Measurement and Analysis of Low Frequency Magnetic Shielding Performance of Open-Cell Nickel Foam

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Abstract. Low frequency magnetic field in the range from 10 to 500 kHz is between very-low and mid-high frequencies, mainly coming from industrial equipments such as antenna, battery, inverter, etc. In some shielding applications simultaneously demanding for ventilation and cooling, high-performance shielding materials with a porous structure are necessary. However, the investigation of these materials in this band was rarely reported. Open-cell nickel foam has excellent electrical conductivity and magnetic permeability, which makes it a potential new kind of shielding material in the field of low frequency magnetic shielding. It is generally believed that, in this band, materials shield the magnetic field mainly through two mechanisms, i.e., flux shunting and eddy current cancellation. With the equation of shielding effectiveness (SE) for a cylindrical shell, SEs of copper foil and Permalloy were calculated. The results indicated that the effect of flux shunting can be ignored, which was further verified by the results of Helmholtz coil test. Thus, only eddy current cancellation mechanism was considered to establish a shielding model, in which the flat open-cell nickel foam was assumed to be a group of coils and the eddy current was assumed to flow along the conductive paths composed of the coils. The prediction of the model was verified by the measured results of a window test method. Both the experimental and theoretical results revealed that, SE is enhanced with the decrease of the average pore size of the foam because the number of conductive paths in the foam increases. In addition, the calculated results of SE indicated that the open-cell nickel foam has no obvious superiority compared to a fully dense nickel strip of the same areal density. However, the structure characteristics of open-cell foam make it definite to find applications simultaneously asking for shielding, ventilating and cooling.

1. Introduction
As an important means to protect electrical equipments and human health, the attention for electromagnetic shielding is growing rapidly. Many devices such as antenna, battery, inverter, etc. can generate magnetic field in the range from 10 to 500 kHz [1, 2]. To shield the magnetic field in this band, some shielding materials, such as metals and alloys with high electrical conductivity and magnetic permeability were recommended[3]. However, these fully dense materials are not suitable for applications simultaneously asking for ventilation and cooling, such as military shelters, communication base stations and backpack communication equipments. In these cases, it is necessary
to adopt porous or honeycomb shielding materials for heat dissipation and decreasing the weight. Recently, studies on foamed materials are increasing due to their lightweight and excellent shielding performance [4]. A kind of foamed materials prepared mainly with carbon foam or carbon nanotubes was found to have high shielding effectiveness (SE) in the X band (8 to 12 GHz) [5, 6]. In view of the lower frequency band, Liu[7] prepared an open-cell titanium foam, and measured its SE with a coaxial flange device. The measured results were found to be approximately 25 to 68 dB in the range from 130 to 1800 MHz. Huang [8] measured the electric field SE of an iron-nickel foam by a coaxial cable method in the frequency range from 30 kHz to 1500 MHz, and the measured results were up to 85 dB. However, the low frequency magnetic shielding of the foamed materials in the band from 10 to 500 kHz has not been investigated. As a commercial material, open-cell nickel foams have a high electrical conductivity and a low areal density, and have been applied as the electrode of fuel cells [9]. In addition, as a ferromagnetic metal, open-cell nickel foam has a high magnetic permeability. It can be inferred that the above-mentioned features make it have potential application in the low frequency shielding for military shelters and backpack communication equipments.

The unique characteristics of open-cell nickel foams and the lack of the investigation of magnetic shielding on foamed materials in the frequencies from 10 to 500 kHz have driven us to explore its shielding performance in this band. At first, based on theoretical and experimental studies on SE of copper foil and Permalloy, the shielding mechanism in this band was elucidated. Then a shielding model of open-cell nickel foam was established and verified by a shielding enclosure test method. Finally, the influences of the average pore size and thickness of the nickel foam on SE were discussed emphatically.

