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MAGNETIC COUPLINGS WITH CYLINDRICAL AND PLANE AIR GAPS: INFLUENCE OF THE MAGNET POLARIZATION DIRECTION

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⁴ **Abstract**—We present a synthesis of cylindrical magnetic couplings
⁵ realized with tile permanent magnets whose polarizations can be
⁶ radial, tangential or axial. The expressions of the torque transmitted
⁷ between the two rotors of each coupling have been determined by
⁸ using the coulombian approach. All the calculations have been
⁹ performed without using any simplifying assumptions. Consequently,
¹⁰ the expressions obtained are accurate and enable a fast comparison
¹¹ between all the structures presented in this paper. Strictly speaking,
¹² there are two great kinds of couplings generally used in engineering or
¹³ medical applications. The first ones use a cylindrical air gap though the
¹⁴ second ones use a plane air gap. The best configuration for obtaining
¹⁵ the greatest torque turns out to be different between couplings using
¹⁶ cylindrical or plane air gaps.

¹⁷ **1. INTRODUCTION**

¹⁸ Up to now, the progress in permanent magnet manufacturing [1]-[3]
¹⁹ have paved the way for the design of very efficient magnetic couplings
²⁰ [4]-[8] or permanent magnet machines [9]-[15]. Indeed, the assembly of
²¹ tile permanent magnets have allowed manufacturers to design devices
²² that can be easily optimized [17]-[2]. Several approaches [19]-[27] are
²³ used for the study of the torque transmitted between two permanent
²⁴ magnet rotors [28]-[7]. For performing such optimizations with ana-
²⁵ lytical approaches, the first step is certainly the determination of the
²⁶ magnetic field [30][32] produced by the permanent magnet structure.
²⁷ The analytical calculation of the magnetic field produced by arc-shaped
²⁸ permanent magnets [33][40] has been largely studied by many authors .
²⁹ In addition, some authors have proposed series expansions for obtain-
³⁰ ing a fast evaluation of the magnetic field produced by ring permanent
³¹ magnets[41][42] . Such analytical methods are suitable for the design

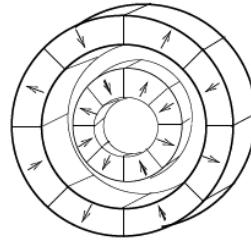


Figure 1. Magnetic coupling using a cylindrical air gap and tile permanent magnets radially magnetized

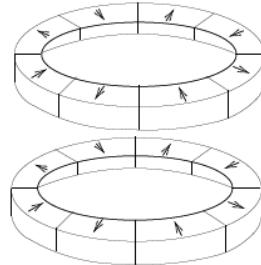


Figure 2. Magnetic coupling using a plane gap and tile permanent magnets radially magnetized

32 of non-classical structures using permanent magnets.

33 Many papers dealing with the optimization of magnetic couplings
 34 use the finite element method. However, as mentioned in [43] , it is
 35 more interesting to use some analytical expressions for calculating the
 36 magnetic field produced by arc-shaped permanent magnets if such an-
 37 alytical approaches are possible. We think that it is also the case when
 38 the calculation of the forces or torques are required.
 39

40 The main configurations generally used for realizing magnetic
 41 couplings are presented below. Indeed, magnetic couplings are
 42 performed with either cylindrical air gaps, as shown in Fig 1, or with
 43 plane air gaps, as shown in Fig 2.

44 Some analytical studies have been performed by several authors
 45 [28]-[44] for studying such magnetic couplings. However, these studies
 46 omitted the curvature effect of the tile permanent magnets. On the
 47 other hand, such approaches, based on the linearized model of a mag-
 48



Figure 3. Magnetic couplings using cylindrical air gaps; from left to right : coupling using tile permanent magnets radially magnetized, coupling using tile permanent magnets tangentially magnetized, coupling using tile permanent magnets axially magnetized

net, are fully analytical and thus interesting to use for optimization purposes.

We propose in this paper to use an exact formulation based on the coulombian model for calculating the torque transmitted bewteen tile permanent magnets radially, tangentially or axially magnetized. Our semi-analytical expressions are based on only one numerical integration whose convergence is fast and robust. All the analytical expressions have been determined without any simplifying assumptions.

2. CONFIGURATIONS STUDIED IN THIS PAPER

We present in this section the six configurations studied in this paper. Strictly speaking, our investigation encompasses both the classical magnetic couplings but also unconventional couplings manufactured with tile permanent magnets tangentially magnetized. The choice of the tile permanent magnet polarization depends greatly on the involved application. Basically, the main criterion for optimizing magnetic couplings is the value of the torque transmitted between the two rotors. To do so, several criteria must be taken into account: the media used, the number and the tile dimensions as well as the intrinsic properties of the magnets (coercitive field). However, the shape of the torque versus the angular shift can also be the main optimization criterion. This is why several configurations of tile permanent magnets with different polarizations must be compared to each other. We have represented in Fig 3 three magnetic couplings using only cylindrical air gaps.

The three magnetic couplings presented in Fig 3 are composed of tile permanent magnets radially, tangentially or axially magnetized.

