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Coulombian Model for 3D Analytical Calculation of the Torque Exerted on Cuboidal Permanent Magnets with Arbitrarily Oriented Polarizations

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ABSTRACT

The paper proposes improved analytical expressions of the torque on cuboidal permanent magnets. Expressions are valid for any relative magnet position and for any polarization direction. The analytical calculation is made by replacing polarizations by distributions of magnetic charges on the magnet poles (Coulombian approach). The torque exerted on the second magnet is calculated by Lorentz force formulas for any arbitrary position. The three components of the torque are written with functions based on logarithm and arc-tangent. Results have been verified and validated by comparison with finite-element calculation. Further, the torque can be obtained with respect to any reference point. Although these equations seem rather complicated, they enable an extremely fast and accurate calculation of the torque exerted between two permanent magnets.

1 INTRODUCTION

Analytical expressions are very powerful, giving a very fast method to calculate magnetic interactions. It is why the analytical expressions of all the interactions, energy, forces, and torques between two cuboidal magnets are very important results. Many problems can be solved by the addition of element interactions.

Up to now, for the torque components, the calculations were first realized for a system of two magnets with parallel polarization direction by Allag [1] and Janssen [2]. For the perpendicular case the results have been recently published [3].

In this paper we develop the calculation for the system of two magnets with inclined polarization direction. The torque expressions are valid for any given point in the space, not only around the center of the moving magnet. The expressions of the torque components are obtained by using the Lorentz force method [4]. A comparison with numerical models using Flux3D software validates our analytical calculation of the torque exerted between two permanent magnets.

2 MATHEMATICAL MODEL

We study the interaction between two parallelepiped magnets, as presented in Figure 1. The polarizations J and J’ are supposed to be rigid and uniform in each magnet. The difference is that J’ are arbitrary oriented in YZ plane. The model can be replaced by distributions of magnetic charges on the poles, generally called coulombian approach. For simplifying calculation, the polarization J’ will be decomposed into parallel component J’∥ and perpendicular one J’⊥ (Figure 2).

In this paper we develop the calculation for the system of two magnets with inclined polarization direction. The torque expressions are valid for any given point in the space, not only around the center of the moving magnet. The expressions of the torque components are obtained by using the Lorentz force method [4]. A comparison with numerical models using Flux3D software validates our analytical calculation of the torque exerted between two permanent magnets.
The energy expressions are:

\[ E_g = \frac{J_J}{4\pi \mu_0} \sum_{p \neq p_0} \sum_{q \neq q_0} (-1)^{p+q} c dV dX dY \, \frac{1}{r} \, dx \]

with

\[ r = \sqrt{(\alpha X - \gamma)^2 + (\beta Y - \nu)^2 + (\gamma + (-\lambda^2) C - (-\gamma^2) \lambda)^2} \]

The obtained expressions of the interaction energy are:

\[ E_g = \frac{J_J}{4\pi \mu_0} \sum_{p \neq p_0} \sum_{q \neq q_0} (-1)^{p+q+1} \varphi(U_q V_r W_{p_0}, r) \]

with

\[ \varphi(U_q V_r W_{p_0}, r) = \frac{U(V^2 - W^2)}{2 \ln(r - U) + V(U^2 - W^2) \ln(r - V)} + UVW \cdot \frac{r}{6} (U^2 + V^2 - 2W^2) \]

The secondary variables are:

\[ U_q = \alpha + (-1)^{p} A - (-1)^{q} a \]

\[ V_r = \beta + (-1)^{p} B - (-1)^{q} b \]

\[ W_{p_0} = \gamma + (-1)^{p} C - (-1)^{q} c \]

\[ r = \sqrt{U_q^2 + V_r^2 + W_{p_0}^2} \]

From the interaction energy, the force components can be obtained by \( \mathbf{F} = -\text{grad} \, E \).