2. Materials and test methods

2.1. Materials

As shown in Fig. 1(a), the material to be investigated is a commercial open-cell nickel foam. To observe its microstructure, a scanning electron microscope (SEM, SIRION200, and Thermo Fisher Scientific) was used. The result is shown in Fig. 1(b). The foam is composed of ligaments with a triangular cross-section, and the outer width of the ligaments is approximately 100 μm. In the preparation of the open-cell nickel foam, a polyurethane foam was used as the precursor during the electrodeposition process. After the nickel being electroplated, the foam was placed in a vacuum furnace for heat treatment, during which the polyurethane foam was pyrolyzed. Thus, it can be deduced that, the ligaments of the open-cell nickel foam should be of hollow structure. However, due to the restriction of the cutting process, the ends of the ligaments were damaged and did not show a hollow structure. Hence, the thickness of the ligament wall was obtained from Ref. [9], in which the open-cell nickel foam was produced with the same process and original materials, and the cross-section of its ligaments is also triangular. According to the corresponding SEM results, the outer width of the ligaments is approximately 95–100 μm and the wall thickness is approximately 10 μm, which will be adopted in our calculation as an approximation. The other parameters of the open-cell nickel foam can be found in Table 1, in which the average pore size and porosity are the main structural parameters. As the average pore size increases, the numbers of the ligaments and connecting nodes in per unit volume decrease, resulting in the increase of porosity and the decrease of areal density.
In order to verify the shielding mechanism in the frequency range from 10 to 500 kHz, copper foil and Permalloy were selected as the representatives because of their high conductivity and high permeability, respectively. Their electromagnetic parameters are given in Table 2. The electromagnetic parameters of copper almost do not vary with frequency. The Permalloy (grade 1J85, with a nickel content of 85%) is a kind of iron-nickel alloy, whose relative permeability ($\mu_r$) is the highest in the very low frequency, and decreases with the increase of frequency and finally approaches 1. In the band from 10 to 500 kHz, the exact permeability of Permalloy 1J85 is rarely reported. In Ref. [10], the Permalloy with a nickel content of 80 % and a thickness of 50.8 $\mu$m was studied, and its relative permeability is approximately 10 in the band from 10 to 500 kHz. Considering that our test sample has a close nickel content, as an approximation, its $\mu_r$ is also assumed to be 10 in this band.

| Sample | Thickness (mm) | Average pore size (mm) | Porosity (%) | Areal density (kg/m$^2$) |
|--------|----------------|------------------------|--------------|-------------------------|
| 1      | 3              | 0.23                   | 98.1         | 1.010                   |
| 2      | 6              | 0.28                   | 98.3         | 0.900                   |
| 3      | 6              | 0.32                   | 98.5         | 0.830                   |

| Materials          | Thickness (mm) | Conductivity (S/m) | Relative permeability |
|--------------------|----------------|--------------------|-----------------------|
| Copper             | 0.05           | $5.9\times10^7$    | 1                     |
| Permalloy(1J85)    | 0.05           | $2.0\times10^6$    | 10                    |
| Nickel             | -              | $1.1\times10^7$    | 110                   |

2.2. Test methods

2.2.1. Helmholtz coil test method. In the verification of the shielding mechanisms, Helmholtz coil test method was selected, and the sketch of the setup is shown in Fig. 2. The two coils were coaxially placed to produce a time-varying magnetic field. A sample in the form of a cylindrical shell with an outer diameter of 30 mm and a length of 300 mm was placed between the two sets of coils, and a magnetic field detector was put inside the cylindrical shell. The coils will generate time-varying magnetic field in the range from 10 to 500 kHz, which is perpendicular to the axial direction of sample.
The magnetic SE can be obtained from the signal intensities received by the detector with and without the sample present, as following:

\[ SE = 20 \log_{10} \frac{B_1}{B_2} \]  

Where \( B_1 \) and \( B_2 \) are the magnetic inductions without and with the sample. In preparation of the sample, a 300 mm × 100 mm × 0.05 mm strip was rolled on a polyethylene plastic tube leaving 5 mm wide overlap approximately. For the copper foil, soldering was carried out at the overlap. For Permalloy, it is difficult to solder, thus the connection was made by a 0.03 mm thick copper foil tape. As mentioned above, the shape of the sample should be in a cylindrical shell for the Helmholtz coil test method, which is difficult to prepare with a nickel foam. Therefore, a shielding enclosure was adopted to test the shielding performance of the nickel foam.

