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► **To cite this version:**

Romain Ravaud, Guy Lemarquand, Valérie Lemarquand. Magnetic Field Created by Tile Permanent Magnets. IEEE Transactions on Magnetics, 2009, 45 (7), pp.2920-2926. 10.1109/TMAG.2009.2014752 . hal-00401733

HAL Id: hal-00401733

<https://hal.science/hal-00401733>

Submitted on 6 Jul 2009

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Magnetic Field Created by Tile Permanent Magnets

R. Ravaud, G. Lemarquand, V. Lemarquand

Abstract

This paper presents the analytical calculation of the three components of the magnetic field created by tile permanent magnets whose magnetization is either radial or axial. The calculations are based on the coulombian model of permanent magnets. The magnetic field is directly calculated, without the magnetic potential. Both axial and radial magnetization of the tiles are considered. The expressions obtained give the magnetic field in all the space. Such analytical expressions are very useful for the design and optimization of many industrial applications.

Index Terms

Analytical model, magnetic field, permanent magnet, axial magnetization, radial magnetization

I. INTRODUCTION

AFTER the parallelepiped, the most common shape for a permanent magnet in electrical engineering is certainly the tile, which can also be described as a ring sector. Such tiles can be either axially or radially magnetized. Therefore, the calculation of the magnetic field created by tile magnets is of great utility and numerous approaches exist.

Numerical approaches do not allow one to perform numerous parametric studies quickly and have generally a high computational cost. Consequently, authors are looking for alternative solutions. Their approaches are often semianalytical ones [1], and they represent important steps toward the ideal analytical

Manuscript Received April 10, 2008.

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18 ones. In fact, different points of view can be adopted, which all look for the same thing: the calculation of
19 the magnetic field and the magnetic forces. Kim et al. [2][3] calculate the magnetic force from the vector
20 potential, with complete elliptic integrals and a mesh-matrix method. Kwon et al.[4] work with spherical
21 coordinates and multipole expansions to calculate the far field of permanent magnet motors. Selvaggi et
22 al.[5] propose an approach with cylindrical coordinates and the use of Green's function and Fourier series
23 expansion to characterize the field from a set of permanent magnets. Babic and Akyel [6]-[8] calculate the
24 force between coils thanks to Heuman's Lambda function. Toroidal harmonics yield interesting solutions
25 to formulate the magnetic field created by permanent magnet cylinders [9]. Conway uses Bessel's function
26 to calculate the inductance of coils using the vector potential [10] and proposes also a direct calculation
27 of the magnetic field -without the vector potential- to reach the same goal [11].

28 While these studies show variety in the starting point for the problem they want to solve, many others
29 are more specific and describe methods to calculate the magnetic field created by toroidal magnets. Perigo
30 et al.[12] present analytical-integral expressions for the axial and radial magnetic flux density components
31 of axially magnetized toroidal magnets, either on- or off-axis. The application considered is an electron
32 beam focusing system. Zhilichev [13] works with cylindrical coordinates and uses separation of variables
33 to evaluate the magnetic field from the scalar potential for tubular linear permanent magnet machines. He
34 gives 2D and 3D approximations. Furlani et al. propose solutions based on the vector potential for radially
35 polarized multipole cylindrical magnets [14] as well as for axially polarized magnets for axial field motors
36 [15][16]. Rakotoarison et al.[17] give a semianalytical method to calculate the field created by radially
37 magnetized tile magnets from the scalar potential. They use a coulombian model of the magnets and take
38 the volume charge density into account.

39 All the studies dedicated to the calculation of the magnetic field created by toroidal or tile magnets are
40 very useful: they constitute tools for the design and the optimization of devices which use such magnets
41 and enable to meet specific requirements. For example, tile magnets with rotating magnetizations are
42 used to make discrete Halbach cylinders [18] which have various applications, such as electrodynamic
43 wheels [19] for maglev devices, the creation of homogeneous fields or tailored gradient fields [20], the
44 magnetization of brushless machines to obtain sinusoidal field variation in the airgap [21]. Tile magnets
45 are used with peculiar profiles to reduce the cogging torque in axial flux machines [22] as well as in radial

46 flux ones [23], but also to control the torque in permanent magnet couplings [24][25] and gears. They
 47 are constitutive parts of displacement sensors [26] and also ironless loudspeakers [27][28] demonstrating
 48 their widespread use.

49 This paper presents analytical expressions for the three components of the magnetic field created by
 50 tile permanent magnets. The magnetic field is directly calculated, without a previous calculation of the
 51 scalar or vector potential[29][30][31]. The expressions given are for a ring sector, but remain valid when
 52 the sector is extended to the whole ring. The axial magnetization of the tiles is considered in the first
 53 section below and the radial magnetization in the second.

