Modeling and simulation of a permanent magnet array in elliptical configurations

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ABSTRACT

Permanent magnet arrays have advantages for magnetic field generation over the traditional current based magnetic flux sources, such as electromagnets, in that they do not require a power supply and cooling system. Magnetic flux density above the magnetic remanence B_R of the permanent magnet material can be achieved by arranging the permanent magnet segments in the form of hollow cylindrical shells (magic rings), or hollow spherical shells (magic spheres). For many applications, it is important to design a permanent magnet array with the highest magnetic flux density for a given size and weight of permanent magnet material. In this paper, we report enhancement of magnetic flux density in the air gap by changing the cross sectional shape of the permanent magnet array into ellipse instead of a circle, as has been conventional until now.

Keywords: Permanent magnet, magnet array, magnetic flux density, finite element method, modeling.

1 INTRODUCTION

To generate magnetic fields traditional current based magnetic flux sources such as electromagnets have been used. But these require a power supply and cooling system. Furthermore due to their weight and power requirements, they often can not be used for applications where portability is required. Compared to this, permanent magnet arrays allow high flux density to be generated without a power supply. These are useful in remote locations (e.g. spacecraft, automotive, transportation) where no conventional power supply is available, or where use of power is limited.

In this paper we report a special configuration of permanent magnets in an array, which produces the highest possible magnetic flux density for a given weight of magnetic material. The magnetic flux density from this array can be utilized for experiments where sources of strong magnetic field are needed to magnetize magnetic materials in applications such as magnetic refrigeration. The permanent magnet array can provide a magnetic flux density of up to 3 Tesla.

2 PERMANENT MAGNET ARRAYS

Magnetic flux density above the magnetic remanence B_R of the permanent magnet material have been achieved before by arranging the permanent magnet segments in the form of hollow cylindrical and hollow spherical shells [1,2]. The orientation of the magnetization vectors followed the Halbach rotation theorem [3]. Fig. 1 shows a cross section of a hollow cylindrical shell. The arrows indicate the direction of magnetization vectors of each segment. The magnetic flux density from each permanent magnet segments produce a homogeneous magnetic dipole field pointing downward through the center air gap of the array. The hollow cylindrical array shown consists of 8 permanent magnet segments. The magnitude of the magnetic flux density in the air gap is reduced about 10 % from the flux density that is achievable with a continuous hollow cylindrical ring. But the small number of segments in Fig. 1 allows easy fabrication. We have compared the magnitude of the magnetic flux densities in the air gap using different numbers of segments.

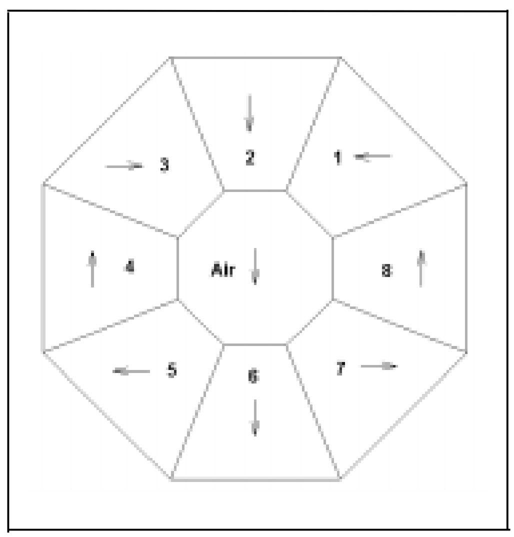

Fig. 1. Arrangement of magnetization vectors of each permanent magnet segment for producing coherent flux density in the center of the permanent magnet array consisting of eight segments.

3 PRODUCTION OF MAGNETIC FIELDS USING MAGNETIC ARRAYS

The analytical formulae for the magnetic flux density at the center of the air gap of radius r_i and outside radius r_o of the magic rings and magic spheres are $B = B_R \ln(r_o/r_i)$ and $B = 4/3 B_R \ln(r_o/r_i)$ respectively [4]. For comparison between the values from the analytical formula and the numerical finite element calculation, we evaluated the "magic ring" configuration as shown in Fig. 1. The assumed remanence B_R of the permanent magnets was 1 T. Therefore if $\ln(r_o/r_i)=1$, then B is 1 T for an ideal flux density from a continuous magic ring .

