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Uniform magnetic field between face-to-face HTS bulk magnets combining concave and convex magnetic field distributions

T. Oka*,a, Y. Takahashi,a, S. Yaginuma,a, J. Ogawa,a, S. Fukui,a, T. Sato,a, K. Yokoyama,b, T. Nakamura,c

*aNiigata University, 8050 Ikarashi-Ninocho, Nishi-Ward, Niigata 950-2181 Japan
bAshikaga Institute of Technology, 268-1 Ohmae-cho, Ashikaga, Tochigi 326-8558 Japan
cRIKEN, 2-1 Hirosawa, Wako 351-0198, Japan

Abstract

The authors have been attempting to obtain the uniform magnetic field distribution in the space between the face-to-face HTS bulk magnets. The magnetic poles containing the HTS bulk magnets are usually characterized as non-uniform magnetic field distribution. Since the distributions show the conical or convex shapes, it is difficult to obtain the uniform magnetic field spaces even when the magnetic poles would be placed face-to-face. The authors have modified the shape of the distribution of one-side magnetic pole by attaching an iron plate on the surface, and formed the concave magnetic field distribution on the pole surface. The steep concave or convex distributions at each pole surface change to be flat with increasing distance from the pole surface. After the experimental result recording the best uniformity of 358 ppm by combining the concave and convex field distributions face-to-face, we attempted to simulate the feasible performance in this configuration. In the numerical simulation, the concave field distribution modified by attaching an imaginary spiral coil on the pole surface was coupled with the original convex field. We succeeded in obtaining the best uniformity of 30 ppm at 1.1 T in 4 x 4 mm² x-y plane at 7 mm distant from the pole surface in the gap of 30 mm. This result suggests that the concave and convex magnetic field distributions compensate the field uniformity with each other with keeping the magnetic field strength in the gap, and also suggests the novel compact NMR/MRI devices in the future.

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Corresponding author. Tel.: +81-25-262-7668 ; fax: +81-25-262-7666 .
E-mail address: okat@eng.niigata-u.ac.jp
1. Introduction

As reported or evaluated by the record-high magnetic flux trapping of 17.6 T [1] and various HTS bulk magnet (abbreviated as bulk magnet) systems [2], the feasible applications of bulk magnets have been expanding in the R&D trends for the compact NMR/MRI magnets. Among them, Nakamura et al. succeeded in detecting the NMR signals in the bore of piled-up bulk magnets for the first time in the world [3]. Furthermore, Ogawa et al. showed the MRI picture of an embryo of a mouse with use of the same system [4]. After such homogeneous fields, we aim to obtain another uniform magnetic field in the gap between face-to-face magnetic poles which contain a pair of bulk magnets in order to apply them to compact NMR device magnets [5]. In this paper, we report the present data of the magnetic field distributions formed by the bulk magnets which were activated by the pulsed field magnetization (PFM) technique, and discuss the uniformity of the magnetic field from the view point of possible utilization for the compact NMR/MRI magnets.

2. Experimental

Figure 1 shows the face-to-face bulk magnet system which was employed in the experiment. We installed a pair of Gd- and Sm-based bulk magnets manufactured by Nippon Steel Sumitomo Metal Co. and Dowa Mining Co. The dimensions are 60 mm in diameter and 15 mm in thickness. The pulsed magnetic fields up to 7 T were successively applied to the bulk magnets with use of the pulse coil by the IMRA method [6]. The magnetic poles were activated to 1.8 T (N) and 1.4 T (S), and horizontally settled face-to-face with gaps less than 70 mm.

As shown in Fig. 2, the magnetic field distributions in the gap between the magnetic poles were measured by scanning the 3D Hall sensor (F. W. Bell, BH703). The sensor was intermittently scanned with 2 mm pitch in every 1 s. The data were expressed in their vector magnitudes. The uniformity in the 4 x 4 mm² x-y planes was estimated as a function of the distance from the pole surface by the following equation in two cases of (a) and (b) in the figure.
\[ U = \frac{A}{B_{\text{max}}} \times 10^6 \text{ ppm} \]

Figure 3 shows the schematic illustration of the magnetic poles whose field distribution was modified from the convex shape (a) to concave shape (b). The iron plate with the size 100 x 60 mm² and 2 mm in thickness was attached on the left-hand side pole. The magnetic fields with concave and the convex shapes were coupled with the gaps of 30 - 70 mm. Possible combination patterns are shown in Fig. 3 (c) - (e).

As shown in Fig. 4, the numerical simulation plan by FEM (J-MAG) exhibits the face-to-face spiral coils (65 mm in diameter and 20 mm in thickness), which correspond to the bulk magnets, and a small spiral coil (13 mm in diameter and 4 mm in thickness) which was attached on the left pole. The small coil generates the inverse magnetic field to the bulk magnet, and modified the convex distribution to concave shape.

3. Results and discussion

The magnetic field generated by the bulk magnets gives us the strongest value at the centre of the surface, and it becomes weak and gentle with increasing distance. In case of countering convex distributions, as shown in Fig. 3(c), since the distributions remain convex, the uniformity reached 5,420 ppm (part per million) at 0.44 T even in the widest 70 mm gap. As well, in case of Fig. 3 (d) where a couple of iron plates were attached on both of magnetic poles, the best uniformity reached 2,520 ppm at 0.48 T in the 60 mm gap. Then, we attached an iron plate of 2 mm in thickness only on the left-side pole surface generating 1.4 T, and coupled it with the countering magnetic pole showing convex-shaped magnetic field of 1.8 T. As shown in Fig. 5, the concave distribution at 7 mm from the pole surface gradually changed to be convex with increasing distance from the surface. In Fig. 5(a), one can see the flat line at the position of 11 mm without lowering the field strength of 1.1 T. When the concave- and convex-shaped
magnetic fields were settled face-to-face, we obtained the most uniform distribution of 358 ppm at 9 mm position in the 30 mm gap.

Figure 6 shows the magnetic field distributions of each magnetic pole in comparison with measured and simulated data. These data agree with each other well, which indicates the simulation is proper. As shown in Fig. 7, the numerically simulated distribution indicates the similar profiles as that in the measurement. We also see the changes from concave to convex shape in all gaps, which suggest us the presence of flat distributions in the regions from 7 - 15 mm for each gap. We must note that this change occurs with keeping the field strength at 1.1 T in 7-15 mm distances in the 30 mm gap. Figure 8 shows the uniformity of magnetic field against the distance from the pole surface. Every profile indicates the sharp valley, which suggests us that the uniform points must exist in each gap. The best uniformity of 30 ppm at 1.1 T was obtained at 10 mm in the 30 mm gap. This performance is regarded as sufficient to detect the NMR signals for the future applications to NMR/MRI devises.

4. Conclusion

We succeeded in obtaining the uniform magnetic field for possible application to the compact NMR/MRI devises. The data of uniformity have reached 358 ppm and 30 ppm at 1.1 T by the experimental and simulation processes, respectively. The data obtained in the practical measurements and the numerical simulations as a function of the positions exhibited the similar profiles in various gaps. This indicates that the minimum values must exist in the valleys in the regions from 9 to 13 mm distance from the pole surface. The performances are sufficient to detect the NMR signals in the gaps of the magnetic poles in near future.

References