54 II. AXIALLY MAGNETIZED TILES

55 A. Notation and Geometry

56 The geometry which is considered is a tile permanent magnet and the related parameters are shown
 57 in Fig.1. The tile inner radius is r_{in} , the tile outer one is r_{out} and its height is h . The angular width of
 58 the tile is $\theta_2 - \theta_1$. The axis z is an axis of symmetry. The coulombian model of a permanent magnet is
 59 used. Consequently, the tile permanent magnet is represented by two curved planes which correspond to
 60 the upper ($z = h$) and lower ($z = 0$) faces of the ring sector. The upper one is charged with a surface
 61 magnetic pole density $+\sigma^*$; the lower one is charged with the opposite surface magnetic pole density
 62 $-\sigma^*$. All the illustrative calculations are done with $\sigma^* = \vec{J} \cdot \vec{n} = 1T$. In order to simplify the calculations,
 63 the upper face only is taken into account to determine the three magnetic field components. However,
 64 the total magnetic field can be calculated by the application of the linear superposition principle to both
 65 faces.

66 Let us consider a point P on the ring sector upper face. The magnetic field \vec{H} created by the source
 67 point $P(r, \theta_s, z)$ at any observation point $M(r, \theta, z)$ of the space is given by (1).

$$\vec{H}(r, \theta, z) = \frac{\sigma^*}{4\pi\mu_0} \int_{\theta_1}^{\theta_2} \int_{r_{in}}^{r_{out}} \frac{\overrightarrow{PM}}{|\overrightarrow{PM}|^3} r_1 dr_1 d\theta_s \quad (1)$$

68 where μ_0 is the vacuum magnetic permeability ($\mu_0 = 4\pi \cdot 10^{-7} SI$) and σ^* is the fictitious magnetic pole

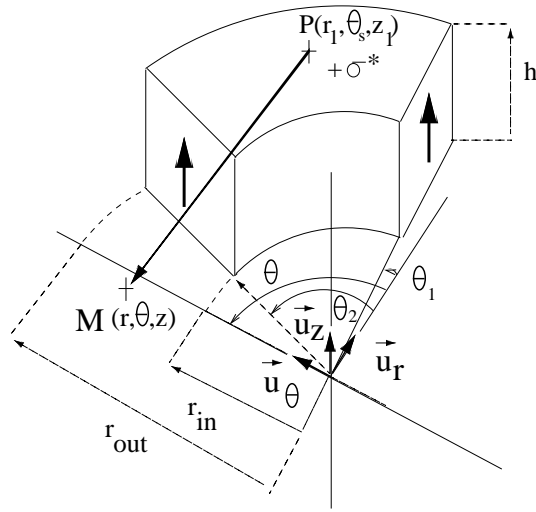


Fig. 1. Axially magnetized tile permanent magnet : parameter definition.

69 surface density in tesla. Equation (1) can be written as follows:

$$\vec{H}(r, \theta, z) = \frac{\sigma^*}{4\pi\mu_0} \int_{\theta_1}^{\theta_2} \int_{r_{in}}^{r_{out}} \frac{(r - r_1 \cos(\theta - \theta_s))\vec{u}_r - r_1 \sin(\theta_s - \theta)\vec{u}_\theta + (z - z_1)\vec{u}_z}{(r_1^2 + r^2 + (z - z_1)^2 - 2r_1 r \cos(\theta - \theta_s))^{\frac{3}{2}}} r_1 dr_1 d\theta_s \quad (2)$$

70 *B. Components along the three directions \vec{u}_r , \vec{u}_θ , \vec{u}_z*

71 The integration of (2) leads to the magnetic field components along the three axes defined $H_r(r, \theta, z)$,
72 $H_\theta(r, \theta, z)$, $H_z(r, \theta, z)$.

73 1) *Azimuthal component $H_\theta(r, \theta, z)$* : The magnetic field azimuthal component $H_\theta(r, \theta, z)$ created by
74 the upper face is given by (3).

$$H_\theta(r, \theta, z) = \frac{\sigma^*}{4\pi\mu_0} (\eta(\theta, \theta_1) - \eta(\theta, \theta_2)) \quad (3)$$

75 with

$$\begin{aligned} \eta(\theta, \theta_i) = & \frac{\sqrt{r^2 + r_{in}^2 + (z - h)^2 - 2rr_{in} \cos(\theta_i - \theta)}}{r} \\ & + \cos(\theta_i - \theta) \log \left[r_{in} - r \cos(\theta_i - \theta) + \sqrt{r^2 + r_{in}^2 + (z - h)^2 - 2rr_{in} \cos(\theta_i - \theta)} \right] \\ & - \frac{\sqrt{r^2 + r_{out}^2 + (z - h)^2 - 2rr_{out} \cos(\theta_i - \theta)}}{r} \end{aligned}$$

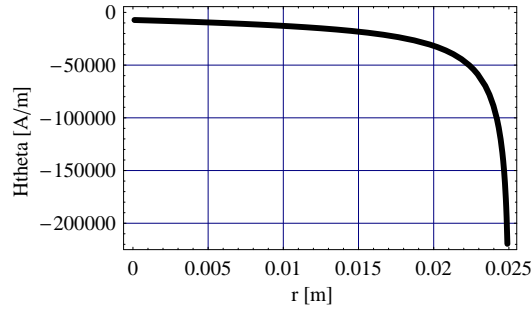


Fig. 2. Field azimuthal component $H_\theta(r, \theta, z)$ versus the radial distance r of the observation point; $h = 3\text{mm}$, $r_{in} = 25\text{mm}$, $r_{out} = 28\text{mm}$, $\theta_1 = 0$, $\theta_2 = \frac{\pi}{2}$, $\theta = \frac{\pi}{2}$

$$-\cos(\theta_i - \theta) \log \left[r_{out} - r \cos(\theta_i - \theta) + \sqrt{r^2 + r_{out}^2 + (z - h)^2 - 2rr_{out} \cos(\theta_i - \theta)} \right] \quad (4)$$

