High-performance magnetically shielded room

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Abstract—An ultrahigh-performance magnetically shielded room was completed as a part of a biomagnetic measuring system using superconducting quantum interference devices. From the difference between environmental magnetic noise and a signal, necessary shielding factor was decided to be 1/100000 at low frequencies and 1/1000 at high frequencies. The soccer ball shaped room consists of four layers of permalloy and a layer of aluminum, and provides a space 4 meters in diameter in which magnetic fields are very weak. An independent base was built and the room was fixed rigidly to it. Because permalloy is very sensitive to shocks, the materials for the room were cut in the factory, carried with care, and assembled with screws on site. Xenon lamps supply light via optical fibers and the room is ventilated by way of many small holes in the floor. The door is equipped with the air pressure system.

I. INTRODUCTION

Magnetically shielded room (MSR) was constructed for the first time in 1962. Since then several MSRs have been built. They have provided weak magnetic field, and have been useful for the study of very weak magnetic signals. A performance of MSR has been becoming higher. In recent years, high performance MSR was built in Helsinki university of Technology in 1980 [1], and another high performance MSR was built in Physikalisch-Technische Bundesanstalt (PTB) in Berlin in 1980 [2].

At the Superconducting Sensor Laboratory we are developing a biomagnetic inspection system with 256 channel superconducting quantum interference devices (SQUIDs) and have completed a high performance magnetically shielded room the name of which we call "COSMOS".

II. REQUIRED PERFORMANCE

The required shielding performance in a magnetic shield room is determined by the difference between the external noise and the internally measured signals. The level of the external noise as determined by actual measurements is \(10^{-8}\) T. Internally measured signals in the brain, in which magnetic signals are at their weakest in an organism, are on the level of \(10^{-13}\) T. From a comparison of these two measurements, the shielding performance required from now on can be expressed as follows:

\[
10^{-13} / 10^{-8} = 10^{-5}
\]  

(1)

The frequency of magnetism in an organism extends from several tens of Hz down to almost 0 Hz. Consequently 1 Hz was adopted as a tentative standard. At high frequencies design goal was decided to be 1/1000 at the frequencies from 1 MHz to 100 MHz from experience.

In the past, a shielding factor for magnetic shields in structures of up to three layers in DC magnetic fields was calculated by Wills in 1899 [3] and a matrix representation for multi-layered structures was developed by Schweizer in 1962 [4]. In 1982, Kelha [1] demonstrated the actual use of the S-matrix to calculate the shielding factor of a spherical shell.

Speaking from the standpoint of configuration, spherical structures have a higher shielding efficiency than cubical structures, and cubical structures have a higher shielding efficiency than rectangular structures. The pre-requisites for the calculations are the size of the shielded room and the shielding efficiency. The width of the shield room was desired to be not less than 2 m. The fundamental calculations are then performed for a DC magnetic field and the optimal value for the thickness of each layer is determined:

\[
S_{12} = -r^3 \frac{2 \mu_d}{3} \frac{r}{r}
\]  

(2)

\[
S_{11} = 1 + \frac{2 \mu_d}{3} \frac{r}{r}
\]  

(3)

\[
S_{21} = r^3 \frac{2 \mu_d}{3} \frac{r}{r}
\]  

(4)

\[
S_{22} = 1 - \frac{2 \mu_d}{3} \frac{r}{r}
\]  

(5)

One S-matrix corresponds to one layer of a shield room. For a multi-layered shield room, the affixed superscript numbers indicate the number of the layer:

\[
[S_1^T S_2^T] = [S_1^1 S_2^1 S_1^2 S_2^2] = [S_1^1 S_2^1 S_1^2 S_2^2] \dots [S_1^n S_2^n]
\]  

(6)

In the above, \(S_1^n\) indicates the shielding factor of a shield room which has \(n\) layers. In a shield room that employs permalloy, it is desirable that a high shielding efficiency be obtained while at the same time reducing the amount of material that is used as much as possible in...
view of the high cost of permalloy. The thickness of each layer and the interval between layers are determined so that $S^I_{nl}$ will be maximized and the amount of material will be minimized.

The following formula gives the amount of materials used for two spherical layers:

$$V = 4 \cdot \pi (r_1^2 \cdot t_1 + r_2^2 \cdot t_2)$$  \hspace{1cm} (7)

Fig. 1 shows the change of shielding efficiency corresponding to the change of thickness of each layer of a spherical shielding room with two layers.