Only a limited number 8, 16, and 32 of array segments were used, for the "magic ring" simulation. The flux densities achieved were 90 %, 97 %, and 99 % of that produced by a continuous magic ring. To fabricate this ideal continuous magic ring would require an infinite number of permanent magnet segments. Using 8 permanent magnet segments it is easy to fabricate the array and it produces 90 % of the ideal flux density as shown in Fig. 2. Thus, for modeling and simulation of a hollow cylindrical permanent magnet array in an elliptical configuration, arrays with only 8 segments were used.

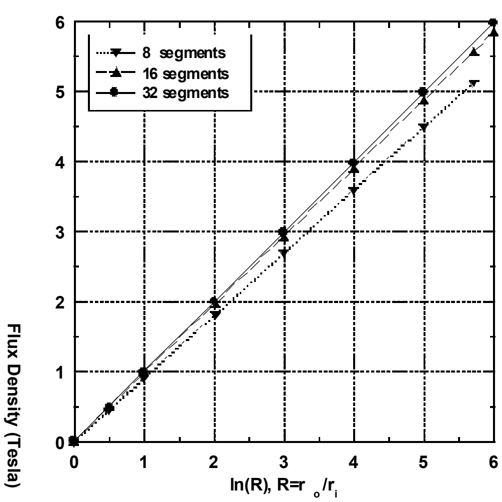

Fig. 2. Magnitude of the magnetic flux density in the air gap of permanent magnet arrays with different numbers of segments.

4 ENHANCEMENTS OF PERMANENT MAGNET FLUX SOURCES

To enhance the magnetic flux density in the gap we changed the cross sectional shape of the permanent magnet array into an ellipse instead of a circle. The ellipticity was varied from 0.5 to 5.0 while keeping the cross sectional area of the array constant. The effects of changing cross sectional ellipticity are described in sections 4.1 and 4.2, respectively. In section 4.3, the construction of the array is presented.

4.1 Enhancements to permanent magnet flux sources without soft magnetic materials

The hollow cylindrical shell and hollow rectangular shell [5] have been used for permanent magnet arrays. But as far as we know, there has been no systematic variation of geometry of the array to enhance the magnetic flux density beyond the values from the conventional configurations. The hollow cylindrical shell was elongated while keeping the cross sectional area of the array the same. This is to make sure that the enhancement of the magnitude of flux density in the air gap originated from the geometrical variation of the array, not from adding more permanent magnetic materials to the array.

The radius used for the finite element numerical calculations was 69.1 mm for the hollow cylindrical and spherical shell at ellipticity 1. The air gap width was 25.4 mm. The magnitude of remanence B_R of the permanent magnet material was 1 Tesla and the coercivity Hc was 0.796 MA/m for both cases. As the hollow cylindrical shell was elongated, the value of ellipticity increased from 1. The value of ellipticity decreased from 1 when the shape of array was squeezed while keeping the same area of cross section of the array. The shape of the air gap of the array was kept the same as that of the cross sectional area of the array. The air gap width was fixed during the variation of the array. The maximum value of the magnetic flux density B in the air gap occurred when the value of the ellipticity of the cross section of the array was 2, as shown in Fig. 3. The same result was obtained for the case of hollow spherical shell. The enhancement of the flux density was 19 % when ellipticity increased from 1 to 2. In the case of a spherical permanent magnet array, the enhancement was 13 % for the same change in ellipticity.

4.2 Enhancements to permanent magnet flux sources with soft magnetic materials

Soft magnetic materials with higher magnetic permeability keep the magnetic flux lines close to the material, and result in a reduction of leakage flux density. In the simulation result shown in Fig. 3, no soft magnetic materials were used as flux concentrators in order to examine the enhancement to permanent magnet flux sources originating solely from the geometry change.