76 Equation (3) is valid for any observation point $M(r, \theta, z)$ with $0 \leq \theta \leq 2\pi$. Figure 2 represents the
 77 azimuthal component $H_\theta(r, \theta, z)$ versus the radial distance r of the observation point. The parameter values
 78 are $h = 3\text{ mm}$, $\theta_1 = 0\text{ rad}$, $\theta_2 = \frac{\pi}{2}\text{ rad}$, $\theta = 0\text{ rad}$, $r_{in} = 25\text{ mm}$, $r_{out} = 28\text{ mm}$.

79 2) *Radial component $H_r(r, \theta, z)$* : The field radial component $H_r(r, \theta, z)$ created by the upper face is
 80 given by (5).

$$H_r(r, \theta, z) = \frac{\sigma^*}{4\pi\mu_0} (\alpha(u_2, r, z) - \alpha(u_1, r, z)) \quad (5)$$

81 where

$$u_i = \cos(\theta - \theta_i) \quad (6)$$

82 and

$$\begin{aligned} \alpha(u_i, r, z) = & F_1(u_i, r, z) \left(G_1(u_i, r, z) \mathbf{E}^* \left[\arcsin \left[\frac{\sqrt{r^2 + r_{out}^2 - 2rr_{out}u_i + (z-h)^2}}{(r+r_{out})^2 + (z-h)^2} \right], \frac{(r+r_{out})^2 + (z-h)^2}{(r-r_{out})^2 + (z-h)^2} \right] \right) \\ & + F_1(u_i, r, z) \mathbf{\Pi}^* \left[\arcsin \left[\frac{\sqrt{r^2 + r_{out}^2 - 2rr_{out}u_i + (z-h)^2}}{(r+r_{out})^2 + (z-h)^2} \right], \frac{(r+r_{out})^2 + (z-h)^2}{(r-r_{out})^2 + (z-h)^2} \right] \\ & - F_2(u_i, r, z) \left(G_2(u_i, r, z) \mathbf{E}^* \left[\arcsin \left[\frac{\sqrt{r^2 + r_{in}^2 - 2rr_{in}u_i + (z-h)^2}}{(r+r_{in})^2 + (z-h)^2} \right], \frac{(r+r_{in})^2 + (z-h)^2}{(r-r_{in})^2 + (z-h)^2} \right] \right) \end{aligned}$$

$$\begin{aligned}
& -F_2(u_i, r, z) \Pi^* \left[\arcsin \left[\frac{\sqrt{r^2 + r_{in}^2 - 2rr_{in}u_i + (z-h)^2}}{(r+r_{in})^2 + (z-h)^2} \right], \frac{(r+r_{in})^2 + (z-h)^2}{(r-r_{in})^2 + (z-h)^2} \right] \\
& + \frac{(u_i^2 - 1)}{\sqrt{1 - u_i^2}} \log \left[r_{out} - ru_i + \sqrt{r^2 + r_{out}^2 - 2rr_{out}u_i + (z-h)^2} \right] \\
& - \frac{(u_i^2 - 1)}{\sqrt{1 - u_i^2}} \log \left[r_{in} - ru_i + \sqrt{r^2 + r_{in}^2 - 2rr_{in}u_i + (z-h)^2} \right]
\end{aligned} \tag{7}$$

83 with :

$$F_1(u_i, r, z) = \frac{1}{\sqrt{1 - u_i^2}} \frac{2r_{out}(1 + u_i) \sqrt{\frac{rr_{out}(u_i-1)}{(r-r_{out})^2 + (z-h)^2}} \sqrt{\frac{r^2 + r_{out}^2 - 2rr_{out}u_i + (z-h)^2}{(r+r_{out})^2 + (z-h)^2}}}{\sqrt{\frac{rr_{out}(1+u_i)}{(r+r_{out})^2 + (z-h)^2}} \sqrt{r^2 + r_{out}^2 - 2rr_{out}u_i + (z-h)^2}} \tag{8}$$

84

$$F_2(u_i, r, z) = \frac{1}{\sqrt{1 - u_i^2}} \frac{2r_{in}(1 + u_i) \sqrt{\frac{rr_{in}(u_i-1)}{(r-r_{in})^2 + (z-h)^2}} \sqrt{\frac{r^2 + r_{in}^2 - 2rr_{in}u_i + (z-h)^2}{(r+r_{in})^2 + (z-h)^2}}}{\sqrt{\frac{rr_{in}(1+u_i)}{(r+r_{in})^2 + (z-h)^2}} \sqrt{r^2 + r_{in}^2 - 2rr_{in}u_i + (z-h)^2}} \tag{9}$$

