Journal of Magnetism and Magnetic Materials 452 (2018) 278–287

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Research articles

Magnetically-driven medical robots: An analytical magnetic model for endoscopic capsules design

Jing Li [a,b,*], Erfan Shojaei Barjuei [b], Gastone Ciuti [b], Yang Hao [c], Peisen Zhang [c], Arianna Menciassi [b], Qiang Huang [a,c], Paolo Dario [a,b]

[a] Advanced Innovation Center for Intelligent Robots and Systems, Beijing Institute of Technology, Beijing, China
[b] The Biorobotics Institute, Sant'Anna School of Advanced Studies, Pontedera (Pisa), Italy
[c] Intelligent Robotics Institute, School of Mechatronical Engineering, Beijing Institute of Technology, Beijing, China

ARTICLE INFO

Article history:
Received 10 July 2017
Received in revised form 15 November 2017
Accepted 25 December 2017
Available online 26 December 2017

Keyword:
Medical robots
Active-locomotion capsule robots
Magnetic modeling
Permanent magnets design

ABSTRACT

Magnetic-based approaches are highly promising to provide innovative solutions for the design of medical devices for diagnostic and therapeutic procedures, such as in the endoluminal districts. Due to the intrinsic magnetic properties (no current needed) and the high strength-to-size ratio compared with electromagnetic solutions, permanent magnets are usually embedded in medical devices. In this paper, a set of analytical formulas have been derived to model the magnetic forces and torques which are exerted by an arbitrary external magnetic field on a permanent magnetic source embedded in a medical robot. In particular, the authors modelled cylindrical permanent magnets as general solution often used and embedded in magnetically-driven medical devices. The analytical model can be applied to axially and diametrically magnetized, solid and annular cylindrical permanent magnets in the absence of the severe calculation complexity. Using a cylindrical permanent magnet as a selected solution, the model has been applied to a robotic endoscopic capsule as a pilot study in the design of magnetically-driven robots.

1. Introduction

Magnetic interaction among magnetic sources including permanent and electromagnetic magnets has shown interesting features, *e.g.* motion transmission free from physical barriers and localization assistance in absence of line-of-sight. Therefore, magnetically-driven medical applications, especially those involving the interaction between the magnetic source and the human body have been explored, and several significant accomplishments have been already achieved [1–8]. Compared to electromagnetically-driven devices, permanent magnets are, most of the time, preferable choices in different applications due to the reduced cost, no need of power supply and high strength-to-size ratio. Permanent magnets have found many applications for the design of medical systems, *e.g.* localization [9], actuation [10,11], screening and drug delivery [12]. In this regard, effective magnetic model is one of the most important requirements for the design of medical devices using permanent magnets as actuation or driving sources.

Up to now, several works have been presented on magnetic modeling. Although there are different approaches to model the forces and torques for magnetic interaction [13–17], challenging issues still exist, *e.g.*, methods depend much on: (1) the different definition of energy/coenergy in permanent magnet which may create uncertainty [13], (2) experimental intermagnetic force estimation using several distributed points on the magnetic cylinder may become quite demanding on point distribution definition, and (3) measurement accuracy [17]. Dipole model is a well developed and widely used magnetic modeling solution [18,19]. This model treats the field source as a magnetic dipole and consequently leads to a simplified mathematical expression of the field. Several magnetics-based studies, *e.g.*, magnetic dipole localization [3], have been proposed based on this modelling approach. However, the disadvantage of this model is that the geometric contribution of the field source is not well included in the mathematical expression, which results in a low-accuracy estimation of the field when the observed point is approaching the source.

Charge model and current models are other kinds of solutions to approximate the magnetic field flux density, interaction forces and torques of magnetic sources. The basic idea of the charge model is to replace the permanent magnet using the equivalent spatial distribution of magnetic charges [20], while the permanent magnet is reduced to a distribution of equivalent current with the current model [21,22]. Both models take the geometry of the magnetic source into consideration and therefore involve volume and

* Corresponding author at: Advanced Innovation Center for Intelligent Robots and Systems, Beijing Institute of Technology, Beijing, China.
E-mail address: 10902016@bit.edu.cn (J. Li).

https://doi.org/10.1016/j.jmmm.2017.12.085
0304-8853/

surface integration in the mathematical expression. Better accuracy can be available in the proximity of the magnetic source when charge model or current models are used rather than the dipole model. However, geometry dependent integration easily leads to increased computation complexity, *e.g.*, the mathematical operations occur in all the surfaces of a diametrically magnetized cylinder in the current–density-based force/torque expression, while the mathematical operations occur in different surfaces of the cylinder with different magnetization directions in the charge-density-based force/torque expression. This will inevitably increase the computation complexity or inconvenience of switching between different surfaces.

In previous works, the authors developed a ready-to-use approach based on the current model to derive the forces and torques exerted on a solid and axially magnetized cylinder [23,24]. In this study, we present a set of unified analytical formulas to model the magnetic interaction forces and torques, as a tool for modelling magnetically-driven medical devices using embedded permanent magnets. Through applying magnetic model based on current density to an axially magnetized cylinder and magnetic model based on charge density to a diametrically magnetized cylinder, all the mathematical operations to calculate the magnetic interaction forces and torques are limited within a continuous lateral surface which leads to a set of unified analytical formulas. The underlying advantage is that the unified analytical models can be used for axially and diametrically magnetized, solid and annular cylindrical permanent magnets without increasing the calculation complexity. In order to demonstrate the application of the proposed magnetic model, a method to define the internal permanent magnet features in a medical endoscopic capsule robot is proposed.

