Presentation and 2-Dimensional Equivalent Magnetic Field Analysis of a Novel 2-DOF Spherical Hybrid Stepping Motor

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This paper proposes a novel spherical hybrid stepping motor with two degrees of freedom (2-DOF). The motor is composed of two sub stepping motors, each is the hybrid stepping type with arc-shaped stator and specially designed bearing structure. The rotational axes of two sub-motors cross at the same point, and this structure enables the developed motor to move in any direction. In order to simplify the 3-D magnetic field analysis of two sub-motors, corresponding 2-D equivalent magnetic field motor models are built, taking into account of the influence of coupling PM leakage flux. Based on which, the 2-D finite element analysis (2-D FEA) can be used for computing motor's electromagnetic performances, such as no-load back-EMF, pull-out torque, holding torque, detent (cogging) torque, and positional holding accuracy. A prototype of the proposed 2-DOF spherical motor with designed outside diameter of 50 mm is newly manufactured, both FEA and experimental results have validated the feasibility of motor's operation principle and the accuracy of the 2-D equivalent motor model.

***Index Terms*—Finite element analysis (FEA), magnetic field analysis, spherical stepping motor, two-dimensional (2-D) equivalent model, two degree of freedom (2-DOF).**

I. INTRODUCTION

THE requirement for the motion in a spherical surface is being increased in many fields. For instance, the motion of robot's eyes, automated astronomical telescope, artificial limb-joints such as wrist, satellite-tracking antenna, and so on, are basically in a shape of spherical surface. In order to realize the spherical surface motions, various types of spherical motors with multiple degree-of-freedoms (DOFs) have been proposed [1]-[5]. In which, the 2-DOF spherical stepping motor is well-suited for low toque, high positioning resolution applications, due to the superiorities of no cumulative error and easy open-loop control [1]. However, due to the small desired air gap, the mechanical structure of the 2-DOF spherical stepping motor is usually complicated, which increases the motor's volume and manufacturing difficulty and decreases the energy index and positioning accuracy. As a result, development of this type of motor is subjected to limitations.

In order to simplify the motor structure and manufacturing process, reduce the volume, and improve the energy index and positioning accuracy, a novel 2-DOF spherical hybrid stepping motor and its two-dimensional (2-D) equivalent magnetic field analysis is proposed in this paper. This work is structured in three parts. Firstly, basic topology and operation principle are described. Then, based on 3-D magnetic field analysis, the 2-D equivalent magnetic field motor model is built for computing electromagnetic performance. Finally, a prototype with outside diameter of 50 mm is designed and fabricated, with feasibility of motor's operation principle and accuracy of 2-D equivalent motor model validated by experimental and 3-D finite element analysis (FEA) results.

II. TOPOLOGY AND OPERATION PRINCIPLE

The structure of the proposed 2-DOF spherical hybrid stepping motor is shown in Fig. 1. The motor is composed of two sub-motors, each is hybrid stepping type. Rotational axes of two sub-motors cross at the same point, i.e., the center point of the spherical motor. This structure enables the motor to move freely in any direction. Motor's operation principle to realize the 2-DOF motions will be presented in detail in this part.

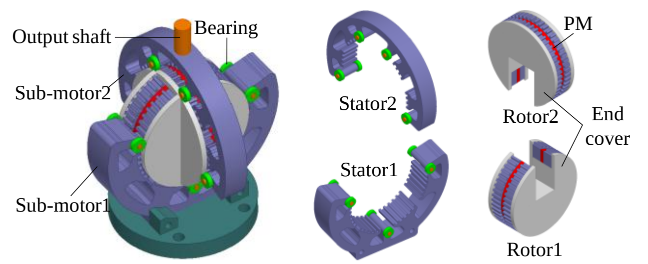


Fig.1 Structure of the 2-DOF spherical hybrid stepping motor.