85

$$G_1(r, z) = \frac{(r - r_{in})^2 + (z - h)^2}{2rr_{in}} \tag{10}$$

86

$$G_2(r, z) = \frac{(r - r_{out})^2 + (z - h)^2}{2rr_{out}} \tag{11}$$

87

$$E^*[k] = \int_0^{\phi = \frac{\pi}{2}} \sqrt{1 - k^2 \sin^2(\theta)} d\theta \tag{12}$$

88 Equation (5) is valid for any observation point $M(r, \theta, z)$ with $\theta \neq \theta_i$ and $0 \leq \theta < 2\pi$. This expression
89 remains valid for ring permanent magnets, for which the angular width is 2π ($\theta_2 - \theta_1 = 2\pi$). It leads
90 to the expression of the radial component already given by the authors for ring magnets [32]. Figure 3
91 represents the field radial component $H_r(r, \theta, z)$ versus the radial distance r . The used parameters are
92 $h = 3$ mm, $\theta_1 = 0$ rad, $\theta_2 = \frac{\pi}{2}$ rad, $\theta = 0$ rad, $r_{in} = 25$ mm, $r_{out} = 28$ mm.

93 3) *Axial component $H_z(r, \theta, z)$* : The field axial component $H_z(r, \theta, z)$ created by the upper face is
94 given by (13).

$$H_z(r, \theta, z) = \frac{\sigma^*}{4\pi\mu_0} (\gamma(\theta, \theta_2) - \gamma(\theta, \theta_1)) \tag{13}$$

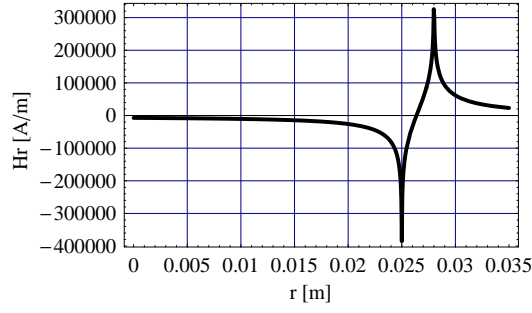


Fig. 3. Field radial component $H_r(r, \theta, z)$ versus the radial distance r of the observation point; $h = 3\text{mm}$, $r_{in} = 25\text{mm}$, $r_{out} = 28\text{mm}$, $\theta_1 = 0\text{ rad}$, $\theta_2 = \frac{\pi}{2}\text{ rad}$, $\theta = \frac{\pi}{2}\text{ rad}$

95 with

$$\begin{aligned}
\gamma(\theta, \theta_i) = & h_1 \eta_1(\theta, \theta_i) \mathbf{\Pi}^* \left[\frac{2(c_1 + d_1)f}{2c_1f - \sqrt{2}\sqrt{d_1^2 f(-e + f)}}, i \sinh^{-1} \left[\sqrt{\frac{-1}{c_1 + d_1}} \sqrt{c_1 - d_1 \cos(\theta - \theta_i)} \right], \frac{c_1 + d_1}{c_1 - d_1} \right] \\
& + h_2 \eta_1(\theta, \theta_i) \mathbf{\Pi}^* \left[\frac{2(c_1 + d_1)f}{2c_1f + \sqrt{2}\sqrt{d_1^2 f(-e + f)}}, i \sinh^{-1} \left[\sqrt{\frac{-1}{c_1 + d_1}} \sqrt{c_1 - d_1 \cos(\theta - \theta_i)} \right], \frac{c_1 + d_1}{c_1 - d_1} \right] \\
& - h_3 \eta_2(\theta, \theta_i) \mathbf{\Pi}^* \left[\frac{2(c_2 + d_2)f}{2c_2f - \sqrt{2}\sqrt{d_2^2 f(-e + f)}}, i \sinh^{-1} \left[\sqrt{\frac{-1}{c_2 + d_2}} \sqrt{c_2 - d_2 \cos(\theta - \theta_i)} \right], \frac{c_2 + d_2}{c_2 - d_2} \right] \\
& - h_4 \eta_2(\theta, \theta_i) \mathbf{\Pi}^* \left[\frac{2(c_2 + d_2)f}{2c_2f + \sqrt{2}\sqrt{d_2^2 f(-e + f)}}, i \sinh^{-1} \left[\sqrt{\frac{-1}{c_2 + d_2}} \sqrt{c_2 - d_2 \cos(\theta - \theta_i)} \right], \frac{c_2 + d_2}{c_2 - d_2} \right]
\end{aligned} \tag{14}$$

96 with

$$\eta_1(\theta, \theta_i) = \frac{\left(-i \sqrt{\frac{d_1(-1 + \cos(\theta - \theta_i))}{c_1 - d_1}} \sqrt{\frac{d_1(1 + \cos(\theta - \theta_i))}{c_1 + d_1}} \frac{1}{\cos(\theta - \theta_i)} \right)}{\left(2 \sqrt{\frac{-1}{c_1 + d_1}} \sqrt{d_1^2 f(-e + d_1)} (d_1^2 (e - f)) + 2c_1^2 f \right)} \tag{15}$$

