Design of Smart Magnetic Devices

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Abstract

The principles for the design of smart magnetic devices using permanent magnet are presented. For a small air gap, replacing the uniform magnetization with a finely tuned multipolar magnetic pattern can enhance the attractive force greatly and limit the flux leakage obviously. The optimal multipolar magnetic pattern is different for different air gap. More fascinatingly, by combining different multipolar magnetic patterns, the sign of interactive force can even be reversed as the air gap is reduced to a certain point. Moreover, a permanent magnet with uneven distributed magnetic pattern based on the Barker code can exhibit a much better performance for alignment than permanent magnet with other magnetic patterns.

Keywords: design, permanent magnet, magnetic force, alignment

1. Introduction

Permanent magnet (PM) has a very broad application in modern industries [1-3]. The magnetic properties of PM, especially for the maximum energy product $(BH)_{max}$ and the intrinsic coercivity H_{cj}, gained a great enhancement in the last century because of more and more discovered new materials and renewed process technologies [4-6]. Sintered anisotropic rare earth PMs, e.g. $SmCo_5$, Sm_2Co_{17}, and $Nd_2Fe_{14}B$ have the most excellent overall performance among the family of PMs. The development of PM gives engineers much more freedom in their design of magnetic devices [4, 7]. Magnetic devices based on rare earth PMs can be made very small and in any desired shape thanks to their high remnant induction B_r as well as high H_{cj}.

Magnetic attachment is one of the important and widespread applications based on the attractive force between PMs. For example, currently more and more electronic tablets are using rare earth PM assemblies to attach with their protective cases. The equation [1] can be used for a rough estimation for the magnetic force even the boundary condition may be slightly different,

$$F = \frac{B^2 A}{2\mu_0} \qquad (1)$$

where F is the attractive force, B is the magnetic induction at the interface, and A is the area of the interface, and μ_0 is the magnetic permeability of the vacuum. From this formula, we can see that the attractive force of an attachment device usually is proportional to the square of remnant induction Br (the magnetic field generated by a rare earth PM is almost proportional to the Br of which) of the PM and increases with the size of the PM. However, a large piece of PM with a high Br usually generates high flux leakage in the region far beyond the working space and produces negative effect on nearby electronic devices. Moreover, precise alignment by magnetic force is highly demanded in some cases, but a PM with uniform magnetization is not suitable to be used for this purpose, because the shear force created by which is weak.

Polymagnets were developed by Correlated Magnetics Research, LLC. (CMR) to solve the above problems [8]. Instead of one north pole and one south pole for a conventional uniformly magnetized PM, Polymagnet has multiple magnetic poles coexisted in one piece of PM, the arrangement of these poles is called the pattern. By finely tuning the pattern, Polymagnet can give maximum attractive force for a given air gap and limit the flux leakage. More fascinatingly, for a pair of Polymagnet with certain asymmetric patterns, the sign of interactive force can even be reversed as the air gap is reduced to a certain point. Polymagnet with certain pattern can also have much better performance for alignment than the normal PM with uniform magnetization. Due to these unique behaviours, Polymagnet deserves the title of smart magnetic device.

This paper presents the idea of how to design various magnetic patterns of Ploymagnet for various applications.

2. Method

The interactive force, and magnetic flux density distribution for Polymagnet with various patterns were simulated using finite element method (FEM). Infolytica's MagNet was chosen to perform the process of FEM computing, h-adaption was adopted, and the tolerance is set to be 0.5% to ensure the accuracy of the results. The Br of the PM is set to be 1.30T, and the demagnetizing permeability is set to be 1.05. No irreversible demagnetization effect is considered, i.e. we assume the H_{cj} of the PM is high enough to resist the self-demagnetizing field and the demagnetizing field from the counterpart, which must be fulfilled by a reasonable design, for most cases, $Nd_2Fe_{14}B$ magnet can fulfil this demand due to its high H_{cj}.

3. Results and discussion

3.1. Dependence of magnetic flux density on the shape of PM

The magnetic field generated by a PM does not only depend on the magnetization, but also on the shape of the PM. For cylindrical rigid PM (the relative demagnetizing permeability for which is 1) magnetized along the axis, the magnetic field along its axis can be analytically expressed [9]:

$$B = \frac{Br}{2}\left(\frac{(\frac{t}{2}+z)}{\sqrt{R^2+(\frac{t}{2}+z)^2}} + \frac{(\frac{t}{2}-z)}{\sqrt{R^2+(\frac{t}{2}-z)^2}}\right) \qquad (2)$$

where Br is the remanence, R is the radius, and t is the thickness of the PM, z is the coordinate along the axis with the origin being set at the centre of the cylinder.