As can be seen in Fig. 1, the shielding efficiency is higher when the inner layer is thicker. It is also thought that the same will hold true when the number of layers is increased. In regard to the total number of layers, the shielding efficiency becomes higher as the number of layers becomes greater. Four layers were necessary since it was difficult to achieve with only three layers a given level of shielding efficiency with the given external configuration. After four layers were adopted, a process was followed in which (1) the thickness that provided the highest shielding efficiency was initially determined by providing identical intervals, (2) the interval that provided the highest shielding efficiency at that layer thickness was then determined, (3) the thickness was then re-determined, etc. This process was repeated several times until the final thicknesses and intervals were determined.

In regard to the electromagnetic-shielding aluminum sheet, since its shielding efficiency virtually did not change relative to its position by calculation, and since the thermal noise was greater with aluminum than with permalloy when the magnetic field became small, aluminum sheet was placed on the outer side of the permalloy in the innermost layer.

S-matrices shown below are used in case when a shield room is in tan alternating magnetic field. The result of calculation using these S-matrices is shown in Fig. 4.

$$S_{11} = \cosh(kd) + \frac{K}{3} + \frac{2}{3K} \sinh(kd)$$  \hspace{1cm} (8)

$$S_{13} = -r^3 \sinh(kd) \cdot \left( \frac{K}{6} - \frac{2}{3K} \right)$$  \hspace{1cm} (9)

$$S_{23} = r^3 \sinh(kd) \cdot \left( \frac{2K}{3} - \frac{2}{3K} \right)$$  \hspace{1cm} (10)

$$S_{22} = \cosh(kd) - \left( \frac{K}{3} + \frac{2}{3K} \right) \sinh(kd)$$  \hspace{1cm} (11)

where

$$k = \frac{1 + j}{\delta}, \quad \delta = \sqrt{\frac{\rho}{\sigma \mu_0 \mu}}, \quad K = \frac{kr}{\mu},$$  \hspace{1cm} (12)

and $\mu_0$ is the relative permeability, $f$ is the frequency, $\rho$ is the resistivity, and $j$ is $\sqrt{-1}$.

III. STRUCTURE

From the standpoint of raising shielding efficiency, spherical shapes are the most efficient. From the manufacturing aspect and also taking the configuration into consideration, shapes with straight sides are easy to make but shapes with curved surfaces are difficult to construct. We decided to build a room with 32 surfaces that is in the shape of a soccer ball. Hexagonal pieces form 20 of the surfaces and pentagonal pieces form the other 12 surfaces. The frame was built of aluminum sheet and the permalloy layers were fastened above the frame by screws. At that stage, the structure was arranged so that the gaps in mating sections were covered by overlapping them with other mating sections. Additionally, the
lines formed between two shapes were covered by shaped angular covers. From the standpoint of the performance of a shield room, it is desirable that the door and other openings be as small as possible.

To seal "COSMOS" tightly, we have provided a structure in which all layers are flexibly fastened to the frame through spring force. The frame rides on a carriage and moves on rails that are on a stage that is at door height. Door opening and closing is conducted manually. A damper that is operated by pneumatic pressure is used to press separately against each layer. A sectional drawing of this arrangement is shown in Fig.3.

![Fig.3 Structure of the door](image)

For sleeves a total of 22 pipes with insidediameters of 60 mm each were used with the objective of reducing the number of pipes and making them as narrow as possible.

**IV. AIR-CONDITIONING AND ILLUMINATION**

In order to achieve a uniform environment even when the air volume is small, we have arranged for a layered flow of air that is made to flow from the bottom to the top of the room by numerous small holes in the skirting board around the periphery of the floor. The air-conditioning equipment has been built exclusively for "COSMOS" and is separate from the air-conditioning equipment for the large room where "COSMOS" is placed ("COSMOS" room). Thus, the system can supply the air to "COSMOS" after it has been minutely adjusted by the conditioning equipment. In addition, a valve change over operation makes it possible to have the system operate in natural draft when necessary.

To prevent noise to be introduced by the electrical cords, optical-fiber illumination has been employed. Xenon lamps are used as the light source. Internal illumination is provided in two locations on the right and left sides of the upper part of the walls.