97

$$\eta_2(\theta, \theta_i) = \frac{\left(-i \sqrt{\frac{d_2(-1 + \cos(\theta - \theta_i))}{c_2 - d_2}} \sqrt{\frac{d_2(1 + \cos(\theta - \theta_i))}{c_2 + d_2}} \frac{1}{\cos(\theta - \theta_i)} \right)}{\left(2 \sqrt{\frac{-1}{c_2 + d_2}} \sqrt{d_2^2 f(-e + d_2)} (d_2^2 (e - f)) + 2c_2^2 f \right)} \tag{16}$$

98

$$h_1 = 2ad_1(\sqrt{2}c_1f + \sqrt{d_1^2 f(-e + f)}) + b_1(\sqrt{2}d_1^2(e - f) - 2c_1\sqrt{d_1^2 f(-e + f)}) \tag{17}$$

| Parameters | |
|------------|-------------------------|
| a | $2(z-h)(r^2+(z-h)^2)$ |
| b_1 | $2(z-h)rr_{out}$ |
| c_1 | $r^2+r_{out}^2+(z-h)^2$ |
| d_1 | $-2rr_{out}$ |
| e | $-r^2-2(z-h)^2$ |
| f | r^2 |
| b_2 | $2(z-h)rr_{in}$ |
| c_2 | $r^2+r_{in}^2+(z-h)^2$ |
| d_2 | $-2rr_{in}$ |

TABLE I
DEFINITION OF THE PARAMETERS USED IN (13)

99

$$h_2 = 2ad_1(-\sqrt{2}c_1f + \sqrt{d_1^2f(-e+f)}) + b_1(\sqrt{2}d_1^2(-e+f) - 2c_1\sqrt{d_1^2f(-e+f)}) \quad (18)$$

100

$$h_3 = 2ad_2(\sqrt{2}c_2f + \sqrt{d_2^2f(-e+f)}) + b_2(\sqrt{2}d_2^2(e-f) - 2c_2\sqrt{d_2^2f(-e+f)}) \quad (19)$$

101

$$h_4 = 2ad_2(-\sqrt{2}c_2f + \sqrt{d_2^2f(-e+f)}) + b_2(\sqrt{2}d_2^2(-e+f) - 2c_2\sqrt{d_2^2f(-e+f)}) \quad (20)$$

102 where $\Pi^*[n, \phi, m]$ is given in terms of the incomplete elliptic integral of the third kind by (21).

$$\Pi^*[n, \phi, m] = \int_0^\phi \frac{1}{(1-n\sin(\theta)^2)\sqrt{1-m\sin(\theta)^2}} d\theta \quad (21)$$

103 Although the result $H_z(r, \theta, z)$ is a real number, equation (14) contains the imaginary number i ($i^2 = -1$)
 104 because we did not succeed in obtaining a real expression for the axial component $H_z(r, \theta, z)$. The
 105 parameters used in (14) are defined in Table I. However, as the imaginary part is the consequence of
 106 numerical noise and nearly equals zero, when the expression (14) is used in symbolic mathematical tools
 107 such as Mathematica or Maple, the real part of $H_z(r, \theta, z)$ only has to be considered. Equation (13) is
 108 valid for any observation point $M(r, \theta, z)$ with $\theta \neq \theta_i$ and $0 \leq \theta < 2\pi$. Here again, this expression
 109 remains valid for ring permanent magnets, i.e. when the angular width is 2π ($\theta_2 - \theta_1 = 2\pi$). It also
 110 leads to the expression of the axial component already given by the authors for ring magnets [32]. Figure
 111 4 represents the axial component $H_z(r, \theta, z)$ versus the radial distance r of the observation point. The
 112 parameter values are $h = 3$ mm, $\theta_1 = 0$ rad, $\theta_2 = \frac{\pi}{2}$ rad, $\theta = 0$ rad, $r_{in} = 25$ mm, $r_{out} = 28$ mm.

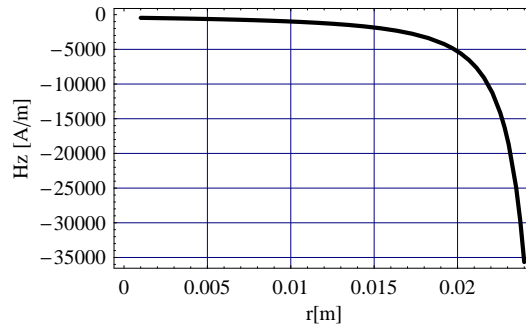


Fig. 4. Field axial component $H_z(r, \theta, z)$ versus the radial distance r of the observation point; $h = 3mm$, $r_{in} = 25mm$, $r_{out} = 28mm$, $\theta_1 = 0$ rad, $\theta_2 = \frac{\pi}{2}$ rad, $\theta = \frac{\pi}{2}$ rad

113

III. RADIALY MAGNETIZED TILES

A. Notation and geometry

115 The geometry and its parameters are shown in Fig.(5). The axis z is an axis of symmetry. Again, the
 116 coulombian model of permanent magnets is used. The permanent magnet ring sector is thus represented
 117 by two curved planes which correspond here to the inner and outer faces of the ring. The inner face is
 118 charged with a magnetic pole surface density $+\sigma^*$; the outer one is charged with the opposite magnetic
 119 pole surface density $-\sigma^*$. We only consider the inner face to simplify the analytical calculation. As stated
 120 previously, the total magnetic field can be calculated by the application of the linear superposition principle
 121 to both faces.