Both sub-motors have arc-shaped stator with designed outside diameter of 50 mm. Two rotors are connected with each other via the end cover made of non-magnetic material, and all rotor cores have the same outside diameter as the end cover. The small bearings are symmetrically mounted on both sides of the stator cores, which can slide around the surface of the end cover and enable the rotor to move smoothly around the stator (in sub-motor1) or opposite (in sub-motor2). Both sub-motors are designed into small length-diameter ratio to obtain relatively large operation range, e.g., ≥±45° in this case.

III. 2-D EQUIVALENT MOTOR MODEL

Setting the PM of sub-motor1 as vacuum, the magnetic field produced by the PM of sub-motor2 is calculated by 3-D FEA, as shown in Fig. 2. It can be seen that the PM leakage flux of sub-motor2 mainly has an influence on rotor magnetic field distribution of sub-motor1, which should be taken into account of for the following 2-D equivalent magnetic field analysis.

Taking sub-motor1 for instance, its structure decomposition diagram considering the influence of PM leakage flux of sub-motor2 is shown in Fig. 3. In which, rotor polarities N, S are produced by the PM of sub-motor1, whilst N′, S′ are produced by the PM of sub-motor2. The N-pole rotor and S-pole rotor are staggered in angle by one-half the rotor tooth pitch.

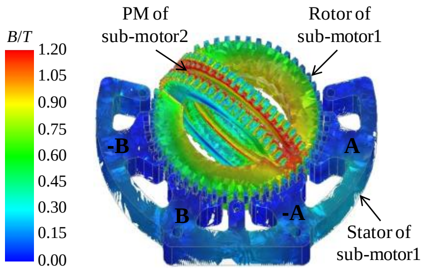
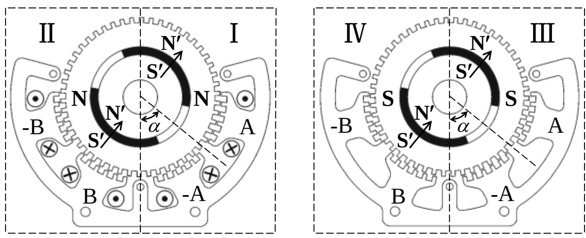


Fig.2 Flux density distribution produced by the PM of sub-motor2.



(a) (b)

Fig.3 Structure decomposition diagram of sub-motor1. (a) Motor part with N-pole rotor. (b) Motor part with S-pole rotor.

Based on Fig. 3, 2-D equivalent motor model corresponding to part I~IV can be respectively established. For example, the one corresponding to part I is shown in Fig. 4. In which, rotor polarities N, S are equivalently produced by two PMs placed symmetrically on stator yoke and magnetized oppositely, and the relative position of rotor PMs with respect to stator poles is the same as that of part I. Calculation results of all 2-D models can be directly added and applied to the actual motor.

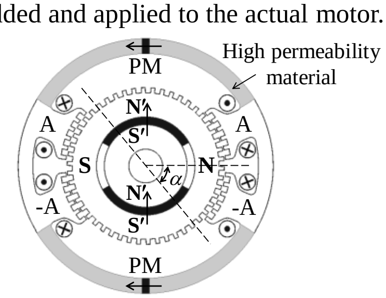


Fig.4 2-D equivalent motor model corresponding to part I of sub-motor1.

IV. FEA AND EXPERIMENTAL STUDY

Electromagnetic performances, such as no-load back-EMF, pull-out torque, holding torque, detent torque, and positional holding accuracy, are calculated by 2-D and 3-D FEA to verify the accuracy of the 2-D equivalent motor model and assess the influence of PM leakage flux on the operation performances. Some important results are shown in Fig. 5~Fig. 7.

