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Using Coulombian Approach for Modeling Scalar Potential and Magnetic Field of a Permanent Magnet With Radial Polarization

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New compact semianalytical expressions of the scalar potential and magnetic fields produced by a radially polarized permanent magnet are described in this paper by using Coulombian approach. It uses fictitious magnetic charge to model the magnetic field intensity. With this fast model, we can compute the demagnetization field in each point inside the permanent magnet and the magnetic fields outside it.

Index Terms—Analytical model, magnetic field, radial polarized magnet.

I. INTRODUCTION

RADIAL polarized sector permanent magnets are often used in electromagnetic device. Most applications of this type of magnet were found in electrical motor and no-contact magnetic torque transmitter [1]. Recently, new application of this type of magnet is encountered in diamagnetic levitation device, used for microparticle sorting [2], 3-D force sensor [3], and accelerometer; those applications lead us to realize this device, used for microparticle sorting [2], 3-D force sensor [3], and accelerometer; those applications lead us to realize this

The magnetic field is only produced by the magnet, so (3) becomes

\[ \nabla \times \mathbf{H} = 0. \]

Taking the material properties into account

\[ \mathbf{D} = \varepsilon_0 \mathbf{E} \]
\[ \mathbf{B} = \mu_0 \mathbf{H} + \mathbf{J} \]

\( \varepsilon_0 \) and \( \mu_0 \) are, respectively, the permittivity and the permeability of the vacuum, and \( \mathbf{J} \) is the polarization of the magnet.

By using (6) and (7), expression (2) and (4) become, respectively, (8) and (9)

\[ \nabla \cdot \mathbf{D} = \rho \]
\[ \nabla \cdot \mathbf{B} = \frac{\nabla \cdot \mathbf{J}}{\mu_0} \]

Equations (1) and (8) show the duality between electrical field and electrical charge density \( \rho \) in electrostatic problem.

If we introduce the fictitious magnetic charge density \( \sigma \) and by applying the same duality as in (1) and (8) between magnetic field and fictitious magnetic charge in magnetostatic equations (5) and (9), we can write

\[ \nabla \cdot \mathbf{H} = \sigma / \mu_0. \]

By identification with (9), the fictitious charge density is

\[ \sigma = -\nabla \cdot \mathbf{J}. \]

This fictitious magnetic charge density \( \sigma \) is composed by a volume charge density \( \sigma_v \) and surface charge density \( \sigma_s \) (Fig. 1).
If the magnetic polarization $J$ is uniform and radial, the expression of $\sigma_v$ in cylindrical coordinate system $(r, \theta, z)$ is

$$\sigma_v = -\nabla \cdot J = \frac{-J}{r}. \quad (12)$$

Finding the surface charge density $\sigma_s$ is straightforward; it can be obtained by referencing (4), which means that, considering the entire volume of the magnet, there was no monopole magnetic charge, so

$$\int \int \sigma_s ds + \int \int \sigma_v dv = 0. \quad (13)$$

$\mathbf{n}'$ defines the unit vector normal to surface; by using (12) and applying Green’s theorems, after identification, we obtain

$$\sigma_s = \mathbf{J} \cdot \mathbf{n}' \quad (14)$$

**B. Electrostatic Equivalent Model**

Finally, the electrostatic equivalent model of the permanent magnet with radial polarization can be illustrated as in Fig. 1. By projecting the polarization into the six surfaces of a magnet, the surface charge densities exist only in the inner and outer surface of the magnet.

The volume charge decreases according to a $1/r$ function from the inner to the outer surface. From (5), we can proof the existence of the magnetic scalar potential $\varphi$ with

$$\mathbf{H} = -\nabla \cdot \varphi. \quad (15)$$

Basic expression for scalar potential and field calculation produced by the permanent magnet are obtained in (17) and (17), by using the electrostatic approach

$$\varphi = \frac{1}{4\pi \mu_0} \left( \int \int_s \frac{\sigma_s}{|\mathbf{r} - \mathbf{r}'|} ds + \int \int_v \frac{\sigma_v}{|\mathbf{r} - \mathbf{r}'|} dv \right). \quad (16)$$

By applying (15), the magnetic field intensity is

$$\mathbf{H}_P = \frac{1}{4\pi \mu_0} \left( \int \int_s \frac{\sigma_s}{|\mathbf{r} - \mathbf{r}'|} d\mathbf{s} + \int \int_v \frac{\sigma_v}{|\mathbf{r} - \mathbf{r}'|} d\mathbf{v} \right). \quad (17)$$

III. SCALAR POTENTIAL

After integrating (16) analytically, we obtain a single numerical integration with the parameterization shown in Fig. 3

$$\varphi(r, \theta, z) = \frac{J}{4\pi \mu_0} \sum_{i=1}^{\theta_2} \sum_{j=1}^{2} e^{i j} \sin(\alpha) d\theta d\theta' \quad (18)$$