**V. CONSTRUCTION**

The foremost objective in the construction of a shield room is the realization to the extent possible of the performance that has been specified in the design of the room. It is therefore essential not only to achieve the forms as specified in the drawings but also to devise plans that will allow the room to demonstrate its full performance. Since materials which have high permeability are used in a shield room, the materials employed must be limited to those from which this special characteristic can be obtained. In addition, since materials change under stress, they must be annealed prior to use. Materials that have been annealed prior to use must then be handled carefully to assure that they are not subjected to stress during usage. In order to improve accuracy, a skeleton structure was first built at a temporary site and was then transported to the site of final construction only after dimensions had been adjusted and analyses performed. The permalloy was cut, heat treated, and then transported in special cartons. At the final site, cranes and other machinery were used to lift the heavy parts and materials and install them in temporary positions. Construction was performed carefully and it was confirmed by supervisors that the fabrication and fastening methods were such that the concentration of stresses was prevented. In order to do this, it was necessary to modify the system of scaffolding frequently so that constant access could be provided to the parts and materials during the start of all stages of construction. The total time required for construction was approximately three months.

**VI. MEASURING MAGNETIC SHIELDING EFFICIENCY**

Shielding efficiency (S) is defined as the ratio between the internal magnetism (Hi) in a uniform magnetic field when shielding exists and the strength of the magnetic field (Ho) when shielding does not exist. It is expressed as follows:

\[
S = \frac{H_o}{H_i} \tag{13}
\]

In order to generate a uniform magnetic field, a couple of opposition coil, i.e., a so-called Helmholtz coil, is normally used. An overlarge coil was needed for our large shield room, however, and it came into contact with a wall on the perimeter of the "COSMOS" room. We made a coil the diameter of which was 2 m and placed it 10 m apart from the center of "COSMOS", and generated a magnetic field that was as uniform as possible, and performed measurements with the SQUID that had been positioned on the center of "COSMOS".

The signals were received by the SQUID after being generated by the generator and amplified by an amplifier to magnetize the coil. The computer averaged the signal from SQUID synchronously to obtain their values. [5] The results are shown in Fig. 4.
By comparing the result of the estimated value of performance and the result of this measurement, we can find that the difference between the two is smallest at about 0.1 Hz.

Fig.4 Shielding factor of "COSMOS" and calculated value of performance at low frequencies.

VI. MEASURING THE ELECTROMAGNETIC SHIELD

In a high-frequency electromagnetic field, the magnetic field is predominant when a loop antenna is used and the electrical field is predominant when rod antenna is used. This tendency is remarkable in the near field of antenna the range of which is within approximately twice as long as wavelength. Beyond the range of near field, the impedance becomes constant and the assumption of plain wave propagation holds good, therefore the field is analyzed rather easily. The predominance of the electrical field is referred to as high impedance; the predominance of the magnetic field is referred to as low impedance. Within the range of the near field, actual measurements to determine shielding efficiency are generally conducted but the most commonly used method for measurements is the MIL Standard 285.

Two same antennas were placed, one was in "COSMOS" and connected to a spectrum analyzer, the other was outside "COSMOS" and connected to a signal generator. Each antenna was placed 30 cm apart from the surface of each surface of the wall of "COSMOS". We conducted measurements with the aim of performing them under actual operating conditions, however, and with the lead wires of SQUIDS inserted into "COSMOS"-measured shielding efficiency at both low and high impedance. The results for the shielding efficiency we obtained at levels of 60 dB (1/10000) and above at from 1 MHz to 100 MHz are shown in Fig.5.

Fig.5 Electromagnetic shielding factor of "COSMOS" at high frequencies. (a) and (c) are high impedance and (b) is low impedance. (c) was measured with biconical antennae.

VII. VIBRATION

In the interiors of "COSMOS" which is weak against magnetism, small amounts of vibration from magnetized metals can cause magnetic noise. Since it was difficult to use large and heavy anti-vibration equipment to counteract these minute vibrations, strong and durable fastening methods were required in addition to an independent and solidly-built foundation. Post-construction vibration measurements have indicated that there is some vibration innate to the structure but that is extremely small and on the order of 1 µm.

VIII. CONCLUSION

A high performance magnetically shielded room has been constructed the shape of which resembles a soccer ball. Measurements have shown that the shielding factor satisfies the objective values of 1/10000 at 1 Hz and 60dB from 1 MHz to 100 MHz.

REFERENCE