Consequently the force components are:

\[ F_g = \frac{J_J}{4\pi \mu_0} \sum_{p \neq p_0} \sum_{q \neq q_0} (-1)^{p+q+1} \varphi(U_q V_r W_{p_0}, r) \]

with

\[ \varphi(U_q V_r W_{p_0}, r) = \frac{U(V^2 - W^2)}{2 \ln(r - U) + V(U^2 - W^2) \ln(r - V)} + UVW \cdot \frac{r}{6} (U^2 + V^2 - 2W^2) \]

The torque exerted in the second magnet at \( O_T \) is calculated by Lorentz formulas \([2, 3, 4]\):

\[ \tau = \frac{J_J}{4\pi \mu_0} \sum_{p \neq p_0} \sum_{q \neq q_0} (-1)^{p+q+1} \varphi(U_q V_r W_{p_0}, r) \]

with

\[ r = \frac{(Y - D_0) \frac{\partial}{\partial x} + (Z - D_0) \frac{\partial}{\partial y}}{\frac{\partial}{\partial z} - r} \]

\[ \Gamma = \frac{J_J}{4\pi \mu_0} \sum_{p \neq p_0} \sum_{q \neq q_0} (-1)^{p+q+1} \varphi(U_q V_r W_{p_0}, r) \]

The distance \( r \) is always the same (see equation (2)), and \( D_x, D_y \) and \( D_z \) are the projections of the distance between the centre of the moving magnet and the point of torque calculation \( O_T \).

For the analysis of the calculations, the torque is given by:

\[ \tau = \frac{J_J}{4\pi \mu_0} \sum_{p \neq p_0} \sum_{q \neq q_0} (-1)^{p+q+1} \varphi(U_q V_r W_{p_0}, r) \]

And the functions \( \varphi \) are respectively:

For \( \Gamma_{\mathbf{x}} \),

\[ \tau_{\mathbf{x}} = \left[ \frac{U(V^2 - W^2)}{2 \ln(r - U) + V(U^2 - W^2) \ln(r - V)} + UVW \cdot \frac{r}{6} (U^2 + V^2 - 2W^2) \right] \]

\[ \left[ \frac{C(-1)^{p} A}{2} \right] \]

\[ \left[ \frac{b(-1)^{q} V}{2} \right] \]

For \( \Gamma_{\mathbf{y}} \),

\[ \tau_{\mathbf{y}} = \left[ \frac{U(V^2 - W^2)}{2 \ln(r - U) + V(U^2 - W^2) \ln(r - V)} + UVW \cdot \frac{r}{6} (U^2 + V^2 - 2W^2) \right] \]

\[ \left[ \frac{A(-1)^{p} C}{2} \right] \]

\[ \left[ \frac{b(-1)^{q} V}{2} \right] \]

For \( \Gamma_{\mathbf{z}} \),

\[ \tau_{\mathbf{z}} = \left[ \frac{U(V^2 - W^2)}{2 \ln(r - U) + V(U^2 - W^2) \ln(r - V)} + UVW \cdot \frac{r}{6} (U^2 + V^2 - 2W^2) \right] \]

\[ \left[ \frac{A(-1)^{p} C}{2} \right] \]

\[ \left[ \frac{b(-1)^{q} V}{2} \right] \]

It is easy to identify the link between the expressions of the torque (12) and the force components \( \varphi_{\mathbf{x}}, \varphi_{\mathbf{y}}, \varphi_{\mathbf{z}} \) from (7). Therefore we can write:

\[ \tau_{\mathbf{x}} = \varphi_{\mathbf{x}} \left[ \frac{C(-1)^{p} A}{2} - \varphi_{\mathbf{y}} \left[ \frac{b(-1)^{q} V}{2} \right] \right] \]

\[ \tau_{\mathbf{y}} = \varphi_{\mathbf{y}} \left[ \frac{A(-1)^{p} C}{2} - \varphi_{\mathbf{z}} \left[ \frac{b(-1)^{q} V}{2} \right] \right] \]

\[ \tau_{\mathbf{z}} = \varphi_{\mathbf{z}} \left[ \frac{b(-1)^{q} V}{2} - \varphi_{\mathbf{x}} \left[ \frac{A(-1)^{p} C}{2} \right] \right] \]
2.2 Perpendicular Polarizations

For the perpendicular polarization case, the chosen system is presented on Figure 4, in which the polarization of a second magnet is collinear with the Y axis.

The analytical expressions of the interaction energy and the forces components for this system were previously developed [6, 7, 8]. The distance \( r \) is given by:

\[
r = \sqrt{(\alpha + X - x)^2 + (\beta + (\gamma - y)^2 + (\gamma + Z - (\gamma)^2)^2}
\]

After analytical integration, the energy is given by:

\[
E = \frac{JJ}{4\pi q}\sum_{i=j}^{\infty} \frac{1}{r}
\]

The \( \phi_{ij} \) function depends on the geometrical parameters \( U, V, W, r \)

\[
\phi_{ij} = \frac{V(r + V)\ln(V + r)}{U + V} + \frac{W(r + W)\ln(W + r)}{U + W} + \frac{U\ln(U + r)}{V + U} + \frac{V\ln(V + r)}{W + V} + \frac{W\ln(W + r)}{U + W}
\]

The variables \( U, V, W \) are identical (equation (5)).