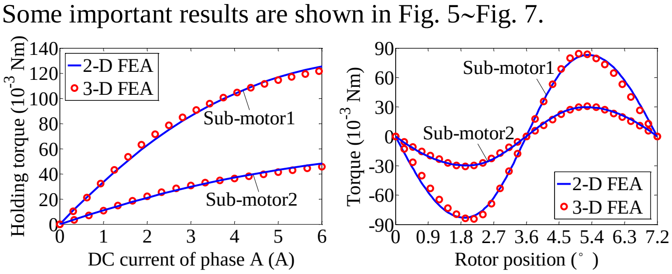


Fig.5 Comparison of holding torque and torque-angle characteristic between actual and 2-D equivalent motor model by using 3-D and 2-D FEA at α=0°.

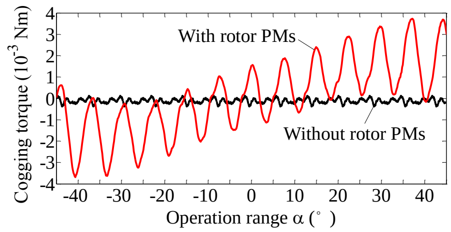


Fig.6 Detent torque of sub-motor1 calculated by 2-D FEA based on the 2-D equivalent motor model.

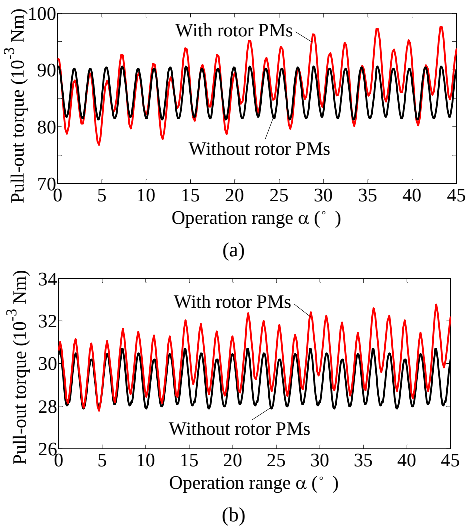


Fig.7 Rated pull-out torque calculated by 2-D FEA based on 2-D equivalent motor model. (a) Sub-motor1. (b) Sub-motor2.

A prototype of the developed 2-DOF spherical hybrid stepping motor is newly designed and fabricated as shown in Fig. 8. Experimental tests would be carried out to validate motor's operation feasibility and the theoretical analysis.

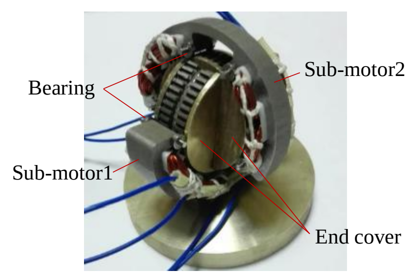


Fig.8 Prototype of the developed 2-DOF spherical hybrid stepping motor.

REFERENCES

[1] K. M. Lee, and C. K. Kwan, "Design concept development of a spherical stepper for robotic applications," *IEEE Trans. Robot. Autom.* vol. 7, no. 1, pp. 175-181, Feb. 1991.

[2] G. S. Chirikjian, and D. Stein, "Kinematic design and commutation of a spherical stepper motor," *IEEE/ASME Trans. Mechatronics*. vol. 4, no. 4, pp. 342-353, Dec. 1999.

[3] K. Kahlen, I. Voss, C. Priebe, and R. W. De Doncker, "Torque control of a spherical machine with variable pole pitch," *IEEE Trans. Power Electron*. vol. 19, no. 6, pp. 1628-1634, Nov. 2004.

[4] L. Yan, I. M. Chen, G. Yang, and K. M. Lee, "Analytical and experimental investigation on the magnetic field and torque of a permanent magnet spherical actuator," *IEEE/ASME Trans. Mechatronics*. vol. 11, no. 4, pp. 409-419, Aug. 2006.

[5] L. Shi, and Y. Motomura, "A small sized spherical stepping motor and the controls," in *Proc. Int. Conf. Elect. Mach. Syst*., 2003, pp. 191-194.