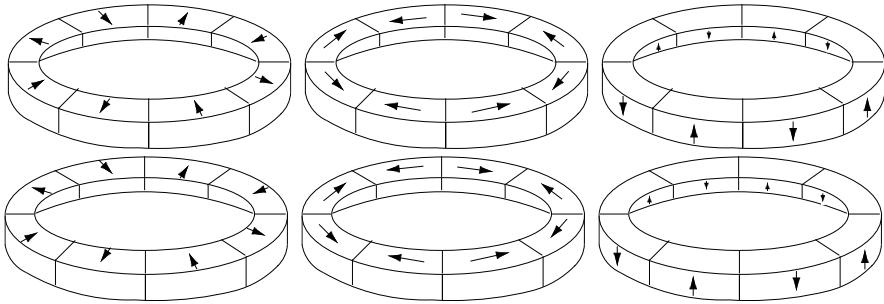


Figure 4. Magnetic couplings using plane air gaps; from left to right : coupling using tile permanent magnets radially magnetized, coupling using tile permanent magnets tangentially magnetized, coupling using tile permanent magnets axially magnetized

75 Magnetic couplings using tile permanent magnets radially or axially
 76 magnetized are rather well known whereas the ones using tile
 77 permanent magnets tangentially magnetized are less known. The
 78 magnetic couplings using plane air gaps are presented in Fig 4.

79 The three magnetic couplings presented in Fig 4 are also
 80 composed of tile permanent magnets radially, tangentially and axially
 81 magnetized. Such couplings are used in pharmaceutical processes.

82 **3. USING THE COULOMBIAN MODEL FOR 83 STUDYING THE MAGNETIC COUPLINGS**

84 We present now the three-dimensional equations for the study of the
 85 structures presented in the previous section.

86 **3.1. Torque transmitted between two tile permanent 87 magnets radially magnetized**

88 The torque transmitted between two tile permanent magnets
 89 radially magnetized is determined by using the analytical expressions
 90 determined in a previous paper [15]. These analytical expressions are
 91 based on the coulombian model of a magnet.

92 **3.2. Torque transmitted between two tile permanent 93 magnets tangentially magnetized**

94 Let us now consider the torque transmitted between two tile permanent
 95 magnets tangentially magnetized. The geometry considered and the

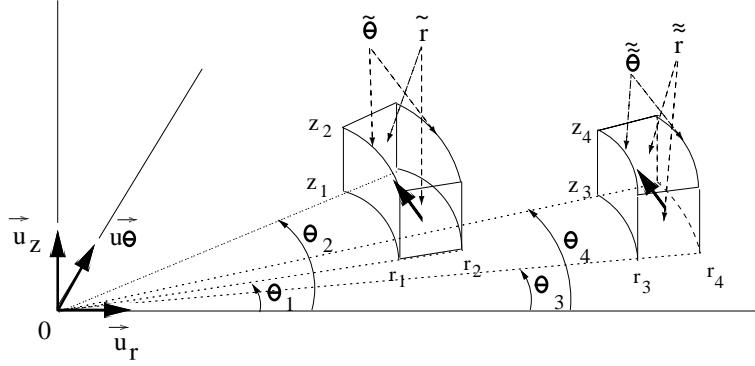


Figure 5. Two tile permanent magnets tangentially magnetized

related parameters are shown in Fig 5. All the calculations are carried out by using the coulombian model. Thus, each tile permanent magnet is represented by magnetic pole surface densities that appear only on the straight faces of the each tile (Fig 5). For the tile located on the left in Fig 5, its inner radius is r_1 and its outer one is r_2 . Its angular width is $\theta_2 - \theta_1$ and its height is $z_2 - z_1$. Its magnetic polarization \vec{J}_1 is directed along \vec{u}_θ in cylindrical coordinates. For the tile located on the left in Fig 5, its inner radius is r_3 and its outer one is r_4 . Its angular width is $\theta_4 - \theta_3$ and its height is $z_4 - z_3$. Its magnetic polarization \vec{J}_2 is directed along \vec{u}_θ in cylindrical coordinates. The torque transmitted between the two tile permanent magnets tangentially magnetized is determined by integrating the magnetic field produced by the inner tile permanent magnet on the magnetic pole surface densities of the outer tile permanent magnet. By denoting $\mathbf{H}(r, \theta, z)$, the magnetic field produced by the inner tile permanent magnet in all points in space, the torque transmitted bewteen the two tile permanent magnets can be expressed as follows:

$$\begin{aligned} T = & J_2 \int_{r_3}^{r_4} \int_{z_1}^{z_2} H_\theta(\tilde{r}, \theta_4, \tilde{z}) \tilde{r} d\tilde{r} d\tilde{z} \\ & - J_2 \int_{r_3}^{r_4} \int_{z_1}^{z_2} H_\theta(\tilde{r}, \theta_3, \tilde{z}) \tilde{r} d\tilde{r} d\tilde{z} \end{aligned} \quad (1)$$

where $H_\theta(r, \theta, z)$ is expressed as follows:

$$H_\theta(r, \theta, z) = -\vec{\nabla} \cdot \left(\int_{r_1}^{r_2} \int_{z_1}^{z_2} G(\vec{r}, \vec{r}') d\phi(\vec{r}') \right) \cdot \vec{u}_\theta \quad (2)$$

