Design of Permanent Magnet Systems Using Finite Element Analysis

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Abstract: Rare earth permanent magnets have a wide range of magnetic properties to meet the requirements of an extensive variety of applications. Sintered Sm_2Co_{17}-type magnets have the best thermal stability with high magnetic performance at temperatures up to 550 ℃. Sintered NdFeB magnets have the highest maximum energy product, $(BH)_{max}$, but are limited to applications with relatively low operating temperatures. Bonded magnets offer some design flexibility at the expense of magnetic properties. In view of these complexities, it is very important to understand the critical factors when designing the magnetic circuit. Using design examples based on finite element analysis (FEA), we will discuss magnetic materials selection, magnetic circuit design principles and design trade-offs for various applications.

Key words: rare-earth permanent magnet; finite element analysis; magnetic coupler; Halbach array; hybrid magnetic bearing

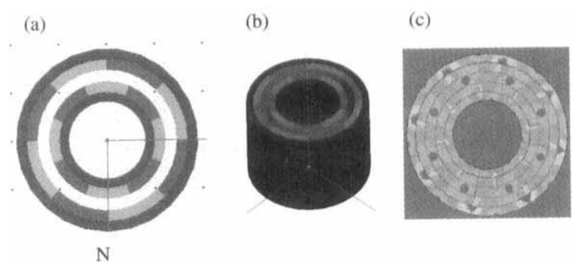
1 Magnetic Coupling Systems

Coupling designs could be divided into four principle categories: flexible couplings, fluid couplings, solid couplings, and magnetic couplings. We will discuss only magnetic couplings in this paper.

Magnetic couplings are used to transmit rotational and/or linear motion without direct contact. Rotary magnetic couplings are principally used to eliminate the use of seals in rotating and reciprocating machines such as seal-less pumps and pistons. Use of magnetic couplers improves the reliability and safety aspects of such machines because seals are prone to deterioration over time, causing leaks. Magnetic couplings are very popular in pharmaceutical industries. Linear and rotary magnetic couplings, and hybrids of the two, also find applications in vacuum technology where position or motion must be transmitted across a vacuum barrier.

1.1 Co-axial magnetic coupling

Rotary magnetic couplings are commonly designed in two configurations: co-axial and face-to-face. In the co-axial magnetic coupling configuration, the two halves of the coupler are mounted co-axially with each other and nested one within the other. The outer assembly is typically connected to the motor and the inner assembly to the driven system. In a coaxial coupling, alternating magnetic poles are arranged on the inner surface of the outer ring, and on the outer surface of the inner ring. An example of a coaxial coupling is shown in Fig.1.



(a) Cross section view shows alternating poles;

(b) 3D model (non-magnetic components are not shown);

(c) Flux map on cross section of coupler

Fig. 1 Example of 8-pole magnetic coupler

The torque characteristics of a co-axial magnetic coupler, as shown in Fig.2, are investigated by finite element method using Maxwell® 3D electromagnetic field solver. Based on the FEA results, the coupling torque increases as the number of poles increases and reaches a peak at 12 poles. When the number of poles exceeds 12, the coupling torque decreases for this specific design. Some of the data on the relationship between the number of poles and torque is shown in Table 1.

Table 1 FEA comparison of torque vs. number of poles of magnetic coupler as shown in Fig.2

Number of poles	6	8	12	14
Torque [Nm]	3.43	12.23	14.41	10.19

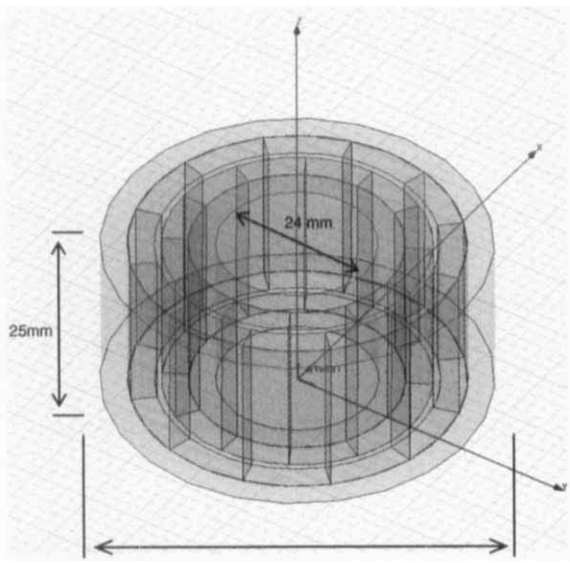


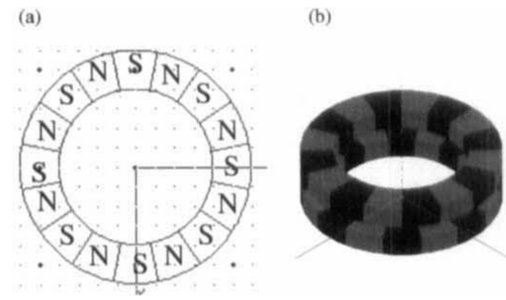
Fig. 2 3D FEA model of 12-pole magnetic coupler

