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Tashiro, Kunihisa
Department of Applied Science for Electronics and Materials, Graduate School of Engineering Science, Kyushu University

Sasada, Ichiro
Department of Applied Science for Electronics and Materials, Graduate School of Engineering Science, Kyushu University

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Separable Magnetic Shield with Magnetic Shaking Enhancement

Kunihisa TASHIRO*1,† and Ichiro SASADA*1
†E-mail of corresponding author: *tashiro@ence.kyushu-u.ac.jp*

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In this paper, we describe a separable cylindrical magnetic shield and a method for evaluating the magnetic shielding performance. A human size magnetic shield (Length: 1.5m, Inner diameter: 0.5m) consisting of two C-shaped building blocks was constructed. Building blocks were made by winding a cobalt-based amorphous ribbon, Metglas2705M, around a non-magnetic tube cut in half along lines parallel to the axis. The effect of the air gaps between the blocks on the shielding factor was examined by a miniature model of 1/10 size. The residual magnetic field inside the shield was measured using a commercial fluxgate magnetometer and a developed induction magnetometer with a noise level better than a few pT/$\sqrt{\text{Hz}}$. A static magnetic field less than 300 nT was achieved, and the noise floor was improved with magnetic shaking enhancement from 22 pT/$\sqrt{\text{Hz}}$ to 3 pT/$\sqrt{\text{Hz}}$ at 10 Hz. This is the first demonstration of the shaking effect on the noise level inside a separable magnetic shield evaluated between 10 Hz and 1 kHz.

Key words: *Magnetic shield, separable, magnetic shaking, induction sensor, noise floor*

1. Introduction

The first demonstration of measuring magnetic signals from the human brain was performed by means of a nonsuperconducting sensor in the 1960s 1). With recent advances in SQUID systems, biomagnetic measurement has become useful for investigating the human somatosensory system 2), studying higher brain functions of humans 3), and detecting the early stages of heart trouble 4). A challenge for biomagnetic instrumentation is the detection of extremely weak magnetic signals (1fT to 100pT) from the human body in the presence of a very noisy background (~ 10 μT). Therefore, such a measurement system needs not only high sensitive magnetic sensors such as SQUID sensors, but also requires an extremely quiet magnetic environment. A traditional but very costly means is to use magnetically shielded room. Best shielding performance ever measured is that for a massive shielded room built by Vacuumschmelze and installed at the PTB's Hermann-von-Helmholtz building in Berlin 5). With one layer of aluminium and seven layers of high-μ material, the completed facility achieved shielding factor at 0.01 Hz of 75,000 and with active shielding over 2,000,000. To improve the shielding factor, active shielding uses large Helmholtz-coil-like coils wound around the external walls of the magnetically shielded room. However, at frequencies above a few Hz, the active shielding may not be effective. It should be noticed that the higher the frequency, the greater the phase shift of the compensation field, caused by the low pass effect of the high permeable walls 6). Magnetic shaking has a fairly long history 7) 8), but recent remarkable techniques 9) enhance the shielding against both constant and time varying magnetic fields. Magnetic shaking dramatically improves the shielding factor of shields employing magnetic materials with a highly rectangular hysteresis loop, such as Metglas2705M amorphous ribbons 10). Our laboratory developed a human-sized, vertical, open cylinder that is a magnetic shielding system with magnetic shaking enhancement 11), and demonstrated a magnetic measurement of spontaneous alpha rhythms from the human brain 12). While such shielded enclosures offer excellent conditions for basic biomagnetic research, measurement systems which can operate depending on needs would be much more important from a practical point of view.