By using $\alpha = \theta' - \theta$ with $\theta_1 \leq \theta' \leq \theta_2$ and

$$\begin{align*}
G(\alpha) &= \sqrt{(r - r' \cos(\alpha))^2 + (r' \sin(\alpha))^2 + (z - z')^2} \\
&= (z - z')^2 (1 - \ln(r' - r \cos(\alpha)) - G(\alpha)) + (z - z')^2 \sqrt{G(\alpha) + r' \ln((z - z')^2)} + G(\alpha) + r' \ln((z - z')^2) + G(\alpha) + r' \sin(\alpha) \frac{\arctan \left( \frac{(z - z')^2 \sin^2(\alpha)}{r \sin^2(\alpha) G(\alpha)} \right)}{r \sin(\alpha)} - \arctan \frac{(z - z')}{(r \sin(\alpha))} \quad (19)
\end{align*}$$

IV. MAGNETIC FIELD EXPRESSION

After defining the magnetic scalar potential of the magnet, we can express the three components of the field by using (15).
A. Radial Component of the Field

Formula of the radial field component is

\[ H_r(r, \theta, z) = \frac{J}{4\pi \mu_0} \sum_{i=1}^{\theta_2} \sum_{j=1}^{2} (-1)^{i+j} r_j^i dH_r(r, \theta, z, r_j^i, \theta_j^i, z_j^i) \]  

(21)

d\( H_r \) can be written as follows:

\[
dH_r(r, \theta, z, r_j^i, \theta_j^i, z_j^i) = \frac{-r_j^i (z - z_j^i) (r - r_j^i \cos(\alpha))}{[(r - r_j^i \cos(\alpha))^2 + (r_j^i \sin(\alpha))^2] \cdot G(\alpha)} + \sin(\alpha) \arctan \left[ \frac{(z - z_j^i) (r_j^i - r \cos(\alpha))}{(r \sin(\alpha)) \cdot G(\alpha)} \right] - \cos(\alpha) \ln[G(\alpha) - (z - z_j^i)]. \]  

(22)

B. Azimuthal Component

\[ H_\theta(r, \theta, z) = \frac{J}{4\pi \mu_0} \sum_{i=1}^{\theta_2} \sum_{j=1}^{2} (-1)^{i+j} r_j^i dH_\theta(r, \theta, z, r_j^i, \theta_j^i, z_j^i) \]  

(23)

with

\[
dH_\theta(r, \theta, z, r_j^i, \theta_j^i, z_j^i) = \frac{-r_j^i (z - z_j^i) (r_j^i \sin(\alpha))}{[(r - r_j^i \cos(\alpha))^2 + (r_j^i \sin(\alpha))^2] \cdot G(\alpha)} - \cos(\alpha) \arctan \left[ \frac{(z - z_j^i) (r_j^i - r \cos(\alpha))}{(r \sin(\alpha)) \cdot G(\alpha)} \right] - \sin(\alpha) \ln[G(\alpha) - (z - z_j^i)]. \]  

(24)

C. Axial Component

\[ H_z(r, \theta, z) = \frac{J}{4\pi \mu_0} \sum_{i=1}^{\theta_2} \sum_{j=1}^{2} (-1)^{i+j} r_j^i dH_z(r, \theta, z, r_j^i, \theta_j^i, z_j^i) \]  

(25)

with

\[
dH_z(r, \theta, z, r_j^i, \theta_j^i, z_j^i) = \frac{r_j^i}{G(\alpha)} \ln[(r_j^i - r \cos(\alpha)) + G(\alpha)] + \frac{1}{2} \ln[(r \sin(\alpha))^2 + (z - z_j^i)^2]. \]  

(26)
Fig. 6. Azimuthal component of the field from $\theta = -45^\circ$ to $\theta = 45^\circ$, with $r = 2.5$ mm and $z = 0$ mm.

Fig. 7. Axial component of the field from $z = -2.5$ mm to $z = 2.5$ mm, with $r = 2.5$ mm and $\theta = 0^\circ$.

C. Comparing the Axial Component

As the azimuthal component, the behavior of the axial component (Fig. 7) is continued, because it is the normal component of the magnetic field intensity.

D. Magnetic Field Radiated by a Cylinder Magnet

The distribution of the modulus of the magnetic field radiated by a ring-shaped magnet is depicted in Fig. 8. The polarization remains radial. Let us remark the presence of a hole of field in the center of the magnet; this feature is significant if diamagnetic levitation is required [3].

VI. Conclusion

This article proposes a fast 3-D semianalytical expression of the scalar potential and the magnetic field produced by an arc-shaped permanent magnet with radial polarization. The result can also be used for ring-shaped magnet. Expressions of the scalar potential and the magnetic field intensity is detailed and compared with a finite element method (FEM) simulation.

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