¹¹⁴ where $G(\vec{r}, \vec{r}')$ is the three-dimensional Green's function defined
¹¹⁵ as follows:

$$G(\vec{r}, \vec{r}') = \frac{1}{4\pi |\vec{r} - \vec{r}'|} \quad (3)$$

¹¹⁶ where \vec{r} an observation point and \vec{r}' a point located on the charge
¹¹⁷ distribution. It is noted that $G(\vec{r}, \vec{r}')$ has been largely used in [37]. In
¹¹⁸ addition, $d\phi(\vec{r}')$ is defined by :

$$d\phi(\vec{r}') = \frac{J_1}{\mu_0} d\tilde{r} d\tilde{z} \quad (4)$$

¹¹⁹ By setting $x = \cos(\theta_m - \theta_j)$, $y = \sin(\theta_m - \theta_j)$ and $c = r_i^2 + (z_n - z_k)^2$,
¹²⁰ the final expression of the torque can be written as follows:

$$T = \sum_{i,j,k,m,n=1}^2 (-1)^{(i+j+k+m+n)} \int_{r_3}^{r_4} \vartheta(\tilde{r}, i, j, k, m, n) d\tilde{r} \quad (5)$$

¹²¹ and $\vartheta(\tilde{r}, i, j, k, m, n)$ is expressed as follows:

$$\begin{aligned} \vartheta(\tilde{r}, i, j, k, m, n) &= \tilde{r}y\sqrt{\tilde{r}^2 + (z_k - z_n)^2 + r_i(r_i - 2\tilde{r}x)} \\ &\quad + \tilde{r}x \log \left[r_i - \tilde{r}x + \sqrt{\tilde{r}^2 + (z_k - z_n)^2 + r_i^2 - 2r_i\tilde{r}x} \right] \\ &\quad - \frac{(z_k - z_n)(\sqrt{x^2 - 1} - x)}{2\sqrt{x^2 - 1}} \log[A_{i,j,k,m,n}] \\ &\quad - \frac{(z_k - z_n)(\sqrt{x^2 - 1} + x)}{2\sqrt{x^2 - 1}} \log[B_{i,j,k,m,n}] \end{aligned} \quad (6)$$

¹²²

$$\begin{aligned} A_{i,j,k,m,n} &= \frac{-2}{(z_k - z_n)^3} \frac{\left(r_i\tilde{r}(x^2 - 1) - \xi + \tilde{r}^2(x^2 - 1)(\sqrt{x^2 - 1} - x) \right)}{(\sqrt{x^2 - 1} - x)(r_i + \tilde{r}(\sqrt{x^2 - 1} - x))} \\ B_{i,j,k,m,n} &= \frac{-2}{(z_k - z_n)^3} \frac{\left(r_i\tilde{r}(x^2 - 1) + \xi - \tilde{r}^2(x^2 - 1)(\sqrt{x^2 - 1} + x) \right)}{(\sqrt{x^2 - 1} - x)(-r_i + \tilde{r}(\sqrt{x^2 - 1} + x))} \\ \xi &= \sqrt{x^2 - 1}(z_k - z_n) \left(z_k - z_n + \sqrt{r_i^2 + \tilde{r}^2 - 2r_i\tilde{r}x + (z_k - z_n)^2} \right) \end{aligned} \quad (7)$$

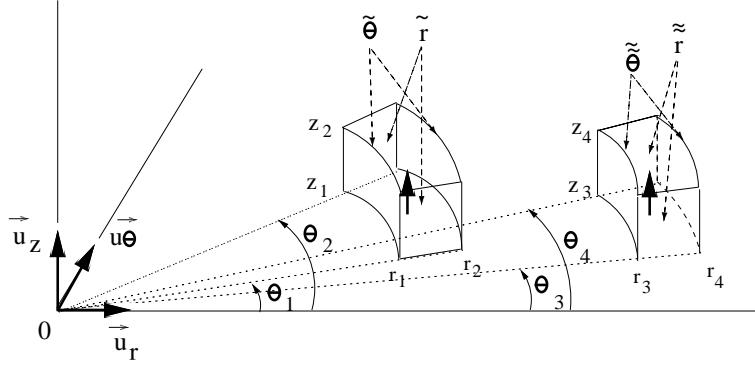


Figure 6. Two tile permanent magnets axially magnetized

¹²³ **3.3. Torque transmitted between two tile permanent**
¹²⁴ **magnets axially magnetized**