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*1 Department of Applied Science for Electronics and Materials

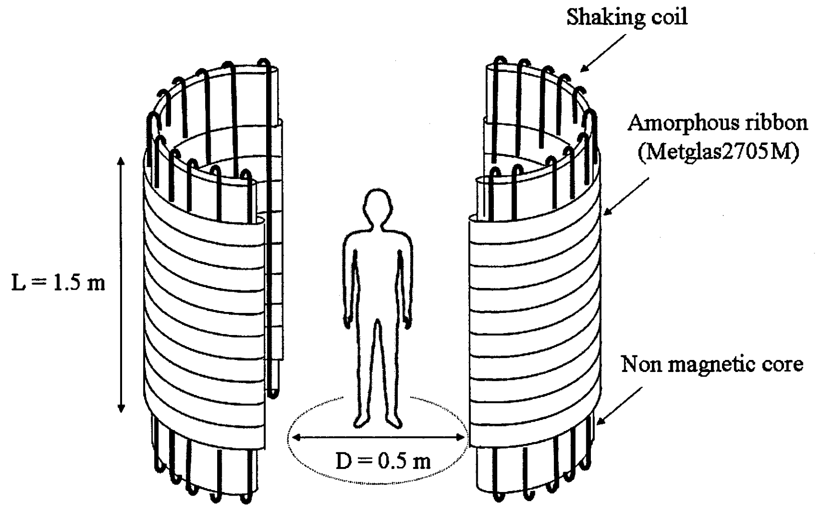


Fig.1 Schematic illustration of the magnetic shield consists of two C-shaped building blocks. The minimum interior of the shield is 0.5 m diameter, 1.5 m height

In order to meet the recent demands for a flexible well-performing shield, we present a new concept for a cylindrical magnetic shield. This shield is separable, and consists of two C-shaped blocks with amorphous ribbons 13).

In this paper, we present a human-size separable magnetic shield. The mechanism of a separable magnetic shield is explained based on a FEM analysis results, and the magnetic shielding factor was estimated using a 1/10 miniature model. We evaluated not only the residual static magnetic field using a commercially available fluxgate sensor, but also the noise floor at lower frequencies by means of a developed induction sensor that has comparable sensitivity to SQUID magnetometer in the frequency range higher than some ten Hz. This is the first report of the shaking effect on the noise level inside a separable magnetic shield.

2. Design

The structure of the shield is shown in Fig. 1. The shield consists of two C-shaped building blocks made of cobalt-based amorphous ribbon (Metglas2705M, width: 50.8 mm, thickness: 0.02mm) wrapped around a non-magnetic core, which have coils for generating a shaking field. Magnetic shaking enhancement was properly applied to the block because of a closed magnetic flux pass. The inner diameter of the shield is 500 mm, so ordinary people can stand inside this area without difficulty. The shape of the shield is conparable to a double concentric shell with two magnetic shunts between the outer and inner shells. To explain the effect of the magnetic shunts on the shielding factor, we calculated the static shielding factor numerically using a FEM program, Maxwell 2D. Fig. 2 shows simulated magnetic flux distributions around a simple model of the shield with infinite length. Since the magnetic flux flowed through the magnetic shunts, (a), the shielding effect is similar to a single cylinder with a thick shell. When the external magnetic flux is perpendicular, (b), a higher shielding factor is obtained, the same as a double cylindrical shield. According to the magnetic circuit theory, there is no magnetic potential between the outer and inner shell, so the existence of magnetic shunts had no significant effect on the shielding mechanism. As a result, it was also found that the outer shell concentrated the flux more than the inner shell. There are interesting results related to the air gaps between the two blocks as shown in Fig. 3. The external field is parallel to a line between the air gaps in the blocks as shown in (a). Although there is no significant disadvantage of the shielding effect compared with or without gaps, the external field that is at a right angle to the line has a fatal effect on the shielding effect as shown in (b). This result shows that the shield should be set parallel to the external field like (a), because an ideal connection without air gaps is difficult in practical use.

Experimental results of the 1/10 model shield are shown in Fig. 4. A homogeneous magnetic field of 10μT in amplitude, 10 Hz in frequency, was generated by a Merrit-4 square coils system 14), and the magnetic field was measured with a fluxgate sensor (Bartington Mag-03). With the optimum shaking strength at 2.4 A/m, residual amplitude of the magnetic field was reduced to 4 nT in the case of (a). This result represents a fairly large shielding factor of 2500. The shaking effect also improved the shielding performance in the case of (b); the shielding factor was close to 50. The relationship between the ribbon and coil is shown in (c). The ribbon makes a closed magnetic circuit, but the coil is not wound the outside. Hence, the coil generates the optimum magnetic shaking field to the inner shell, but not to the outside. This may suppress the enhancement effect of the outside. It is difficult to connect the two blocks magnetically, which badly affects the shielding performance in the case of (b). However, we adopted this structure in order to obtain a fair shielding performance with lightweight and easiness of fabricate. Another important result due to the magnetic shaking enhancement is shown in Fig. 5. The shielding performance was promising as a function of air gaps between the blocks.