This paper is organized as follows: first, the proposed magnetic models are derived in Section II; second, validation of the proposed magnetic models through comparison with the FEM methods is demonstrated in Section III; then, in the following Section IV, the application of the proposed magnetic models through design of the permanent magnet component in a capsule robot is exemplified; finally, Section V provides the conclusions of the paper.

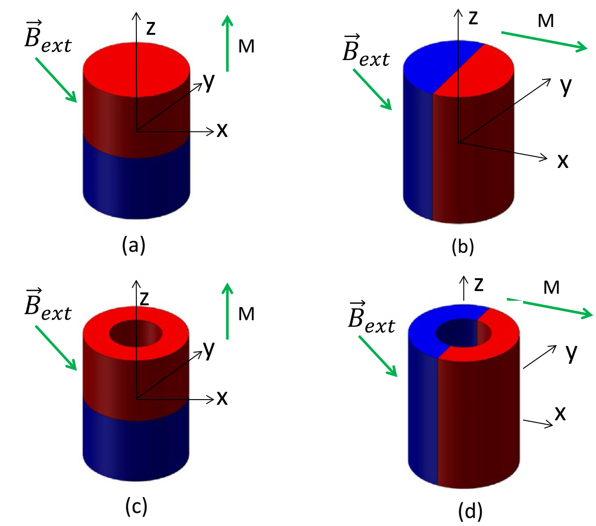

Fig. 1. Solid and annular cylinders with axial and diametrical magnetization. $\vec{B}_{ext}$ is an arbitrary external magnetic filed, M is the magnetization of the solid or annular cylinder. In (a) and (c), M is along z axis, while in (b) and (d), M is along x axis.

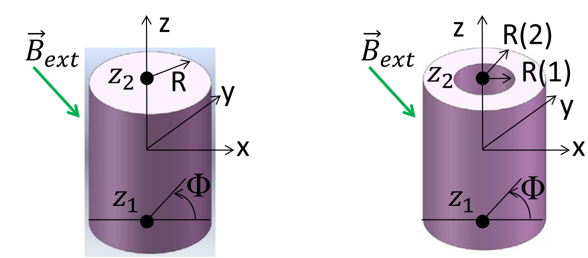

Fig. 2. Geometric parameters for the solid and annular cylinders. z_1 and z_2 are positions where the center of the bottom and top surfaces cross the z axis, $R(2)$ and $R(1)$ are the radii of the outer and inner lateral surfaces, Φ is the angle rotates form the x axis

2. Analytical magnetic model for force and torque calculating

2.1. Problem description

Derivation of the forces and torques exerted on a solid or annular cylinder with axial or diametrical magnetization by an arbitrary external field (Fig. 1) is a kind of widely used application scenario. The main objective is to develop the analytical magnetic model to derive the magnetic interaction forces and torques for this application. In the following of this section, through combining the derived formulas based on current model and charge model for magnetic forces and torques, the unified formulas without increased computation complexity are presented. The unified formulas are realized because the mathematical operations, e.g., integration, for magnetic forces and torques are successfully limited within the continuous lateral surface of the cylinder (defined by the geometric parameters of z and Φ in Fig. 2).

2.2. Magnetic model for axially magnetized cylindrical magnet

The current model with constant magnetization given in the work [25] is as follows:

$$\vec{F} = \int \vec{j_m} \times \vec{B_{ext}}\, ds = M \int_{z_1}^{z_2} \int_0^{2\pi} \vec{\Phi} \times \vec{B_{ext}}\, R d\Phi' dz'$$
$$\vec{T} = \int \vec{r} \times (\vec{j_m} \times \vec{B_{ext}}) ds \quad (1)$$

where $j_m = \vec{M} \times \vec{n}$ is the surface current density, $\vec{\Phi}$ is the unit angular vector, R is the radius for the integration surface, $\vec{r}$ is the displacement from the point where torque is calculated to the integration point on the surface.

In order to derive the final formulas for forces and torques, we introduce the necessary intermediate mathematical relations as follows:

$$\begin{aligned} \vec{B_{ext}} &= B_x \vec{x} + B_y \vec{y} + B_z \vec{z} \\ \vec{r} &= r_x \vec{x} + r_y \vec{y} + r_z \vec{z} \\ \vec{r} &= (x_t - x_o)\vec{x} + (y_t - y_o)\vec{y} + (z_t - z_o)\vec{z} \end{aligned} \quad (2)$$

where (x_t, y_t, z_t) is the integration point on the surface and (x_o, y_o, z_o) is the point where torque is calculated.

The derived force and torque formulas are as follows:

$$\vec{F} = M \int_{z_1}^{z_2} \int_0^{2\pi} \left[cos\Phi B_z \vec{x} + sin\Phi B_z \vec{y} + (-sin\Phi B_y - cos\Phi B_x)\vec{z} \right] R d\Phi' dz' \quad (3)$$

$$\begin{aligned} \vec{T} = M \int_{z_1}^{z_2} \int_0^{2\pi} \Big[& -(r_y sin\Phi B_y + r_y cos\Phi B_x + r_z sin\Phi B_z)\vec{x} \\ & + (r_x sin\Phi B_y + r_x cos\Phi B_x + r_z cos\Phi B_z)\vec{y} \\ & + (r_x sin\Phi B_z - r_y cos\Phi B_z)\vec{z} \Big] R d\Phi' dz' \end{aligned} \quad (4)$$