¹²⁵ The torque transmitted between the two tile permanent magnets
¹²⁶ axially magnetized is determined by integrating the magnetic field
¹²⁷ produced by the inner tile permanent magnet on the magnetic pole
¹²⁸ surface densities of the outer tile permanent magnet. By denoting
¹²⁹ $\mathbf{H}(r, \theta, z)$, the magnetic field produced by the inner tile permanent
¹³⁰ magnet in all points in space, the torque transmitted bewteen the two
¹³¹ tile permanent magnets can be expressed as follows:

$$\begin{aligned} T = & J_2 \int_{r_3}^{r_4} \int_{\theta_3}^{\theta_4} H_\theta(\tilde{r}, \tilde{\theta}, z_2) \tilde{r} d\tilde{r} d\tilde{\theta} \\ & - J_2 \int_{r_3}^{r_4} \int_{\theta_3}^{\theta_4} H_\theta(\tilde{r}, \tilde{\theta}, z_1) \tilde{r} d\tilde{r} d\tilde{\theta} \end{aligned} \quad (8)$$

¹³² where $H_\theta(r, \theta, z)$ is expressed as follows:

$$H_\theta(r, \theta, z) = -\vec{\nabla} \cdot \left(\int_{r_1}^{r_2} \int_{\theta_1}^{\theta_2} G(\vec{r}, \vec{r}') d\phi(\vec{r}') \right) \cdot \vec{u}_\theta \quad (9)$$

¹³³ where

$$d\phi(\vec{r}') = \frac{J_1}{\mu_0} \tilde{r} d\tilde{r} d\tilde{\theta} \quad (10)$$

¹³⁴ By setting $\xi = \sqrt{r_i^2 + r_l^2 - 2r_i r_l x + (z_n - z_k)^2}$ and $\xi_2 = \xi + r_l - r_i x$,
¹³⁵ the expression of the torque transmitted between two tile permanent

¹³⁶ magnets axially magnetized can be written as follows:

$$T = \sum_{i,j,k,l,n=1}^2 (-1)^{(i+j+k+l+n)} \int_{\theta_3}^{\theta_4} \vartheta(\tilde{\theta}, i, j, k, l, n) d\tilde{\theta} \quad (11)$$

$$\begin{aligned} \vartheta(\tilde{\theta}, i, j, k, l, n) = & \frac{b^{\frac{3}{2}}x}{3(x^2 - 1)^{\frac{3}{2}}} \tanh^{-1} \left[\frac{r_l \sqrt{x^2 - 1}}{\sqrt{b}} \right] - \frac{r_l^3 x}{9} - \frac{b r_l x}{3(x^2 - 1)} \\ & + \frac{x \xi}{6(x^2 - 1)} \left(-r_i r_l - 2bx - 3r_i^2 x + r_i r_l x^2 + 3r_i^2 x^3 \right) \\ & + x \log(\xi_2) \left(-\frac{b r_i}{2} + \frac{r_i^3 x^2}{2} + \frac{r_i^3}{6} \right) \\ & + \frac{\xi}{6} \left(-r_i r_l x + r_i^2 (2 - 3x^2) + 2(r_l^2 + (z_n - z_k)^2) \right) \\ & - \frac{\log(\xi_2)}{2} \left(r_i x (r_i^2 (x^2 - 1) - (z_n - z_k)^2) \right) \\ & + \frac{\left(b^{\frac{3}{2}} r_i x - b^{\frac{3}{2}} r_i x^3 + b^2 x^2 \right) \log(A^I)}{6(x^2 - 1)^{\frac{3}{2}} \sqrt{bx^2 - 2\sqrt{b} r_i x \sqrt{x^2 - 1} + r_i^2 (x^2 - 1)}} \\ & + \frac{\left(-b^{\frac{3}{2}} r_i x + b^{\frac{3}{2}} r_i x^3 + b^2 x^2 \right) \log(A^{II})}{6(x^2 - 1)^{\frac{3}{2}} \sqrt{bx^2 + 2\sqrt{b} r_i x \sqrt{x^2 - 1} + r_i^2 (x^2 - 1)}} \end{aligned} \quad (12)$$

¹³⁷ By setting $\alpha^{+,-} = \sqrt{bx^2 \pm 2\sqrt{b} r_i x \sqrt{x^2 - 1} + r_i^2 (x^2 - 1)}$, the parameters ¹³⁸ A^I and A^{II} are defined as follows:

$$\begin{aligned} A^I = & \frac{6(x^2 - 1)^2 (-r_i^2 + r_i r_l x + r_i^2 x^2 - r_i r_l x^3)}{b^{\frac{3}{2}} (r_l - r_l x^2 + \sqrt{b} \sqrt{x^2 - 1}) \alpha^- (r_i - r_i x^2 + \sqrt{b} x \sqrt{x^2 - 1})} \\ & + \frac{6(x^2 - 1)^2 (\sqrt{b} (r_l - r_i x) \sqrt{x^2 - 1} + b(x^2 - 1) + \xi \sqrt{x^2 - 1} \alpha^-)}{b^{\frac{3}{2}} (r_l - r_l x^2 + \sqrt{b} \sqrt{x^2 - 1}) \alpha^- (r_i - r_i x^2 + \sqrt{b} x \sqrt{x^2 - 1})} \end{aligned} \quad (13)$$

