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# Magnetic field modeling based on geometrical equivalence principle for spherical actuator with cylindrical shaped magnet poles

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ABSTRACT

Spherical actuator is a device that can achieve multiple degree-of-freedom (DOF) rotary motions in a single joint. It has a bright application prospect on moment gyros and satellite systems. Cylindrical shaped PM pole is widely used because of easy fabrication and pattern of magnetization. However, its topology and structure cause difficulties in accuracy magnetic modeling. Thus, the structure optimization and performance design become complicated. This paper proposes a novel magnetic field method for spherical actuator with cylindrical shaped PM poles based on geometrical equivalence principle. For convenient expression of magnetic field, three types of approximated dihedral cone shaped magnet poles are put forward based on different equivalent principles. On the basis of optimal equivalent principle, accurate harmonic model is set up with the magnetic field formulated. In addition, the analytical result is confirmed by numerical simulation from different dimensions. A research prototype with 8-PM-poles outer rotor and 24-coils stator is assembled and an experimental setup is established. The experimental results show experimental curves, analytical curves and FEM curves match with each other well which proves the accuracy of the proposed model. Thus, the indirect method of modeling magnetic field for spherical actuator with cylindrical shaped PM poles can be an effective tool. The magnetic field results can be the foundation for further study.



## 1. Introduction

Multiple degree-of-freedom (DOF) actuators have gained more and more interest in recent years due to their compact structure and efficient operation in replacing traditional single-axis actuators connected in series [1,2]. Typically, spherical actuator is a device that can achieve multiple degree-of-freedom rotary motions in a single joint. Therefore, the intended applications can be specifically embodied in controlling the satellite or the gyro for three-axis attitude adjusting by using just single spherical actuator [3–5]. A benefit from this, the size and the weight of mechanisms of moment gyros and satellite systems could be economically reduced. Particularly, the replacement of conventional single-axis driving system by spherical actuator could contribute to higher reliability and faster response. More importantly, the motion precision will be improved to ensure accurate tasks such as acquiring high quality satellite images and orbit control [6]. Most existing spherical actuators are based on principles similar to their single-axis counterparts and can be basically classified into four categories, i.e., ultrasonic actuators, induction actuators, variable reluctance actuators and permanent magnet (PM) actuators [7–10]. Among them, the PM spherical actuators driven by the electromagnetic force have become the most impressive ones because of their fast response, high torque output and moderate voltage operation [11,12].

Modeling of magnetic field is extremely important for torque calculation and precision control. Various methods have been proposed to formulate the magnetic field distribution. The distributed multiple (DMP) model originally suggested by Fitz Gerlad in 1883 has been developed by Lee et al. to permanent-magnet-based spherical actuator [13]. Three examples are given to illustrate the procedure of developing a DMP model. The magnetic field can be characterized by superposition of an appropriate distribution of sources and sinks. Similar studies can be found in [14,15]. However, the shape of magnet is very limited and the accumulated error results in low modeling precision. The magnetic equivalent

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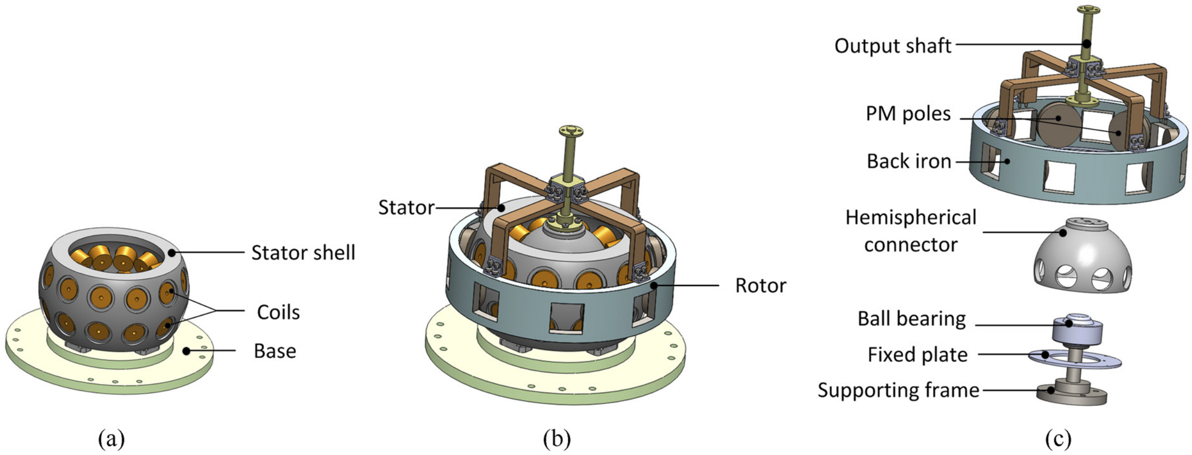