122 The magnetic pole volume density is not taken into account in this paper. This means that the total sum
 123 of all the charges in the model does not equal zero. Indeed, as the magnetization is radial, the magnetic
 124 pole surface density of the curved planes is uniform. The charge on the outer plane is thus greater than
 125 the charge on the inner plane, as the surfaces of these planes. The volume charge density, linked to the
 126 magnetization divergence, appears in fact to set the global charge to zero. If the radial width of the tile is
 127 small, which also means that the tile is thin, then the difference between the inner and outer plane surface
 128 is small, and so is the magnetic pole volume density: its neglecting is an acceptable approximation. This
 129 approximation becomes less and less valid when the thickness of the tile increases. This paper presents
 130 expressions for radially magnetized thin tiles.

131 Let us consider a point P on the tile inner face. The magnetic field \vec{H} created by the source point

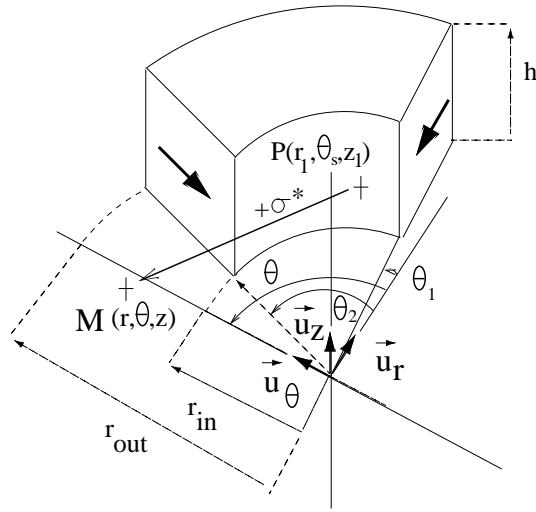


Fig. 5. Radially magnetized permanent magnet tile: parameter definition

132 $P(r, \theta_s, z)$ at any observation point $M(r, \theta, z)$ of the space is given by (22).

$$\vec{H}(r, \theta, z) = \frac{\sigma^*}{4\pi\mu_0} \int_{\theta_1}^{\theta_2} \int_0^h \frac{\overrightarrow{PM}}{|\overrightarrow{PM}|^3} r_1 dz_1 d\theta_s \quad (22)$$

133 where μ_0 is the magnetic permeability of the vacuum ($\mu_0 = 4\pi \cdot 10^{-7} SI$) and σ^* is the fictitious magnetic
134 pole surface density given in tesla . Equation (22) can be written as follows:

$$\vec{H}(r, \theta, z) = \frac{\sigma^*}{4\pi\mu_0} \int_{\theta_1}^{\theta_2} \int_0^h \frac{(r - r_1 \cos(\theta - \theta_s))\vec{u}_r - r_1 \sin(\theta_s - \theta)\vec{u}_\theta + (z - z_1)\vec{u}_z}{(r_1^2 + r^2 + (z - z_1)^2 - 2r_1 r \cos(\theta - \theta_s))^{\frac{3}{2}}} r_1 dz_1 d\theta_s \quad (23)$$

135 **B. Components along the three directions \vec{u}_r , \vec{u}_θ , \vec{u}_z**

136 The integration of (23) leads to the magnetic field components created by the inner face along the three
137 axes defined $H_r(r, \theta, z)$, $H_\theta(r, \theta, z)$, $H_z(r, \theta, z)$.

138 1) *Azimuthal component $H_\theta(r, \theta, z)$* : The field azimuthal component $H_\theta(r, \theta, z)$ is given by (24).

$$H_\theta(r, \theta, z) = \frac{\sigma}{4\pi\mu_0} (\beta(\theta, \theta_1) - \beta(\theta, \theta_2)) \quad (24)$$

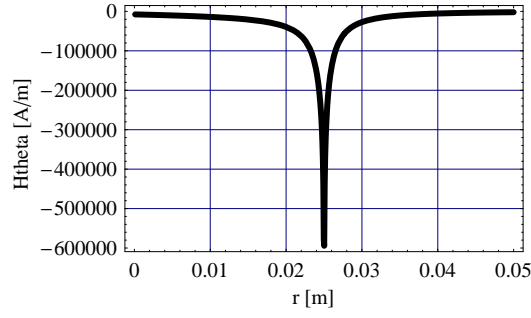


Fig. 6. Field azimuthal component $H_\theta(r, \theta, z)$ versus the radial distance r of the observation point; $h = 3$ mm, $r_{in} = 25$ mm, $r_{out} = 28$ mm, $\theta_1 = 0$ rad, $\theta_2 = \frac{\pi}{2}$ rad, $\theta = 0$ rad