¹³⁹

$$A^{II} = \frac{6(x^2 - 1)^2 (b + r_i^2 - r_i r_l x - bx^2 - r_i^2 x^2 + r_i r_l x^3)}{b^{\frac{3}{2}} (\sqrt{b} x \sqrt{x^2 - 1} + r_i (x^2 - 1)) \alpha^+ (\sqrt{b} \sqrt{x^2 - 1} + r_l (x^2 - 1))}$$

$$+ \frac{6(x^2 - 1)^2 (\sqrt{b}(r_l - r_i x) \sqrt{x^2 - 1} - \xi \sqrt{x^2 - 1} \alpha^+)}{b^{\frac{3}{2}} (\sqrt{bx} \sqrt{x^2 - 1} + r_i(x^2 - 1)) \alpha^+ (\sqrt{b} \sqrt{x^2 - 1} + r_l(x^2 - 1))} \quad (14)$$

4. COMPARISON OF THREE KINDS OF MAGNETIC COUPLINGS USING A CYLINDRICAL AIR GAP

This section presents a comparison between three kinds of magnetic couplings using cylindrical air gaps. The torque transmitted between the outer (led rotor) and inner (leading rotor) rotors is determined for three configurations using 8, 16 and 32 tile permanent magnets. In other words, the angular widths of each tile permanent magnet are $\frac{\pi}{4}$ rad, $\frac{\pi}{8}$ rad, $\frac{\pi}{16}$ rad, $\frac{\pi}{32}$ rad and $\frac{\pi}{64}$ rad. For each tile permanent magnet, we have $r_1 = 0.0219$ m, $r_2 = 0.0249$ m, $r_3 = 0.025$ m, $r_4 = 0.028$ m, $z_1 = 0$ m, $z_2 = 0.003$ m, $z_3 = 0$ m, $z_4 = 0.003$ m. For the rest of this paper, all the simulations have been carried out with 2 tile permanent magnets on each rotor.

4.1. Simulations

The simulations have been carried out with the following dimensions: each tile permanent magnet has a magnetic polarization that equals 1 T. Their radial width is 3 mm and their height is 3 mm. The air gap between the two rotors is 0.1 mm. The torque transmitted between the two rotors is represented versus the angle θ , that is, versus the angular shift between the two rotors.

4.2. Discussion

Figure 7 shows that tile permanent magnets radially magnetized are the best solution for having the greatest torque between two rotors with a cylindrical air gap. However, as tile permanent magnets radially magnetized are rather difficult to manufacture, it can be interesting to compare the torque transmitted between two rotors made of tile permanent magnets tangentially magnetized and two rotors made of tile permanent magnets axially magnetized. Figure 7 shows that tile permanent magnets tangentially magnetized are required when the number of tile permanent magnets used is high (typically superior to 32 for each rotor). When this number is lower, it is more interesting to use tile permanent magnets axially magnetized.

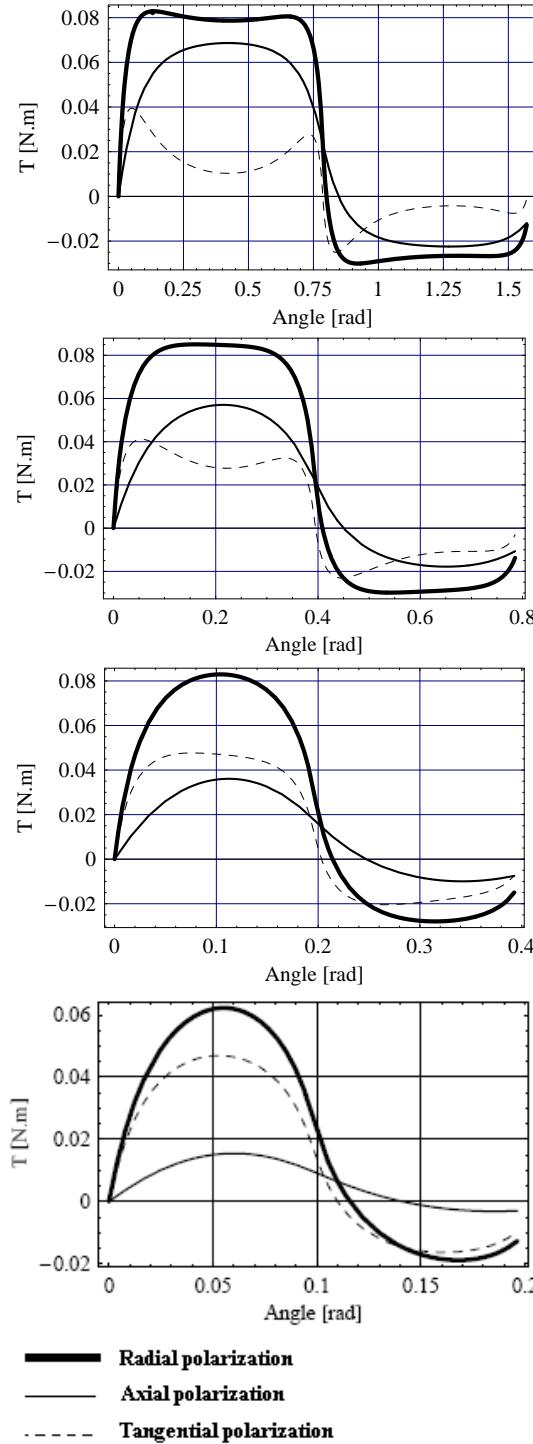


Figure 7. Representation of the torque transmitted between two rotors with a cylindrical air gap with tile permanent magnets radially, tangentially and axially magnetized. The angular widths taken are $\frac{\pi}{4}$ rad, $\frac{\pi}{8}$ rad, $\frac{\pi}{16}$ rad and $\frac{\pi}{32}$ rad respectively from the upper figure to the lower figure