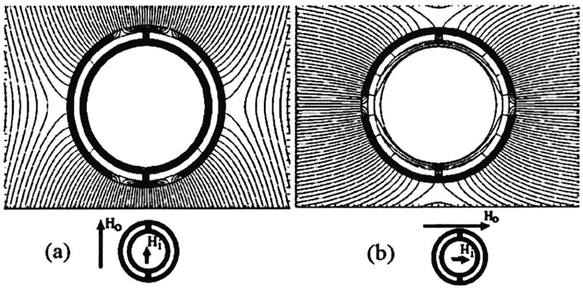


Fig.2 Calculated static magnetic flux distribution around the shield. The external field is (a) parallel or (b) perpendicular to the magnetic shunt between the outer and inner shell. The outer shell concentrated the flux more than the inner shell in the case of (b).

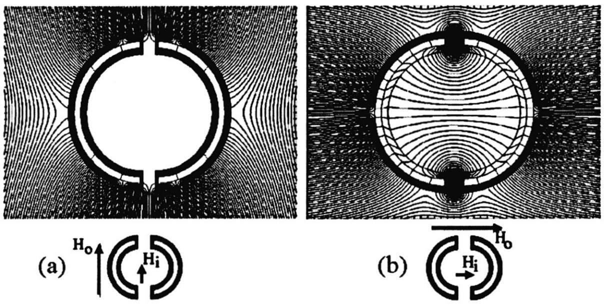


Fig.3 Effects of the air gaps between the two C-shaped blocks on the field distribution around the shield. The external field is (a) parallel or (b) perpendicular to the air gaps between the blocks. This result shows that the shield should be parallel to the external field like (a).

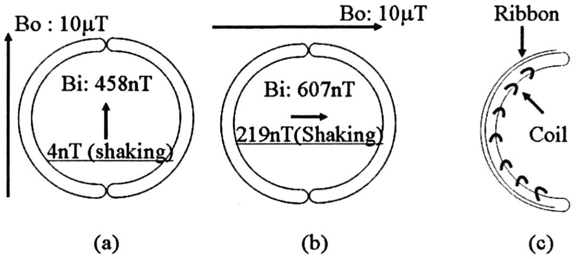


Fig.4 Experimental results of the magnetic shielding effect. Miniature model of 1/10 size was used in this experiment. A homogeneous ac magnetic field of 10 Hz was generated with Merritt's 4-square coils system. The relationship between the ribbons and coil is shown in (c). The coil is not wound around the outside.

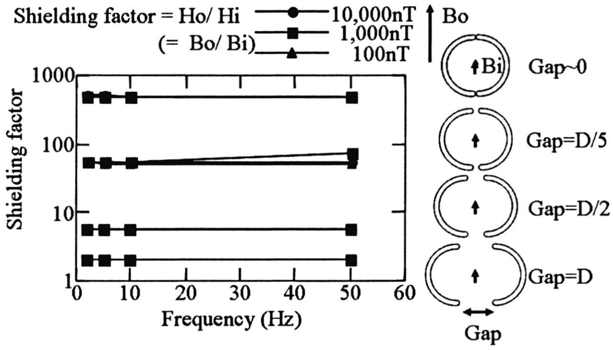
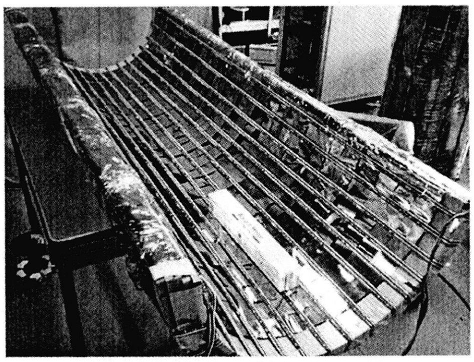