To further enhance the flux density, a soft magnetic material was used around the air gap to focus the flux lines. The permanent magnet array was also enclosed on the outside by a soft magnetic "shell" to reduce flux leakage.

This resulted in a further increase of flux density in the air gap. For this simulation, NdFeB having magnetic energy of 35 MGOe, remanence of 1.2 T, and coercivity of 1.5 MA/m was used, and FeVCo was used for the soft magnetic material. The result is shown in Fig. 4. The radius r_o of the hollow cylindrical shell was 96.4 mm at ellipticity 1. The air gap width was 15.2 mm. During the variation of ellipticity, the cross sectional area (πr_o^2) of the array was maintained at a constant value. The details of dimension of the array with ellipticity 2 which produces the highest magnetic flux density is described in the next section.

The variation of the magnitude of the magnetic flux density in the air gap as the radius of the magic cylinder increases is shown in Fig. 5. In the figure, "with sm'' indicates that soft magnetic materials are used in the calculation. The simulated data was obtained using NdFeB for permanent magnet and FeVCo for soft magnetic material. The number of permanent magnet segments was 8 for all cases. A permanent magnet having a geometry with ellipticity 2 with soft magnetic shell and "pole pieces" generated a stronger magnetic flux density in the air gap than other geometries without soft magnetic materials.

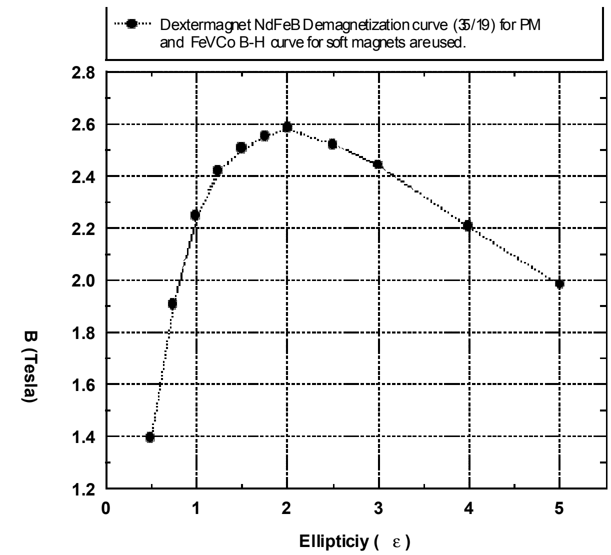

Fig. 4. Variation of the magnitude of the flux density in the air gap as ellipticity varies from 0.5 to 5 for hollow cylindrical flux source. For the calculation, permanent magnet NdFeB and soft magnetic FeVCo were used.

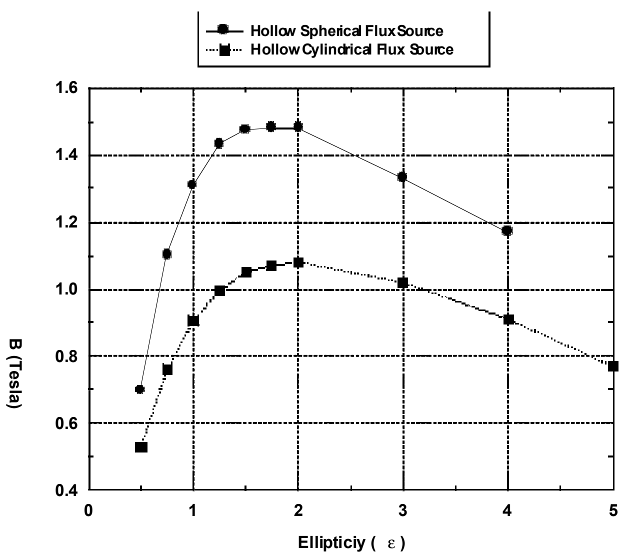

Fig. 3. Variation of the magnitude of the flux density in the air gap with ellipticity. In this calculation, no soft magnet materials were used as flux concentrators or flux return paths.