¹⁷¹ **5. COMPARISON OF THREE KINDS OF MAGNETIC
172 COUPLINGS USING A PLANE AIR GAP**

¹⁷³ **5.1. Simulations**

¹⁷⁴ The simulations have been carried out with the following dimensions:
¹⁷⁵ each tile permanent magnet has a magnetic polarization that equals
¹⁷⁶ 1 T. Their radial width is 3 mm and their height is 3 mm. The air gap
¹⁷⁷ between the two rotors is 0.1 mm. For each tile permanent magnet,
¹⁷⁸ we have $r_1 = 0.025$ m, $r_2 = 0.028$ m, $r_3 = 0.025$ m, $r_4 = 0.028$ m,
¹⁷⁹ $z_1 = 0.0031$ m, $z_2 = 0.0061$ m, $z_3 = 0$ m, $z_4 = 0.003$ m.

¹⁸⁰ **6. PARAMETRIC STUDY OF THE TORQUE
181 TRANSMITTED IN CYLINDRICAL AIR GAPS USING
182 TILE PERMANENT MAGNETS RADIALLY, AXIALLY
183 AND TANGENTIALLY MAGNETIZED**

¹⁸⁴ **6.1. Couplings using cylindrical air gaps**

¹⁸⁵ We present in this section a parametric study of the torque transmitted
¹⁸⁶ between the stator and the rotor of a coupling made of two tile perma-
¹⁸⁷ nent magnets with radial, axial or tangential polarizations located on
¹⁸⁸ the led and leading parts of this machine. For this purpose, we consider
¹⁸⁹ first a coupling using a cylindrical air gap with the following dimen-
¹⁹⁰ sions: $r_2 - r_1 = 0.003$ m, $r_4 - r_3 = 0.003$ m, $z_1 = 0$ m, $z_2 = 0.003$ m,
¹⁹¹ $z_3 = 0$ m, $z_4 = 0.003$ m, $J_1 = J_2 = 1$ T, $\theta_4 - \theta_3 = \theta_2 - \theta_1 = \frac{\pi}{32}$.

¹⁹² We represent in Figs 9-A, 9-B and 9-C the torque transmitted
¹⁹³ between the leading and led parts of a coupling for four air gaps
¹⁹⁴ (0.1 mm, 0.3 mm, 0.5 mm, 1 mm). In the three configurations,
¹⁹⁵ the smallest the air gap is, the greatest the torque is. These figures
¹⁹⁶ also show that the way the torque decreases versus both the angular
¹⁹⁷ shift and the air gap is similar for the three polarizations of the tile
¹⁹⁸ permanent magnets.

¹⁹⁹ The other important parameter that can be optimized in a
²⁰⁰ magnetic coupling is certainly the thickness of the permanent magnets
²⁰¹ on each parts.

²⁰² We represent in Figs 10-A, 10-B and 10-C the torque transmitted
²⁰³ between the leading and led parts of a coupling for three magnet
²⁰⁴ thicknesses (0.003 m, 0.005 m, 0.011 m). In the three configurations,
²⁰⁵ the smallest the magnet thickness is, the greatest the torque is. These
²⁰⁶ figures also show that the way the torque decreases versus both the
²⁰⁷ angular shift and the air gap is similar for the three polarizations of
²⁰⁸ the tile permanent magnets.