1.2 Face-to-face magnetic couplings

Face-to-face type magnetic couplings are used where axial length is limited and some misalignment needs to be tolerated. Face-to-face magnetic couplings are typically made of two pancake-shaped parts with magnets mounted on the near faces. The separation barrier in this case can be as simple as a flat wall. One aspect of the face-to-face type couplings is the considerable attraction force between the two members. In a face-to-face coupling, the equal-sized magnet rings with alternating poles face each other. An example of a 16-pole face-to-face magnetic coupling is shown in Fig.3[1].

1.3 Linear magnetic couplings

Linear magnetic couplings can offer precise control of robotics and part positioning inside vacuum systems. These couplers are often used in the semiconductor industry to position objects within a clean, high vacuum chamber. Elimination of seals and reduction of the number of components inside the chamber improves contamination control and enhances system reliability.



(a) Cross section of magnet assembly showing alternating poles;
(b) 3D model (non magnetic components not shown)

Fig. 3 Example of 16-pole face-to-face magnetic coupling system

Both sintered and bonded rare earth magnets can be used in the permanent magnetic couplings. If the application has a moderate torque requirement in a moderate operating environment (<150 ℃), bonded Nd-Fe-B type magnets are a good choice. If the application has a high torque requirement in a moderate operating environment (<150 ℃), sintered Nd-Fe-B type magnets could be considered. If the application requires high torque at higher temperatures (>200℃), sintered Sm-Co magnets are the best choice [2,3].

2 Halbach Arrays

Permanent magnet Halbach arrays are very useful for a variety of applications, including high field magnet sources, magnetizing and de-magnetizing systems, and permanent magnet motors[4] and generators. Halbach progressive magnetization design can maximize the coupling torque. Halbach progressive magnetization is based on the Halbach theorem, which states that if the magnetization of an infinite line source oriented perpendicular to its axis is rotated about that axis, the field it produces remains everywhere constant in magnitude and is everywhere rotated by the same angle in the opposite sense. For an infinite dipole, the tangential and radial field components are:

$$H_\theta = \lambda \sin\theta / 2\pi r^2 \quad (1)$$

$$H_r = \lambda \cos\theta / 2\pi r^2 \quad (2)$$

where λ is the moment per unit length, and θ is the angle measured from the dipolar axis. Therefore the magnitude of H is:

$$|H| = (H_\theta^2 + H_r^2)^{1/2} = \lambda / 2\pi r^2 \quad (3)$$

where $|H|$ is independent of dipolar orientation.

The field orientation angle α with respect to the axis is twice θ. Halbach principle has been used extensively in a variety of applications [5-7], including permanent magnet brushless machines [4]. Due to the self-shielding of the Halbach progressive magnetization, back iron is not essential; therefore the mass and the inertia can be reduced. This will improve the dynamic performance.

In addition, magnets can have a significantly higher working point compared to conventional designs. This improves the effective utilization of the magnet material and increases the coupling torque.

Fig.4 is an example of a 4-pole magnetic coupler with Halbach progressive magnetization. The optimum number of poles is related to the geometry and the air gap, which can be determined by finite element analysis. A Halbach ring assembly with progressive magnetization can be realized by discrete magnet segments as shown in Fig.4. The direction of magnetization in each individual magnet segment can be expressed by the following relation:

$$\theta_m = (1 \pm p)\theta_i \quad (4)$$

where θ_i is the angle between θ=0 and the center of the i^{th} magnet segment, p is the number of pole-pairs, "+" is for an internal field cylinder, and "–" is for an external field cylinder.

A conventional face-to-face magnetic coupler, as shown in Fig.5, is compared to a Halbach coupling design, as shown in Fig.6, by finite element analysis.