**Fig. 1.** Structure of the spherical actuator: (b) overview construction; (a) the stator and (c) exploded view of the rotor.

circuit (MEC) model has been adopted as an effective tool to formulate the magnetic field of conventional single-axis actuators [16,17]. The principle of MEC lies in that each lumped element with equivalent permeance is regarded as a part of the magnetic circuit network. The magnetic potential and flux can be calculated utilizing the similarity of electric circuit and magnetic circuit. Although Li et al. have developed it to three-dimensional (3-D) magnetic field modeling [18], this method is mostly used in two-dimensional (2-D) modeling. Hence, together with its numerous approximations and accuracy loss, the technique is not suitable for spherical actuator to some degree. The magnetic charge (MC) model is employed by Van Ninhuijs et al. [19] to describe the spatial distribution of the magnetic field. In this model, the magnets are replaced by an equivalent spatial distribution of magnetic charges. But this method is not convenient for torque calculation and design optimization. The harmonic model by solving the Laplace's equations based on certain boundary conditions seems to be a good choice. The magnetic field model is established through linear superposition, and then the force and torque expressions can be derived directly. However, in most studies [20–22,31,32], for the purpose of simplifying equations and facilitating modeling, only the fundamental terms are taken for magnetic modeling. This will unavoidably lead to some extent inaccuracy. Moreover, the harmonic model cannot be directly used for magnetic field modeling of spherical actuator with cylindrical shaped PM poles. In the previous studies, hybrid models were put forward. Yan et al. proposed a hybrid analytical-experimental torque output model [23,24]. The process of parameters correcting is time consuming. Rossini et al. developed a hybrid FEM-analytical model for reaction sphere (RS) rotor [25,26]. The magnetic field model used general analytical solution to the Laplace equation, while the harmonic decomposition coefficients were determined by FEM simulations. However, this method is not suitable for magnetic field modeling of cylindrical shaped magnets.

The objective of this paper is to provide a suitable magnetic field model of spherical actuator with cylindrical shaped PM poles which are more suitable for electromagnetic machine design. Therefore, a novel magnetic field modeling method that combines geometrical equivalence principle and harmonic model is proposed. In this method, three equivalence principles are put forward. Thus, the key parameters of cylindrical shaped poles are replaced by parameters of approximated dihedral cone shaped poles which are more flexible in spherical coordinates. Then, the optimal principle is chosen according to the result of finite element method (FEM). By employing the accurate harmonic model that takes multiple order harmonic terms into consideration, the magnetic field of spherical actuator is formulated. In addition, the numerical validation is conducted. The results prove that this method can be effective for magnetic field modeling of cylindrical shaped PM poles with high accuracy. The proposed magnetic field model can be directly used for subsequent performance testing and precision control. Furthermore, the modeling technique can be utilized within the optimization loop. The rest is organized as follows:

(1) The structure is presented in details and the connection of rotor and stator is illustrated. And then, the working principle of realizing 3-DOF motions is introduced.
(2) Three equivalence principles are recommended to replace the cylindrical PM pole with pole of dihedral cone shape. The parameters are corresponding respectively.
(3) The magnetic field of spherical actuator with outer rotor is figured in both 2-D and 3-D view. The result is validated by FEM.
(4) The research prototype is described and the obtained experiment data is used to prove the analytical and numerical process. The whole paper ends with a comprehensive conclusion.

## 2. Structure and working principle

### 2.1. Structure

The structure of the spherical actuator is illustrated in Fig. 1(b). The actuator is mainly composed of stator with coils and rotor with PM poles. The other two sub-figures present the details and the assembly relationship of stator and rotor, respectively. Fig. 1(a) implies that twenty four coils are mounted on the stator evenly in two layers. The stator shell is placed on the base of spherical actuator. There are totally eight PM poles distributed along the rotor equator to produce flux density around stator, shown as Fig. 1(c). The back iron is holed to reduce the mass of spherical actuator. The shape of PM poles is designed as solid cylinder and the poles are parallel magnetized along the axis of the cylinder. The output shaft is connected with the rotor through the back iron and a ball bearing is installed on the supporting frame. More specifically, the hemispherical connector and the fixed plate are connected to the output shaft and the ball bearing helps to realize multiple DOF motions output. There are mainly two reasons for designing holes in the hemispherical connector. On the one hand, the holes can be used to reduce the moment of inertia. On the other hand, it is a design option to hold additional PM to improve the torque output for future study.