The force components can be calculated from the gradient of energy:

\[
F_x = \frac{JJ}{4\pi q}\sum_{i=j}^{\infty} \sum_{r=0}^{\infty} \sum_{l=1}^{\infty} \frac{1}{r} \partial \phi_{ij}(U, V, W, r)
\]

For \( F_x \), the function \( \phi_{ij} \) is given by:

\[
\phi_{ij} = -V W \ln(r + r) + U V \ln(r + r) + W U \ln(r + r)
\]

\[
- \frac{U^2}{2} + \ln(U + V) - \frac{V^2}{2} + \ln(V + W) - \frac{W^2}{2} + \ln(U + W)
\]

For \( F_y \) and \( F_z \):

\[
\phi_{ij} = \frac{U^2 + V^2}{2} \ln(r + r) - \frac{W^2}{2} + \ln(U + V) - \frac{V^2}{2} + \ln(V + W) - \frac{W^2}{2} + \ln(U + W)
\]

Similarly to the parallel polarization case, the torque exerted on the second magnet at \( O_T \) (Figure 4) is expressed by:

\[
\Gamma = \frac{JJ}{4\pi q} \int \left( i \mathbf{r} \cdot \mathbf{B} - r \mathbf{r} \cdot \mathbf{B} \right) dS = \frac{JJ}{4\pi q} \int \left( i \mathbf{r} \cdot \mathbf{B} - r \mathbf{r} \cdot \mathbf{B} \right) dxdz
\]

with

\[
\mathbf{r} = r_x \mathbf{i} + r_y \mathbf{j} + r_z \mathbf{k} = (X - D_Y) \mathbf{i} + (Y - D_Y) \mathbf{j} + (Z - D_Z) \mathbf{k}
\]

The torque can be also written as:

\[
\Gamma = \frac{JJ}{4\pi q} \int \left( (Y - D_Y) \frac{\partial}{\partial x} + (Z - D_Z) \frac{\partial}{\partial y} \right) dxdy dxdz
\]

The final result is given by:

\[
\Gamma = \frac{JJ}{4\pi q} \int \left( (Y - D_Y) \frac{\partial}{\partial x} + (Z - D_Z) \frac{\partial}{\partial y} \right) dxdy
\]

For the torque component \( \tau_{xY} \), parallelly oriented to the Ox axis, the \( \tau_{xY} \) function is given by:

\[
\tau_{xY} = \phi_{ij} \cdot \left( (1)^Y - D_Y \right) - \phi_{ij} \cdot \left( (1)^Y - D_Y - W \right)
\]

\[
\phi_{ij} = \frac{U^2 + V^2}{3} \ln(U + r) - \frac{V^2 + W^2}{3} \ln(U + r) + \frac{W^2 + U^2}{3} \ln(U + r)
\]

The torque components in perpendicular case are also function of the force ones \( (\phi_{ij}, \phi_{ij}, \phi_{ij}) \).

3 TORQUE CALCULATION FOR INCLINED POLARIZATION DIRECTION

For an inclined polarization \( J' \) as presented on Figure 1 and Figure 2. It can be represented as:

\[
J' = J' \sin(\theta) + J' \cos(\theta)
\]

Therefore the total torque will be:

\[
\Gamma = \Gamma_\theta \sin(\theta) + \Gamma_\theta \cos(\theta)
\]

Using equations (11) and (23), final expressions of the torque are:
\[ \Gamma = \frac{J \cdot J' \sin(\theta)}{4\pi \mu} \sum_{i,j,k,l,p,q} \sum_{\text{odd}} (-1)^{q+p+i+j+k+l} \tau_{\alpha}(U_i, V_j, W_k, r) \] (27)

\[ \frac{J \cdot J' \cos(\theta)}{4\pi \mu} \sum_{i,j,k,l,p,q} \sum_{\text{odd}} (-1)^{q+p+i+j+k+l} \tau_{\alpha}(U_i, V_j, W_k, r) \] (28)

The components of \( \mathbf{T}_H \) and \( \mathbf{T}_L \) are given by equations (12), (13) and (24).