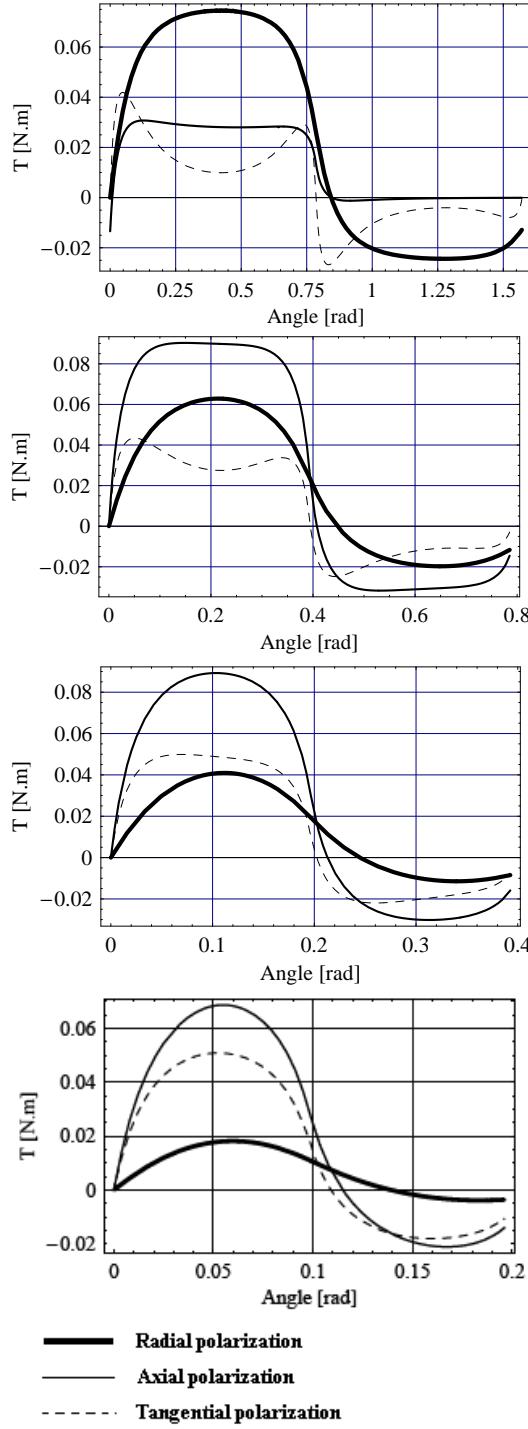


Figure 8. Representation of the torque transmitted between two rotors with a plane air gap with tile permanent magnets radially, tangentially and axially magnetized. The angular widths taken are $\frac{\pi}{4}$ rad, $\frac{\pi}{8}$ rad, $\frac{\pi}{16}$ rad and $\frac{\pi}{32}$ rad respectively from the upper figure to the lower figure

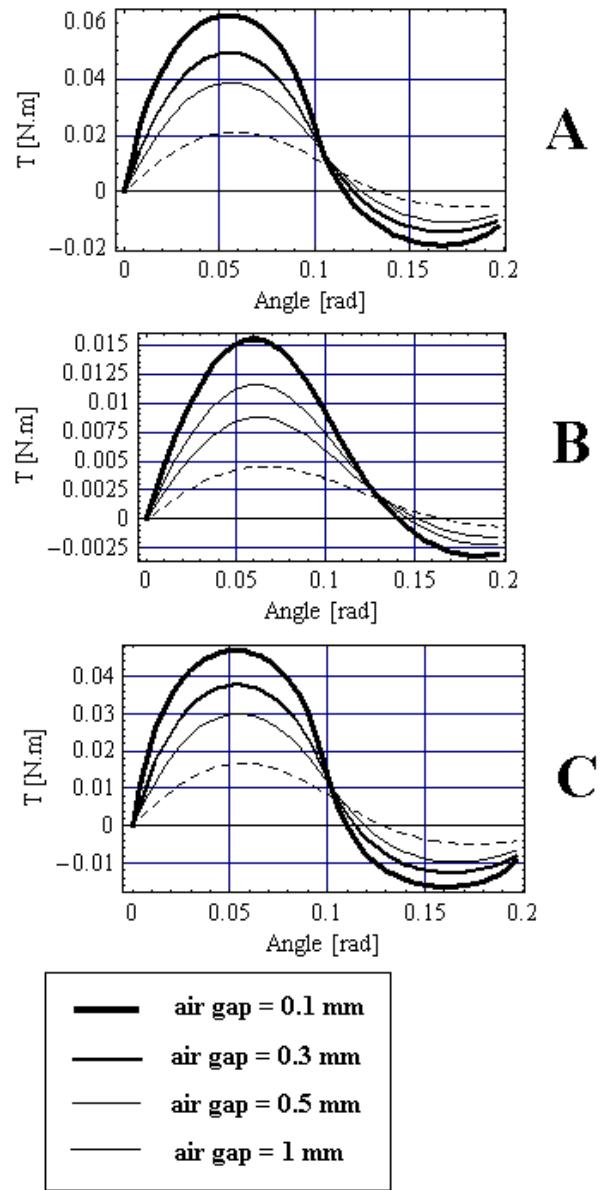


Figure 9. Representation of the torque transmitted between two rotors with a cylindrical air gap with tile permanent magnets radially (**A**), axially (**B**) and tangentially (**C**) magnetized with four air gaps (0.1 mm, 0.3 mm, 0.5 mm, 1 mm); we take the following dimensions: $r_2 - r_1 = 0.003$ m, $r_4 - r_3 = 0.003$ m, $z_1 = 0$ m, $z_2 = 0.003$ m, $z_3 = 0$ m, $z_4 = 0.003$ m, $J_1 = J_2 = 1$ T, $\theta_4 - \theta_3 = \theta_2 - \theta_1 = \frac{\pi}{32}$