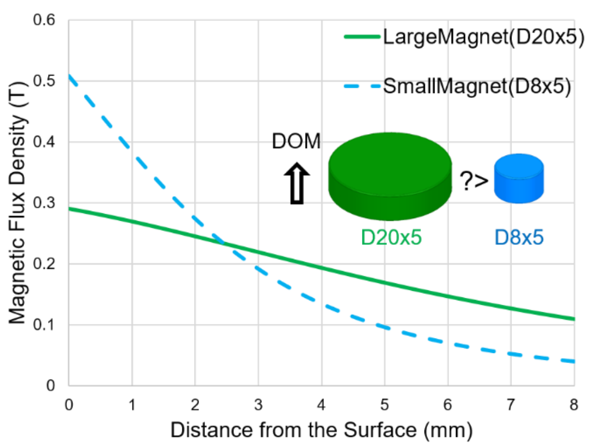

Fig. 1. Magnetic field along the axes of two cylindrical rigid PMs with dimensions of D20mmx5mm and D8mmx5mm.

Figure 1 shows the magnetic flux density along the axes generated by two rigid cylindrical PMs whose directions of magnetization (DOM) is parallel to the axes, the diameters of PMs are 20mm, and 8mm, respectively, and the thicknesses are 5mm for both. The attenuation behaviour of the flux density for these two PM is obviously different. For distance from the surface larger than 2.5mm, the magnetic field for the large PM is stronger than that for the small PM, however, as we move towards the surfaces, the latter boosts much faster than the former, for the distance from the surface smaller than 2.5mm, the magnetic field for the small PM becomes stronger. Nearby the surface, the small PM is almost 1.7 times stronger than the large PM, i.e., in magnetics, the larger one is not always the stronger one with respect to flux density. In general, because that the self-demagnetizing field inside the PM increases as the aspect ratio (in the case of cylinder, aspect ratio is defined as the division of thickness by diameter) of the PM decreases, for a thin and flat PM, the magnetic field is usually weak near its surface [1, 10].

3.2. Breaking a large PM into small parts

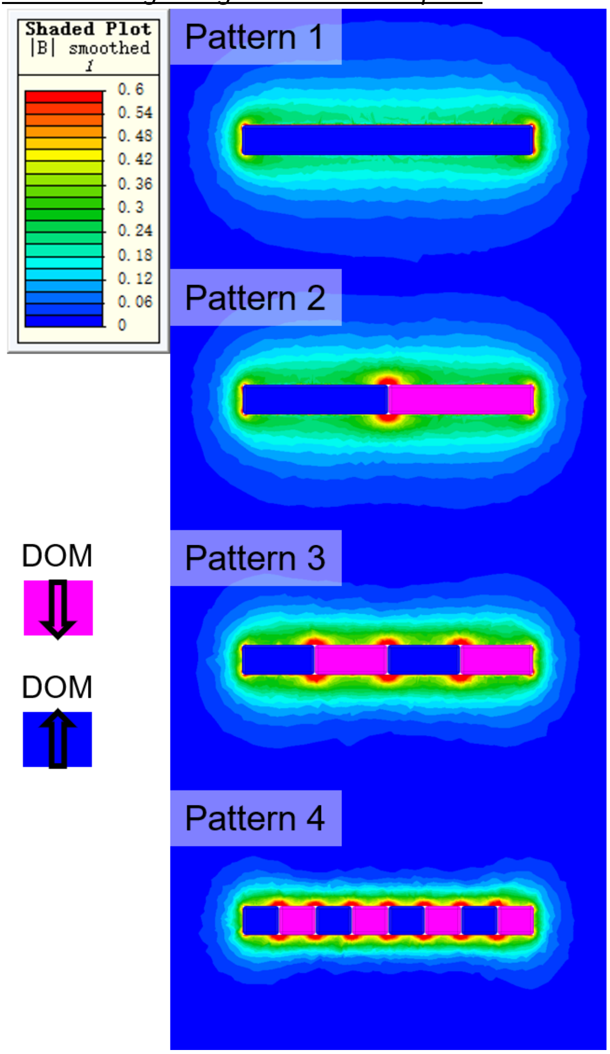

Fig. 2. Flux density distribution for Polymagnet with different patterns, the overall sizes are kept the same as 20mm*5mm*2mm. DOM is along with the 2mm edge. DOM is represented by the colors of blue and pink.

In most of the engineering cases for magnetic attachment, the working distance between two interactive PMs is small, and sometimes only a thin and flat space is left for PMs. The idea of Polymagnet is to create many magnetic poles in one surface, instead of just one north pole and one south pole on each surface. This is equivalent to breaking a large flat PM into many small slim PMs which will increase the magnetic field near the noticeably, as indicated by the discussion of subsection 3.1.