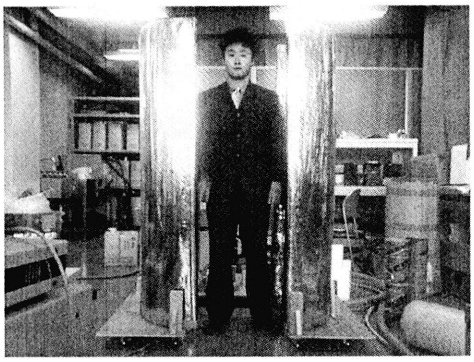
Fig.5 Experimental results between the shielding factors due to air gaps between two C-shaped building blocks. A 1/10 miniature shield and Merritt's 4-square coil system were used for the evaluation. Optimum magnetic shaking enhancement was properly applied to the blocks.

3. Shielding Performance

Fig. 6 is a photograph of our developed human-size separable magnetic shield. The shield was made of cobalt-based amorphous ribbons Metglas2705M; the gross weight of the ribbon is less than 8 kg. These ribbons are laminated into 10 layers as in Fig.4 (c) around a paper pipe (diameter: 500mm, thickness: 50 mm) cut in half transversally. The coil for providing the shell with the shaking field is wound around each block 17 times surrounding the inside, and connected in a serial to feed the shaking current. These blocks are easy to move with or without removable wooden base plates on casters. Fig. 7 shows experimental results of static magnetic fields measured with a fluxgate magnetometer. It enables one to reduce the residual field of horizontal components to less than 300 nT so the level may be suitable for cooling down the SQUID sensors without flux trapping phenomena.

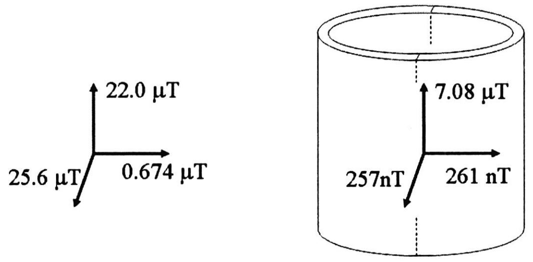


(a) C-shaped block



(b) Separable shield

Fig.6 A photograph of the human-size separable shield that consists of two C-shaped blocks. (a)View of the C-shaped block's inside. A thin polyethylene film was wound around the C-shaped block. (b) Side view of the separable shield. Amorphous ribbon is laminated into 10 layers around the nonmagnetic C-shaped paper core, and the gross weight of the ribbon is less than 8 kg.



(a) Geomagnetic field　(b) Residual static magnetic field

Fig.7 Static magnetic field measured with a fluxgate magnetometer, (a) geomagnetic field and (b) residual static magnetic field inside the shield. Magnetic shaking was not applied. Horizontal component level of the field is less than 300 nT, and the level is suitable for cooling SQUID sensors without flux trapping phenomena.