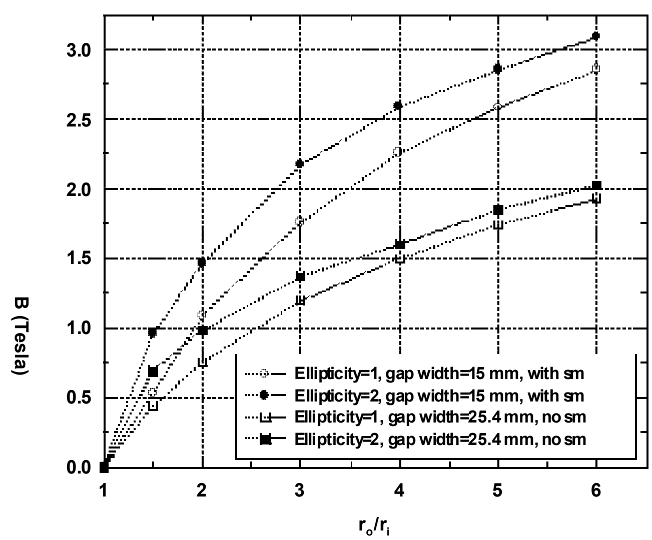

Fig. 5. Variation of the magnitude of the flux density B in the air gap as the outside radius r_o of the magic cylinder increases.

4.3 Details of the construction of the array

The cross sectional area of the elongated hollow cylindrical shell with ellipticity 2 is shown in Fig. 6. Eight permanent magnet segments are used for forming the array and their orientation of magnetization vectors are shown in the figure. The magnetic flux lines are shown on the left part of the figure. Numbers from 1 to 8 represent the Nd-Fe-B permanent magnets. The directions of magnetization vectors are the same as those in shown Fig. 1. Number 9 and 10 are FeVCo soft magnetic “inserts” or "pole pieces" to focus the magnetic flux in the air gap. The air gap is represented by number 11. Number 12 is an outer soft magnetic “shell” to prevent magnetic leakage flux. A magnetic flux density of about 2.6 Tesla across a 15 mm air gap can be generated by this configuration using materials with a remanent magnetic induction of only 1.2 Tesla.

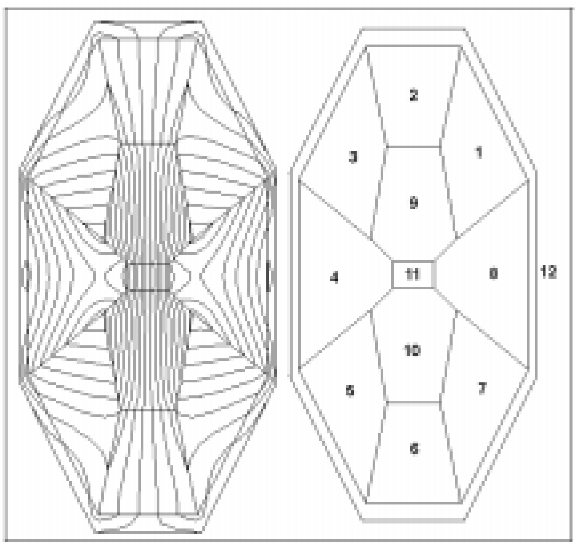

Figure 6: The magnetic flux lines of the permanent magnet array with ellipticity 2. Soft magnetic materials are used inside and outside. The air gap (section 11) is at the center of the array.

5 SUMMARY AND CONCLUSION

A method of enhancement of permanent magnet flux sources by geometrical change has been described and numerical values from finite element method have been presented. The change of geometry of hollow cylindrical permanent magnet array was made by elongation of the cross sectional area of the hollow cylindrical permanent magnet array along the vertical axis. At the value of ellipticity 2, the maximum value of magnetic flux density in the air gap occurred. Further enhancement of the flux density in the air gap was possible by using soft magnetic material, both as pole piece "inserts" and as flux concentrators, or return path ‘shell”

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