Expressions of the torque components:

- For \( \Gamma_x \)

\[ \tau_{x,x} = \phi_{x,x} \left( c(-1)^y - D_y \right) - \phi_{x,y} \left( b\left(-1\right)^{1} - D_y - r \right) \]

\[ \tau_{x,y} = \phi_{x,y} \left( a\left(-1\right)^{1} - D_y \right) - \phi_{x,z} \left( c\left(-1\right)^{1} - D_y - W \right) \]

\[ \tau_{x,z} = \phi_{x,z} \left( b\left(-1\right)^{1} - D_y \right) - \phi_{x,y} \left( a\left(-1\right)^{1} - D_y - U \right) \]

- For \( \Gamma_y \)

\[ \tau_{y,x} = \phi_{y,x} \left( a\left(-1\right)^{1} - U \right) - \phi_{y,z} \left( c\left(-1\right)^{1} \right) \]

\[ \tau_{y,y} = \phi_{y,y} \left( a\left(-1\right)^{1} - D_y \right) - \phi_{y,z} \left( c\left(-1\right)^{1} - D_y - W \right) \]

\[ \tau_{y,z} = \phi_{y,z} \left( b\left(-1\right)^{1} - D_y \right) - \phi_{y,y} \left( a\left(-1\right)^{1} - D_y - U \right) \]

- And finally, For \( \Gamma_z \)

\[ \tau_{z,x} = \phi_{z,x} \left( b\left(-1\right)^{1} - V \right) - \phi_{z,z} \left( a\left(-1\right)^{1} \right) \]

\[ \tau_{z,y} = \phi_{z,y} \left( a\left(-1\right)^{1} - D_y \right) - \phi_{z,z} \left( a\left(-1\right)^{1} - D_y - U \right) \]

\[ \tau_{z,z} = \phi_{z,z} \left( b\left(-1\right)^{1} - D_y \right) - \phi_{z,y} \left( a\left(-1\right)^{1} - D_y - U \right) \]

4 EXAMPLES OF APPLICATION

The following example presents the torque calculation between two magnets. These magnets are identical: two cubes of 1 cm edge. The lower magnet has a vertical polarization (oriented in Z direction). For the second magnet, its polarization is inclined in the YZ plane (Fig. 5). The intensity of polarization is 1 Tesla for the two magnets. The upper magnet moves in translation along the Ox axis above the lower fixed one. The vertical distance between them (airgap when the upper magnet is above the fixed magnet) is 0.01 m (\( \beta=0 \) m and \( \gamma=0.02 \) m).

![Figure 5: Geometrical disposition of the magnets](image)

For the first application, the second magnet polarization is inclined (\( \theta = 45^\circ \)). The torque is calculated in the centre of the second magnet (\( DX, DY \) and \( DZ \) are equal to zeros). The results from analytical and numerical model using Flux3D are given in Figure 6, proving a good accuracy of our approach.

![Figure 6: Torque components for 45\(^\circ\) inclined polarization of PM2](image)

![Figure 7: Torque components for 30\(^\circ\) inclined polarization of PM2 (second magnet)](image)

We let the same physical and geometrical parameters as in previous example, except for the degree of
incli\textit{nation} which is changed to $\theta = 30^\circ$. In this case also, the results are compared with Fl\textit{ux3D} finite element software (Fig. 7).

In the second application, the second magnet are fixed at $\alpha = 0.0025\, \text{m}$, $\beta = 0\, \text{m}$, $\gamma = 0.02\, \text{m}$. We simulate and calculate the torque for one complete rotation of polarization (Figure 8). The torque is computed at the centre of the magnet and their three components are presented on Figure 9.

![Figure 8: Magnet position and polarization directions](image)

**Figure 8: Magnet position and polarization directions**

The result in this case is presented as a function of a rotation angle $\theta$ on Figure 11.

![Figure 11: Torque calculation at $Dx = -0.005\, \text{m}$, $Dy = 0\, \text{m}$ and $Dz = 0\, \text{m}$, as function of rotation angle $\theta$](image)

**Figure 11: Torque calculation at $Dx = -0.005\, \text{m}$, $Dy = 0\, \text{m}$ and $Dz = 0\, \text{m}$, as function of rotation angle $\theta$**

5 CONCLUSION

This paper presents a new contribution in analytical torque calculations for cuboidal permanent magnets with inclined polarizations from any position. These investigations allow the direct calculation of many systems working by the forces or the torques between magnetized cuboidal elements (magnetic bearings, Halbach arrays...). These results can also be used for many other calculations, like complex shapes of magnets which can be replaced by a combination of several parallelogram ones.

REFERENCES