139 with

$$\beta(\theta, \theta_i) = \frac{r_{in}(b-z)}{r\sqrt{-(b-z)^2}} \arctan \left[\frac{\sqrt{r^2 + r_{in}^2 + (b-z)^2 - 2rr_{in} \cos(\theta_i - \theta)}}{\sqrt{-(b-z)^2}} \right] - \frac{r_{in}}{r} \tanh^{-1} \left[\frac{\sqrt{r^2 + r_{in}^2 + z^2 - 2rr_{in} \cos(\theta_i - \theta)}}{z} \right] \quad (25)$$

140 Equation (24) is valid for any observation point $M(r, \theta, z)$ with $0 \leq \theta \leq 2\pi$. Figure 6 represents the
 141 azimuthal component $H_\theta(r, \theta, z)$ versus the radial distance r of the observation point. The parameters
 142 values are $h = 3$ mm, $\theta_1 = 0$, $\theta_2 = \frac{\pi}{2}$, $\theta = 0$, $r_{in} = 25$ mm, $r_{out} = 28$ mm.

143 2) Radial component $H_r(r, \theta, z)$: The radial component of the field $H_r(r, \theta, z)$ is given by (26).

$$H_r(r, \theta, z) = \frac{\sigma^*}{4\pi\mu_0} (\beta(u_1) - \beta(u_2)) \quad (26)$$

144 with

$$u_i = \cos(\theta - \theta_i) \quad (27)$$

145 and

$$\beta(u_i) = \left(\frac{2i(1+u_i)\sqrt{\frac{d(-1+u_i)}{c+e_1+du_i}}(- (a_1d + b_1(c+e_1))) \mathbf{F}^* \left[i \sinh^{-1} \left[\frac{\sqrt{-c+d-e_1}}{\sqrt{c+e_1+du_i}}, \frac{c+d+e_1}{c-d+e_1} \right] \right)}{d\sqrt{-c+d-e_1}e_1\sqrt{\frac{d(1+u_i)}{c+e_1+du_i}}\sqrt{1-u_i^2}} \right)$$

| Parameters | |
|------------|---------------------|
| a_1 | $r_{in} r z$ |
| b_1 | $-r_{in}^2 z$ |
| c | $r^2 + r_{in}^2$ |
| d | $-2r r_{in}$ |
| e_1 | z^2 |
| a_2 | $-r_{in} r (z - h)$ |
| b_2 | $r_{in}^2 (z - h)$ |
| e_2 | $(z - h)^2$ |

TABLE II
DEFINITION OF THE PARAMETERS USED IN (26)

$$\begin{aligned}
& + \left(\frac{2i(1+u_i) \sqrt{\frac{d(-1+u_i)}{c+e_1+du_i}} (b_1 c - a_1 d) \mathbf{\Pi}^* \left[\frac{e_1}{c-d+e_1}, i \sinh^{-1} \left[\frac{\sqrt{-c+d+e_1}}{c+e_1+du_i} \right], \frac{c+d+e_1}{c-d+e_1} \right]}{d \sqrt{-c+d-e_1} e_1 \sqrt{\frac{d(1+u_i)}{c+e_1+du_i}} \sqrt{1-u_i^2}} \right) \\
& + \left(\frac{2i(1+u_i) \sqrt{\frac{d(-1+u_i)}{c+e_2+du_i}} (-a_2 d + b_2 (c+e_2)) \mathbf{F}^* \left[i \sinh^{-1} \left[\frac{\sqrt{-c+d-e_2}}{\sqrt{c+e_2+du_i}} \right], \frac{c+d+e_2}{c-d+e_2} \right]}{d \sqrt{-c+d-e_2} e_2 \sqrt{\frac{d(1+u_i)}{c+e_2+du_i}} \sqrt{1-u_i^2}} \right) \\
& + \left(\frac{2i(1+u_i) \sqrt{\frac{d(-1+u_i)}{c+e_2+du_i}} (b_2 c - a_2 d) \mathbf{\Pi}^* \left[\frac{e_2}{c-d+e_2}, i \sinh^{-1} \left[\frac{\sqrt{-c+d+e_2}}{c+e_2+du_i} \right], \frac{c+d+e_2}{c-d+e_2} \right]}{d \sqrt{-c+d-e_2} e_2 \sqrt{\frac{d(1+u_i)}{c+e_2+du_i}} \sqrt{1-u_i^2}} \right)
\end{aligned} \tag{28}$$

146 where $F^*[\phi, m]$ is defined by (31) and $\mathbf{\Pi}^*[n, \phi, m]$ is given by (21). Here again, Eq.(28) contains the
147 imaginary number i ($i^2 = -1$) although the result $H_r(r, z)$ is a real number because we did not succeed in
148 obtaining a real expression for the radial component $H_r(r, \theta, z)$. The parameters used in (28) are defined
149 in Table II. Of course, when using the expression (28) in tools like Mathematica or Mapple, the imaginary
150 part of $H_r(r, \theta, z)$ has to be dropped, as it only corresponds to numerical noise and nearly equals zero.