Figure 2 shows an example of the effect of magnetic patterns on the flux density distribution. Pattern 1 is a magnet with uniform magnetization, whereas Pattern 2, Pattern 3, and Pattern 4 are obtained by equipartitioning Pattern 1 to two, four, and eight parts, respectively, and set the DOMs upward and downward alternatively for each part. For Pattern 1, the field distribution is spread. As we equipartition the magnet into small parts, the field distribution becomes confined to smaller region near the magnet. Taking Pattern 4 for example, the flux density in the region 2mm away from the Polymagnet is almost negligible, therefore, Pattern 4 will have much less influence on other devices. In the meanwhile, the field near the Polymagnet is strengthened noticeably, which will result in stronger interactive force when the air gap is small, as discussed below.

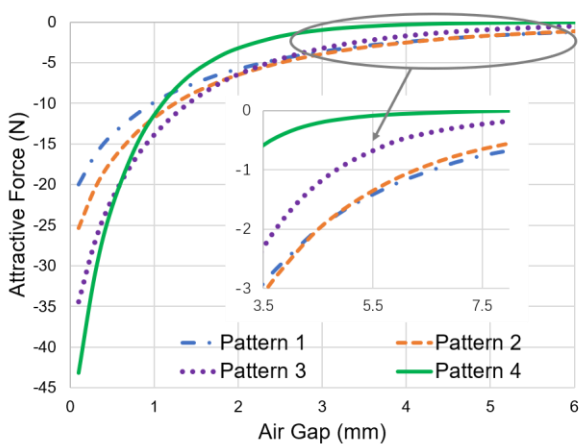

Fig. 3. The attractive force variation with air gap for a pair of Polymagnets with given pattern.

In accordance with the flux density distribution, the attractive force between a pair of Polymagnets depends closely on the pattern and the air gap. As the air gap is enlarged, the attenuation of the attractive force is different for different magnetic patterns. As shown in Fig.3, for air gap smaller then 0.5mm, the attractive force between two Polymagnets with Pattern 4 is the strongest, however, the force decreases very fast as the air gap increases. Pattern 1 exhibits the weakest force when the air gap is small, however, when the air gap is larger than 5mm, it is the strongest one. For the air gap in the range of 0.5mm~2mm, and 2mm~5mm, Pattern 3 and Pattern 2 are the strongest, respectively. In general, the optimum design for an attachment device is different for different air gap range.

3.3. The reversal of interactive magnetic force

It should be noted that the pattern for Polymagnet is not confined to the case of equal size for each pole, and the patterns for the two mutual interactive Polymagnets can also be asymmetric.

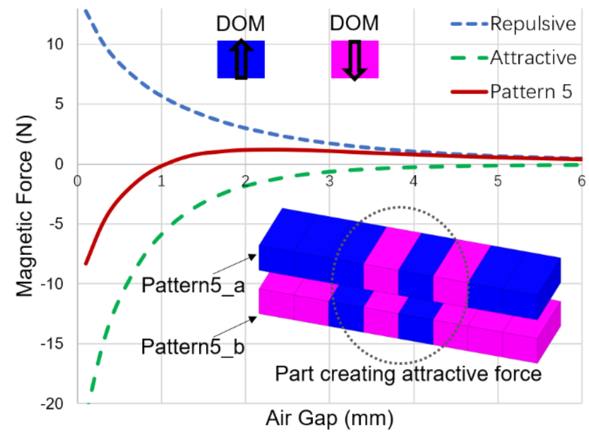

Fig. 4. The reversal of interactive magnetic force for Polymagnets with Pattern 5. The inset shows the arrangement of magnetic poles for the two sub-patterns. The overall size is 20mm*5mm*2mm for each sub-pattern.

The interactive force between two conventional PMs is either attractive (for DOMs being aligned parallel) or repulsive (for DOMs being aligned antiparallel), regardless of the air gap. However, for a Polymagnet with certain pattern, the sign of interactive force can be reversed when the air gap is changed, as shown in Fig. 4. The pair of Polymagnets with Pattern 5 is constituted by two sub-patterns, Pattern 5_a and Pattern 5_b, the arrangement of magnetic poles is different for these two sub-patterns, as shown in the inset of Fig. 4. For large air gap, the interactive force is repulsive. When we decrease the air gap, the repulsive force gets stronger, and reaches its summit at air gap of 2.5mm. Further reducing the air gap will decrease the repulsive force, and after the air gap is smaller than 1mm, the force becomes attractive.