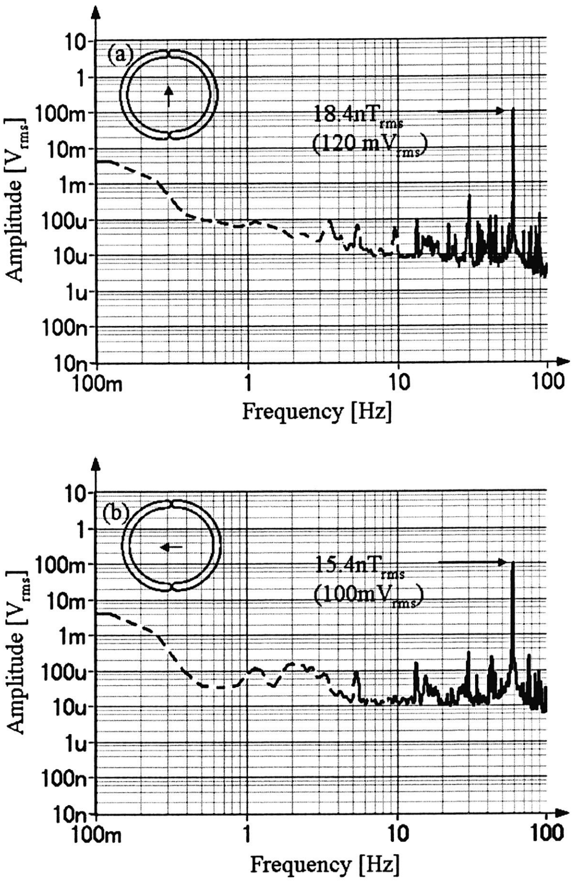


Fig.8 Residual magnetic field inside the shield evaluated with a developed induction magnetometer (This sensor has a first order response (20 dB/dec) to 10 Hz, and flat response (154pT/mV) to a few kHz). Magnetic shaking enhancement was not applied to the shield.

The best way to evaluate a highly quiet magnetically shielded area is by SQUID sensors. However, they must be cooled a very low temperature for proper operation. For example, currently MEG system use LTS-SQUID, hence liquid helium is used as cooling fluid to reach a temperature of 4.2K. The cryostat (Dewar) enclosing the probe needs to contain liquid helium, therefore, the external dimension and weight of the system become large. They also have to be kept away from existing high frequency electromagnetic fields (rf noise) the noise floor of the sensor system. Rf noise, such as mobile phones, badly influence the SQUID sensor operation by causing either the feedback circuit to unlock or by increasing the noise floor in a low frequency region. For robust and room-temperature measurement, we have developed an induction magnetometer (100 mm in length, 70 mm in inner diameter) with sensitivities close to SQUID sensors [15]. The sensor has a high pass characteristic with the corner frequency (20 dB/dec) of 10 Hz, and flat response (154pT/mV) to a few kHz. The sensor can potentially, evaluate noise floor to a few pT/√Hz at that time. Fig. 8 shows a residual magnetic field inside the shield evaluated by means of the induction magnetometer with FFT analyser (Stanford research systems SRS780) averaged over 16 readings. When magnetic shaking was not applied, a power line noise of 60 Hz over the 10 nT in amplitude and other noise spectra were found. With a magnetic shaking current of 100mA, the residual magnetic environment was improved as shown in Fig. 9. The line spectrum noise at 60 Hz became less than 10 nT, and a quite flat noise floor of 3pT/√Hz was achieved in each case. These differences had not been confirmed before by the fluxgate due to the noise level limit of our sensitive fluxgate sensor (~40 pT/√Hz). This is the first demonstration of the shaking enhancement's effect on the noise floor performance inside a separable shield.

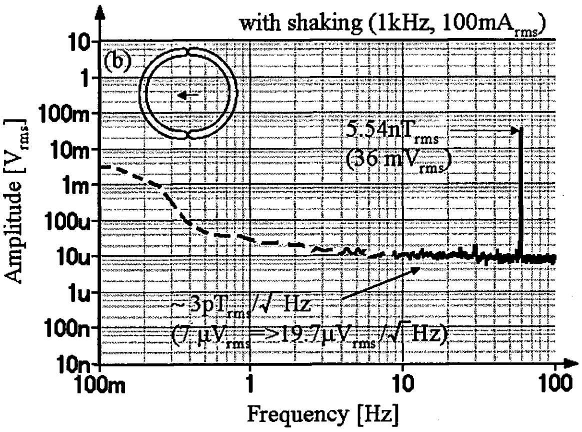
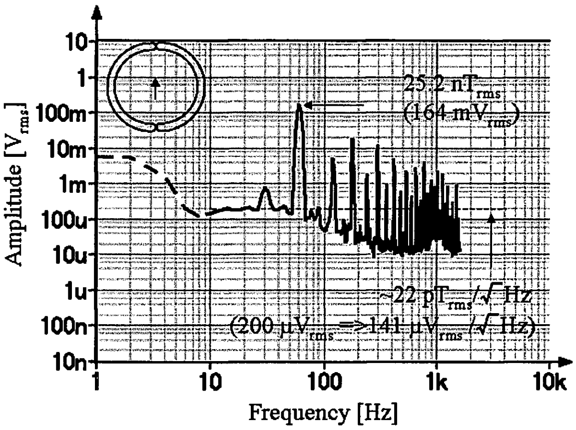
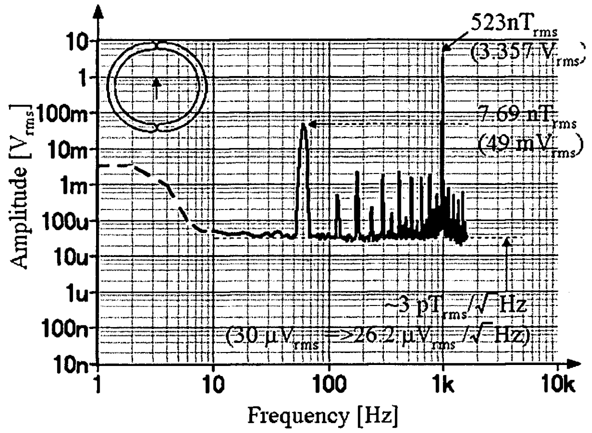