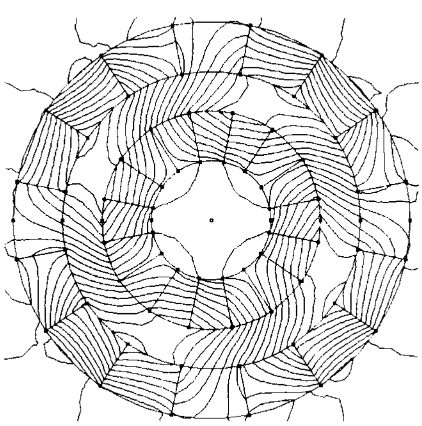


Fig. 4 Flux lines on cross-section of 4-pole 16-segment magnetic coupler with progressive magnetization (Non-magnetic components are not shown)

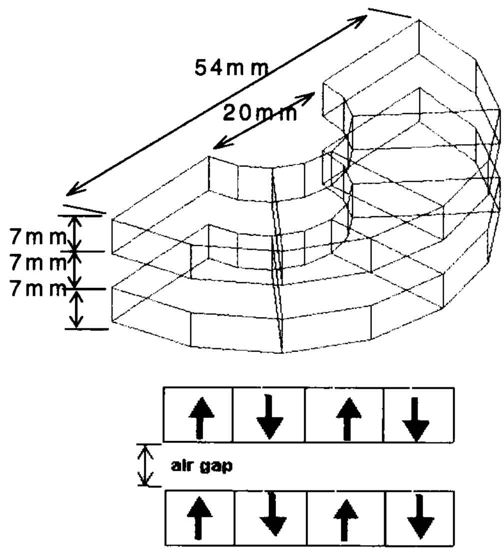


Fig. 5 Example of conventional 8-pole magnetic coupling design with alternating polarity

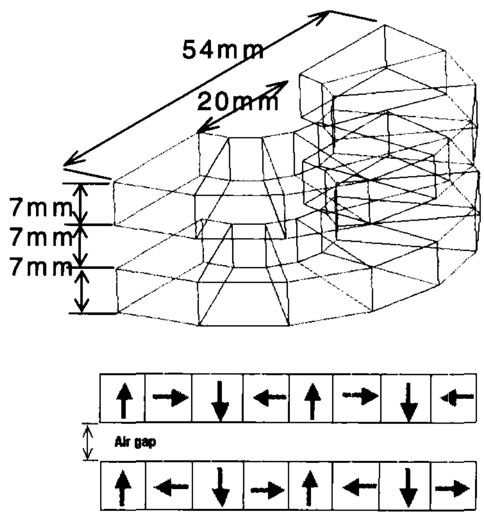


Fig. 6 Example of magnetic coupler with 8-pole 16-segment Halbach array design

The magnet material used in this comparison is a sintered Nd-Fe-B magnet with the following properties: B_r =13 kG, H_c=11.3 kOe and $(BH)_{max}$= 42 MGOe.

Fig.7 shows the air gap flux density comparison for 8-pole face-to-face coupling systems with conventional and Halbach designs. The maximum air-gap flux density of the Halbach array design and the conventional alternating polarity design are 8,056 G and 5,419 G, respectively. The magnetic flux density increased by 48.7% when the Halbach array design is applied to this application.

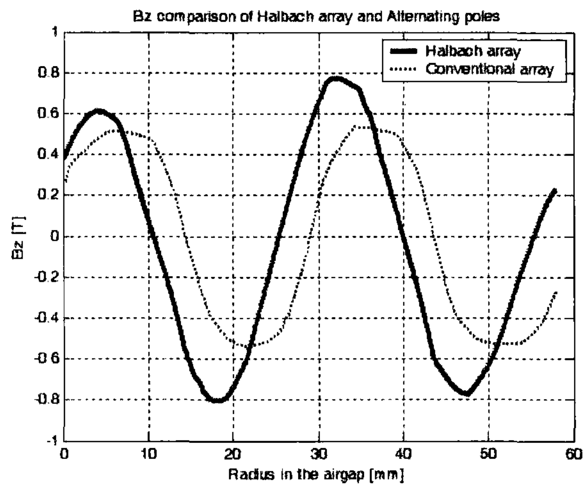


Fig. 7 FEA results comparison between Halbach design, as shown in Fig.6, and conventional alternating polarity design, as shown in Fig.5

A bonded Nd-Fe-B magnet can be magnetized into a Halbach multi-pole configuration using a specially designed magnetizing fixture. Although the magnetic performance of bonded magnets is much lower than that of their sintered counterparts, the single piece bonded magnet Halbach array design could lower the cost for large volume production. Segmented Halbach designs have to be considered if sintered magnets are used. Of course, the magnetic performance of sintered magnets is superior to that of bonded magnets.

3 Hybrid Magnetic Bearings

Magnetic bearings technology is considered to be an enabling technology for new advanced engine designs. Rolling element bearings and squeeze dampers are currently used to support gas turbine engine rotors. These types of bearings are limited in application temperature (<260 ℃) and speed. They require both cooling air and a lubrication system. Rolling element bearings in gas turbines are being pushed to their limits and new bearing technologies are critical for various industries.