In fact, Pattern 5 can be divided into two parts, the inner part as indicated by the dotted circle, for which the interactive force is attractive, and the outer part, for which the interactive force is repulsive. As stated in subsection 3.2, the attractive force for the inner part with small magnetic poles is very strong at small air gap and prevails over the repulsive force for the outer part with big magnetic poles, however, at large air gap, the situation is reversed, i.e., the repulsive force dominates. The combination of the inner part and the outer part gives the unique effect of sign reversal of magnetic force.

3.4. Polymagnet for alignment applications

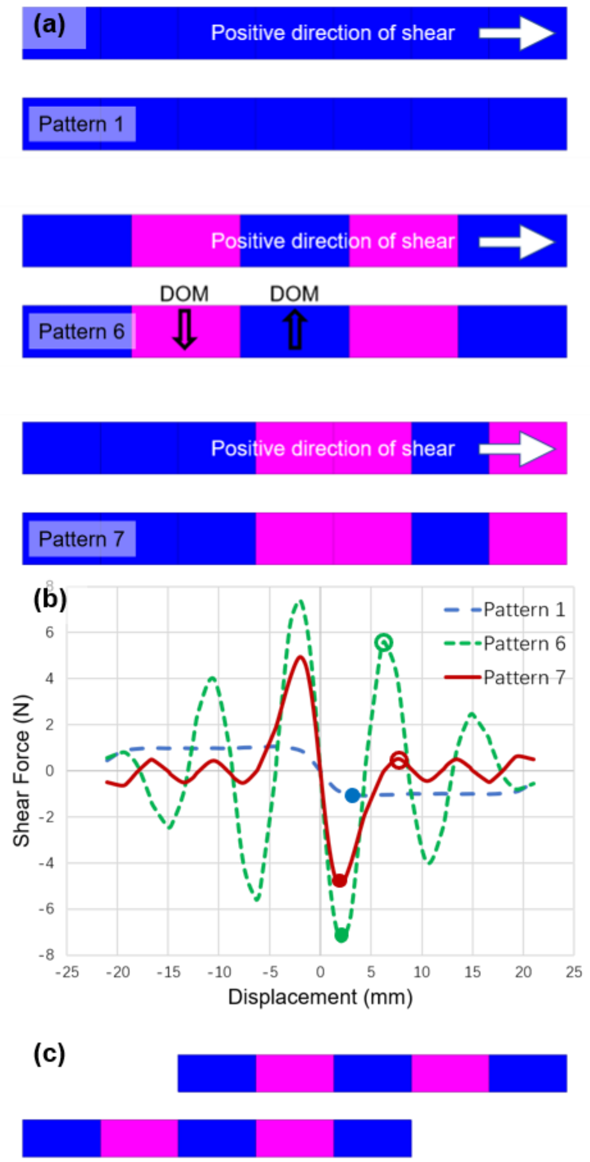

Fig. 5. The alignment behavior for a pair of Polymagnets with a certain pattern. The overall size for each sub-pattern is 20mm*5mm*2mm, the air gap is kept to be 1.5mm while one sub-pattern is sheared relative to the other. (a), arrangement of magnetic poles for different patterns, (b), the variation of shear force for different patterns with shear displacement, (c), one possible misalignment for Pattern 6.

In many magnetic applications, the alignment between two counterparts is important, i.e., the magnetic system must present forces to bring components into the right position. Fig. 5 gives a comparison for the alignment performance for three pairs of Polymagnets with different magnetic patterns. Pattern 1 is the same as the one in subsection 3.2. Pattern 6 is obtained by equipartitioning Pattern1 into five parts and set the DOMs for each part upward and downward alternatively. Pattern 7 is obtained by dividing Pattern 1 into four parts with unequal sizes, the length ratio is 3:2:1:1. The idea behind Pattern 7 is borrowed from the coding technology in the field of communication, in this example, Barker code of length seven is adopted[8, 11].

For each Polymagnet, we hold the bottom sub-pattern while moving the upper sub-pattern in horizontal direction, as shown by the white arrows in Fig. 5(a). If the shear force felt by the upper sub-pattern is antiparallel to the direction of moving, the shear force tries to restore the upper sub-pattern to its origin, i.e., the two sub-patterns tend to align with each other. The maximum restoring shear force, which can be used as a criterion for the alignment performance, for Pattern 1, Pattern, 6 and Pattern 7 is 1.07N, 7.39N, and 4.94N, respectively, as shown by the solid dot in Fig. 5(b). However, when we move the upper sub-pattern away further, the shear force becomes parallel with the direction of moving and tries to deflect the upper sub-pattern away from its origin, which is unfavourable for the alignment. The maximum deflective shear force, which can be regarded as a noise for the alignment, for Pattern 1, Pattern, 6 and Pattern 7 is 0N, 5.60N, and 0.51N, respectively, as shown by the hollow dot in Fig. 5(b). Although Pattern 6 has the strongest maximum restoring force, the noise for with is also very strong and may cause misalignment, as shown by Fig. 5(c). There is no deflective shear force for Pattern 1, however, the restoring force is also very weak. Pattern 7 has a relatively strong restoring shear force as well as a quite weak noise, therefore, it is the best choice for alignment applications among these three patterns.