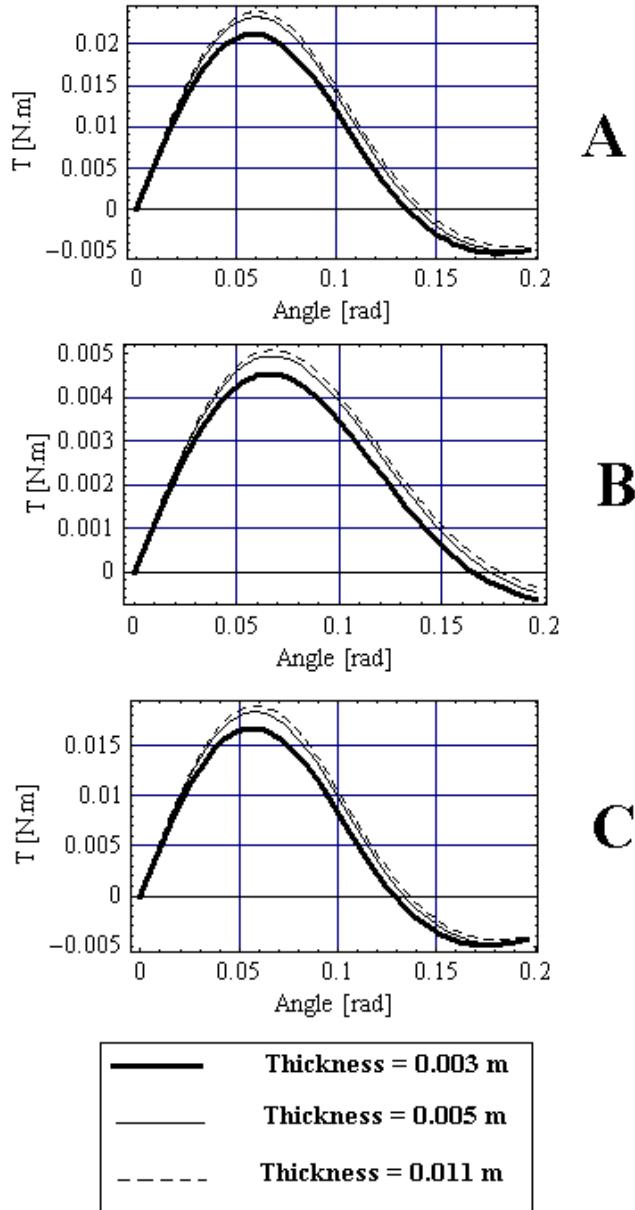


Figure 10. Representation of the torque transmitted between two rotors with a cylindrical air gap with tile permanent magnets radially (**A**), axially (**B**) and tangentially (**C**) magnetized with three magnet thickness (0.003 m, 0.005 m, 0.011 m); we take the following dimensions: $r_2 = 0.024$ m, $r_3 = 0.025$ m, $z_1 = 0$ m, $z_2 = 0.003$ m, $z_3 = 0$ m, $z_4 = 0.003$ m, $J_1 = J_2 = 1$ T, $\theta_4 - \theta_3 = \theta_2 - \theta_1 = \frac{\pi}{32}$

210 In short, the previous figures show that for a cylindrical coupling,
211 the air gap must be the smallest and the magnet thickness must be
212 the greatest and the magnet polarization should be radial.

213
214 We can apply the previous results to the case of plane magnetic
215 couplings. Indeed, in the case of plane air gaps, the air gap must also
216 be the smallest, the magnet height must be the greatest and the mag-
217 net polarization should be axial.

218

219 6.2. Discussion

220 Figure 8 shows that tile permanent magnets axially magnetized are
221 not always the best solution for having the greatest torque between
222 two rotors with a plane air gap. When the number of tile permanent
223 magnets used is high, it is more interesting to stack tile permanent
224 magnets axially magnetized. In the other hand, when the number of
225 tile permanent magnets used is low, it is more interesting to stack tile
226 permanent magnets radially magnetized. Furthermore, tile permanent
227 magnets tangentially magnetized can also be a good compromise what-
228 ever the number of tile permanent magnets used.

229

230 Figures 9 and 10 present elements of information about how to
231 optimize cylindrical magnetic couplings with radial, axial or tangen-
232 tial polarizations. In short, the air gap must always be the smallest
233 and the magnet thickness should be the greatest. However, the cost
234 and the weight of the magnet structure must also be taken into account.

235

236 7. CONCLUSION

237 This paper has presented a synthesis of magnetic couplings made of
238 tile permanent magnets radially, tangentially or axially magnetized.
239 First, we have presented new semi-analytical expressions of the torque
240 transmitted between two tile permanent magnets tangentially and
241 axially magnetized. Such a three-dimensional approach allows us
242 to compare several configurations made of tile permanent magnets
243 radially, tangentially or axially magnetized. All the calculations have
244 been carried out without any simplifying assumptions. Therefore,
245 these expressions are accurate whatever the tile permanent magnet
246 dimensions. Then, we have proposed to compare magnetic couplings
247 using cylindrical air gaps and magnetic couplings using plane air gaps.
248 For the ones using cylindrical air gaps, it is always more interesting

²⁴⁹ to use tile permanent magnets radially magnetized. For the couplings
²⁵⁰ using plane air gaps, the most interesting polarization depends greatly
²⁵¹ on the number of tile permanent magnets used. However when the
²⁵² angular width of the tile permanent magnet is greater than $\frac{P_i}{4}$, the
²⁵³ axial polarization is the most interesting in the case of plane air gaps.

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