NASA has a need for high temperature bearing systems to achieve its goals of lighter weight, higher temperature capable gas turbine engines to improve efficiency and decrease noise and emissions, which is well documented in published literatures [8].

Innovative technologies are necessary for the design and development of advanced space vehicles. NASA Glenn Research Center and the U.S. Army have been working on high temperature magnetic bearings with industry participation. The NASA/Army emphasis is on high-temperature applications for future gas turbine engines. Magnetic bearings could increase the reliability and reduce the weight of the engines by eliminating the lubrication system. With recent development in high temperature magnets funded by the Air Force, more design options are available to us. The recently developed and patented high temperature magnets [9] have a straight-line extrinsic demagnetization curve up to 550 ℃ (1022 ℉), which makes it possible for the design of high temperature hybrid magnetic bearings using permanent magnets.

A radial, redundant high temperature magnetic bearing was designed via iterative search employing 3D finite element (Fig.8) based electromagnetic field simulations. This bearing was designed to produce 500 lbs of force at 538 ℃ (1000 ℉) and the design weight is 48 lbs. Bias flux is produced by EEC high temperature permanent magnets in order to significantly reduce the related ohmic losses of an electromagnetically biased design. The stator was designed with 1002 and 1010 steels to significantly reduce the cost while maintaining required saturation flux levels. Fig.9 and Fig.10 show the section view of magnetic bearing and the first generation prototype, respectively, built by EEC and Texas A&M University.

The permanent magnets used in this application is EEC T550 ultra-high temperature magnets with the following properties: B_r = 8.55 kG, H_c = 8.0 kOe, $(BH)_{max}$ = 17 MGOe.

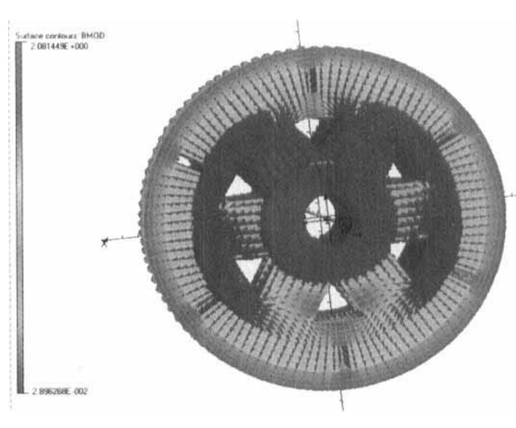


Fig. 8 FEA model of hybrid magnetic bearing

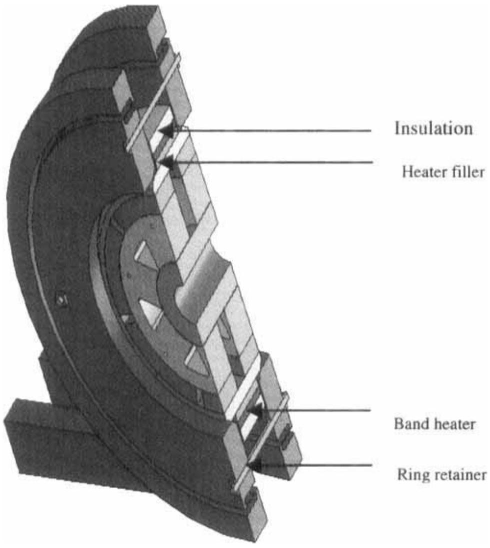


Fig. 9 Hybrid magnetic bearing section view

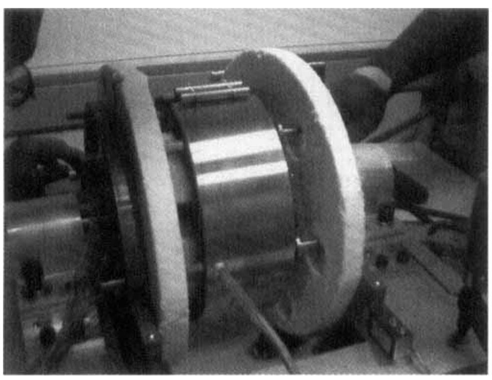


Fig. 10 Hybrid magnetic bearing prototype

4 Summary

Finite element analysis is a useful tool for the design optimization of electromagnetic systems. Halbach array design offers significant performance improvement over conventional design options. The selection of rare earth magnet materials is a trade-off between magnetic performance, thermal stability, design flexibility and cost. Sintered Nd-Fe-B type magnets should be considered for high performance low operating temperature applications, while Sm-Co magnets are the best choice for high performance and moderate temperature applications. A high temperature hybrid magnetic bearing was developed using ultra high temperature magnets. This radial bearing produces 500 lbs of force at 538 ℃ (1000 ℉).

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