathrm{K}^{-}_{\mathrm{m}} = \mathrm{N}^{-1}\mathrm{K}^{\mathrm{T}}(\mathrm{K}\mathrm{N}^{-1}\mathrm{K}^{\mathrm{T}}) \tag{4}$$

Then using pseudo-inverse matrix in the equation(4), unknown parameter $\vec{I}$ is given as follows. N is diagonal matrix, having winding resistance.

$$\vec{I} = \mathrm{K}^{-}_{\mathrm{m}}\mathrm{T}'_{\mathrm{current}} \tag{5}$$

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 proposed 3-DOF actuator. In order to compute the characteristics of the actuator, T-Ω method is employed. In T-Ω method, (6) (7) is satisfied.

$$\mathrm{div}\left\{\mu\left(T_m + T_e + T_0 - \mathrm{grad}\,\Omega\right)\right\} = 0 \tag{6}$$

$$J = \mathrm{rot}\,(T_m + T_e + T_0) \tag{7}$$

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.

$$I_i \frac{d^2\theta_i}{dt_i^{\,2}} + D_i \frac{d\theta_i}{dt_i} \pm T_{s\,i} = T_{m\,i} \qquad (i = x, y, z) \tag{8}$$

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. In the dynamic analysis, the two kinds of control methods mensioned above are taken into consideration.

B. Analysis condition and analyzed results

As an example, static and dynamic analyses around the X-axis are conducted. Table I shows the discretization data and the analysis condition. The static torque characteristics of cogging torque and output torque are shown in Fig. 6. As shown in this figure, the output torques around X-axis are always positive from −38 to 38 degrees. This means that this actuator can rotate over this range. The rotation angles around the X-axis using Stronger field control and Torque control under dynamic analysis are shown in Fig. 7. From these results, the rotation angles agree with the desired rotation angle qualitatively. By using Torque control, the rotation angle follows the target more correctly. In the full paper, we would like to compare the analysis results and the experimental results.

Fig. 1 Assembled structure of the actuator

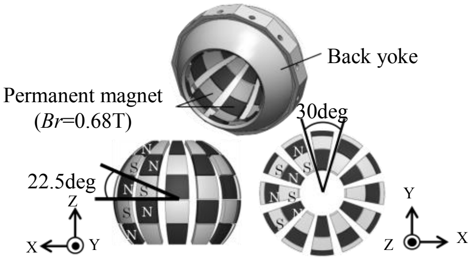


Fig. 2 Structure of the rotor

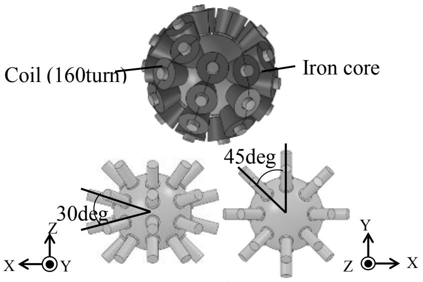


Fig. 3 Structure of the stator

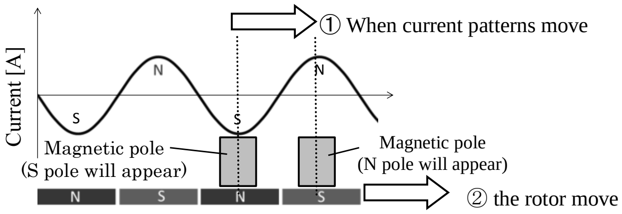
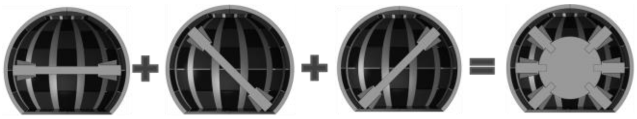


Fig. 4 Stronger field control



Single pole Single pole Single pole Full model

Fig. 5 Superposition of the torque

TABLE I
DISCRETIZATION DATA AND ANALYSIS CONDITION

	Static torque	Dynamic characteristic
Number of elements	878,909	1957,944
Number of nodes	153,580	344,295
Number of steps	79	501
Total CPU time	4.5 [hours]	39 [hours]
Max excited current	5[A]	

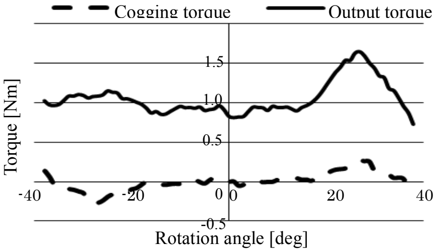


Fig. 6 Static torque characteristic around X-axis

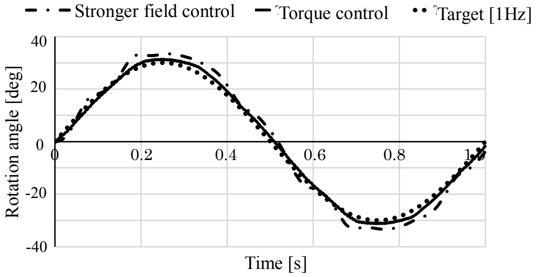


Fig. 7 Dynamic characteristic around X-axis

IV. CONCLUSION

This paper proposed a new 3-DOF outer rotor spherical actuator for realizing a small structure, high torque and wide rotation angle, and static and dynamic characteristics were computed by employing 3-D FEM, in which the control methods are taken into account. As a result, the effectiveness of this actuator was clarified.

V. REFERENCES

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