3.5. The production of Polymagnet

In general, there are two ways to produce Polymagnet. One way is to take each pair of magnetic poles in the pattern as an individual PM and assemble these PMs together according to the magnetic pattern. The basic process includes machining PMs to the dimension of each magnetic pole, magnetizing, and gluing. This assembling approach is easy to carry out for Polymagnet with simple magnetic pattern with regular rectangle magnetic poles. One drawback is that there is some chance that some PMs may be assembled

with opposite magnetic polarity, even though fool-proof fixture may be used. Another drawback is that if the Polymagnet is very thin (e.g. less than 1mm), a plate is necessary to hold all the PMs and thus will increase the volume. Furthermore, for patterns with irregular and complex magnetic poles, the machining of PM is very difficult and costly.
The other way to produce Polymagnet is by magnetizing a whole piece of PM directly to the desired multipolar pattern. The magnetizing approach is usually more efficient than the assembling approach and has the inherent merit of being fool-proof.

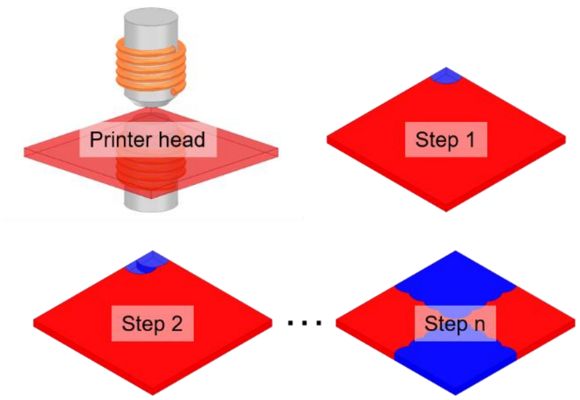

Fig. 6. The process of multipolar magnetizing by magnetic printer. The DOM is upward in red region and downward in blue region.

A device for multipolar magnetizing, named Magnetic Printer, was invented by CMR to produce the Polymagnet from a whole piece of PM [12]. Magnetic Printer can "Print" magnetic pattern point by point, just like the process of printing a photograph by needle printer. The printer head of Magnetic Printer is actually a pair of small magnetizer which can magnetize the PM locally, the minimum magnetic pixel (local magnetized region), or we can name it maxel, is about 1mm. The process of printing is controlled totally by a computer program, thus magnetic printing is also called programmable magnetizing. To save time and cost, the PM is usually first to be magnetized uniformly by solenoid, and then the magnetization in some local region is reversed by Magnetic Printer according to the designed magnetic pattern, as shown in Fig. 6. Magnetic Printer is very flexible for various patterns. In most cases, to produce a new design of Polymagnet, only the program needs to be modified, and no extra hardware is needed. Thus, Magnetic Printer is very suitable for prototyping of new designs. Magnetic Printer can produce Polymagnet with any complicated patterns (providing that the maxel is larger than 1mm) which may be impossible to be realized by other multipolar magnetizing method.

4. Conclusion

The magnetic field generated by a PM is not only depend on the grade, but also on the shape of the PM. For a small PM with low self-demagnetizing factor, the field is strong near the surface but decreases fast as the distance from the surface increases. For a large PM with high self-demagnetizing factor, the field is relatively weak near the surface but can extend far away from the surface. The idea of Polymagnet is to break a large PM into small parts, the distribution of DOMs for these parts is called the pattern of a Polymagnet. For attachment applications, the attractive force as a function of air gap depends on the pattern of the Polymagnet. The more magnetic poles in the pattern for one Polymagnet, the stronger attractive force is produced at small air gap, but the force will attenuate fast as the air gap is enlarged. By combination of Polymagnets with different patterns, the sign of interactive force can even be reversed when the air gap is changed. Polymagnet with magnetic pattern in accordance with Barker code has a better performance of alignment than others. Programmable magnetizing realized by Magnetic Printer can produce complicated magnetic patterns and is very suitable for the production and prototyping of Polymagnet.

Acknowledgement

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