151 Equation (26) can be used to calculate the radial component of the magnetic field at any observation
152 point $M(r, \theta, z)$ with $\theta \neq \theta_i$ and $0 \leq \theta < 2\pi$. When the tile angular width becomes 2π ($\theta_2 - \theta_1 = 2\pi$),
153 so for ring magnets, the expression becomes the one already given in a previous paper [32]. Figure 7
154 represents the field radial component $H_r(r, \theta, z)$ versus the radial distance r of the observation point. The
155 parameter values are $h = 3$ mm, $\theta_1 = 0$ rad, $\theta_2 = \frac{\pi}{2}$ rad, $\theta = 0$ rad, $r_{in} = 25$ mm, $r_{out} = 28$ mm.

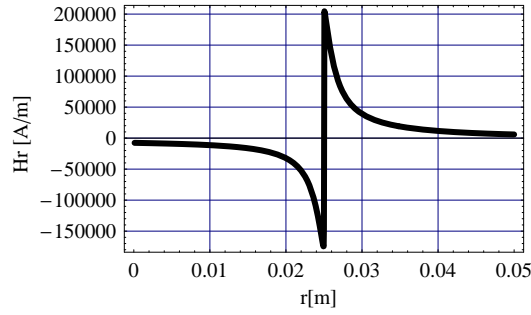


Fig. 7. Field radial component $H_r(r, \theta, z)$ versus the radial distance r of the observation point; $h = 3$ mm, $r_{in} = 25$ mm, $r_{out} = 28$ mm, $\theta_1 = 0$ rad, $\theta_2 = \frac{\pi}{2}$ rad, $\theta = \frac{\pi}{2}$ rad

156 3) Axial component $H_z(r, \theta, z)$: The field axial component $H_z(r, \theta, z)$ is given by (29):

$$H_z(r, \theta, z) = \frac{\sigma^*}{4\pi\mu_0} (\alpha(\theta, \theta_2) - \alpha(\theta, \theta_1)) \quad (29)$$

157 with

$$\alpha(\theta, \theta_i) = \frac{2r_{in}}{(r - r_{in})^2 + (z - h)^2} \mathbf{F}^* \left[\frac{\theta - \theta_i}{2}, -\frac{4rr_{in}}{(r - r_{in})^2 + (z - h)^2} \right] - \frac{2r_{in}}{(r - r_{in})^2 + z^2} \mathbf{F}^* \left[\frac{\theta - \theta_i}{2}, -\frac{4rr_{in}}{(r - r_{in})^2 + z^2} \right] \quad (30)$$

158 where $\mathbf{F}^*[\phi, m]$ is given in terms of the elliptic integral of the first kind by (31).

$$\mathbf{F}^*[\phi|m] = \int_{\theta=0}^{\theta=\phi} \frac{1}{\sqrt{1 - m \sin^2(\theta)}} d\theta \quad (31)$$

159 Equation (29) is valid for any observation point $M(r, \theta, z)$ with $0 \leq \theta \leq 2\pi$. Figure 8 represents
 160 the field axial component $H_z(r, \theta, z)$ versus the radial distance r of the observation point. The parameter
 161 values which are taken for the calculation are $h = 3$ mm, $\theta_1 = 0$ rad, $\theta_2 = \frac{\pi}{2}$ rad, $\theta = 0$ rad, $r_{in} = 25$ mm,
 162 $r_{out} = 28$ mm.

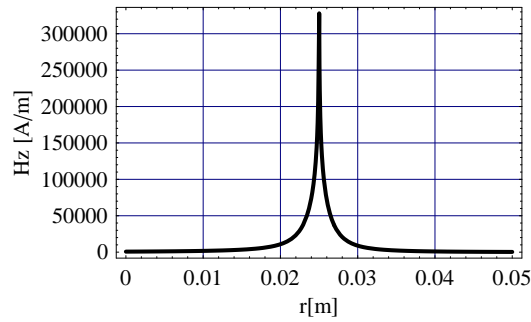


Fig. 8. Field axial component $H_z(r, \theta, z)$ versus the radial distance r of the observation point; $h = 3$ mm, $r_{in} = 25$ mm, $r_{out} = 28$ mm, $\theta_1 = 0$ rad, $\theta_2 = \frac{\pi}{2}$ rad, $\theta = \frac{\pi}{2}$ rad

IV. CONCLUSION

This paper gives the analytical expressions of the three components of the magnetic field created by tile permanent magnets whose magnetization is either radial or axial. When the tiles are axially magnetized, the magnetic field can be calculated using these expressions at any point in space. For radially magnetized tiles, the expressions given correspond to the field created by thin tiles, whose inner and outer radii are not too different, and can be used at any point of the space as well. The magnetic field is directly calculated, without the help of the magnetic potentials. The utility of such analytical expressions for the three components of the magnetic field created by tile permanent magnets lies in the fact that the related calculations have a low computational cost, especially with regard to methods using finite elements or finite differences, and that they allow efficient parametric optimization studies of devices, which is very important for all applications.

The Mathematica files containing the analytical expressions used to calculate the three components of the magnetic field for axial and radial magnetizations are available online [33].

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