Fig.7 Residual magnetic field inside the shield evaluated with a developed induction magnetometer. A shaking current fed to the coil (100 mA in amplitude, 1 kHz in frequency); this represents the half value of the optimum shaking strength at the frequency.



(a) Without



(b) With magnetic shaking enhancement

Fig.10 Residual magnetic field inside the shield evaluated by means of a developed induction magnetometer. Even though the shaking strength is half the optimum value, the noise floor was improved more than without as in (a), but shaking field leaks as shown in (b).

4. Discussion

A human-size separable magnetic shield was developed and evaluated. A 1/10 miniature model indicated that the best shielding factor obtained was 2,500, and the shielding factor is a function of the air gaps between the blocks. The horizontal component inside the static magnetic field was less than 300 nT, which may allow the SQUID sensor to cool without the flux trapping phenomena. With a magnetic shaking current of 100mA (half the value of optimum shaking strength at 1 kHz), the noise floor inside the enclosure was improved 3pT/√Hz, which was evaluated by means of a developed induction sensor. The true noise level will be revealed using a sensor with more sensitive settings or using SQUID sensors with simple rf shielding with conductive clothes [12]. It should be noted that the leakage field of the shaking field shown in Fig. 10 was evaluated in the range of 1.6 kHz averaged over 16 experiments with and without a shaking current of 100mA. Improvement on the noise floor was clearly found, but leakage in the shaking field greater than 500 nT was also found even though the shaking strength is half the optimum value. On a normal cylindrical magnetic shield of helical structure, the leakage field is less than 100 nT at optimum shaking strength. Also, it was reported that the leakage does not depend on the number of winding coils, but on the effect of the ribbons' edge [16]. From the results shown in Fig.4, it was also pointed out that the outer shell may not apply magnetic shaking enhancement properly. Therefore, we should consider winding the coil as shown in Fig. 11. In an ideal design, the coil should surround the ribbon as (a). To keep it light weight and easy to make structure, winding the coil around the edges may also be effective also. It will not only reduce the leakage, but also improve the shielding factor due to a smoothly shaking flux path.

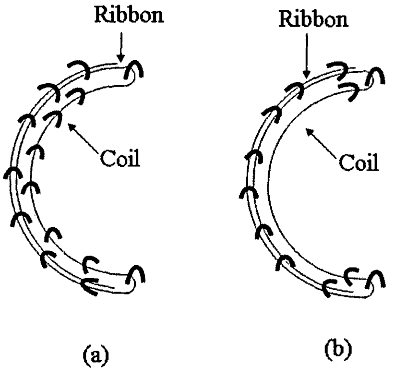


Fig.11 Effective coil winding for the C-shaped blocks. In an ideal designing, the coil should be around the ribbon as shown in (a). To keep it light weight and easy to produce, extending the coil winding around the edges may also be effective.

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