Figure 2. Schematic diagrams of the Helmholtz coil test device

2.2.2. Measuring SE with a shielding enclosure. In the standard [11], a method of measuring SE of large-size materials was proposed, which can be applied here to measure SE of the open-cell nickel foam. A sketch of the test devices is shown in Fig. 3. On a wall of a shielding enclosure, there is an opening with a size of 600 mm × 600 mm to install a sample. To decrease magnetic leakage, the sample at the opening should be fixed by a square steel frame and rivets. Thus, the sample of the open-cell nickel foam was made slightly larger (685 mm × 685 mm) than the opening. Besides, the transmitting antenna was located outside the enclosure, leaving the receiving antenna inside. Both of them were loop antennas, placed coplanar in a plane perpendicular to the wall, and the distance from the center of each antenna to the respective sides of the shielding wall was approximately 45 cm. During the test, the transmitting antenna produced a time-varying magnetic field with frequencies of 14, 150, 500 kHz. Similar to the Helmholtz coil test method, the magnetic induction can be measured by the receiving antenna with and without the sample at the opening, then the magnetic SE can be obtained by Eq. (1).
3. Results and discussion
The SE of some regular structures, such as a cylindrical shell, a spherical shell or an infinite flat plate, can be obtained with Maxwell electromagnetic equations [12, 13]. However, it is difficult to calculate SE of a foam structure with Maxwell electromagnetic equations directly. If we can confirm the dominant shielding mechanism in the band from 10 to 500 kHz, a simplified shielding model based on which can be established to calculate the SE of the open-cell nickel foam.

3.1. Analysis of the shielding mechanisms between 10 ~ 500 kHz
It is generally believed that, there are two shielding mechanisms responsible for magnetic shielding in the band from 10 to 500 kHz, i.e., eddy current cancellation and flux shunting. The flux shunting is that, due to the difference between the permeability of a shield and the air, the magnetic field can be pulled toward the shield and only flow in the direction almost parallel to the surface of the shield, finally it is released to the air. The eddy current cancellation is that when the magnetic field through a certain section is time-varying, an electric field will be induced, and if there is a conductor in this section, the electric field will lead to an eddy current in the conductor, which will produce a new time-varying magnetic field to suppress the original one. In the extremely low frequency of 30 Hz or less, the flux shunting dominates. And when the frequency increases to hundreds of kilohertz, the effect of flux shunting is weakened, and the effect of eddy current cancellation gradually increases [3]. Kühn [14] established an analytical model based on the mechanism of eddy current cancellation in the band from 10 to 150 kHz, and the theoretical results were found to be in good agreement with the measured results of copper mesh. To further verify the shielding mechanism in the band from 10 to 500 kHz, SE of cylindrical shells of copper and Permalloy will be calculated and compared with the measured results.

The theoretical SE of a cylindrical shell can be calculated with the Maxwell electromagnetic equations. When the direction of the low frequency magnetic field is perpendicular to the axial direction of the cylindrical shell, the SE can be expressed as [3]

$$SE = 20 \log \left| \cosh (\gamma d) + \frac{1}{2} \frac{\gamma R_0}{\mu_r} \sinh (\gamma d) + \frac{1}{2} \frac{\mu_r}{\gamma R_0} \sinh (\gamma d) \right|$$  (2)
Where \( r \) and \( d \) are the radius and wall thickness of the cylinder shell respectively, \( \gamma \) is the propagation factor. If the material is a good conductor, \( \gamma \) can be approximated as \( \sqrt{2\pi\mu_0\mu\sigma f} \), where \( \mu_0 \) is the vacuum permeability, \( \sigma \) is the electronic conductivity, and \( f \) is the frequency. In Eq. (2), the first two terms and the last term of the logarithmic function represent the contribution of eddy current cancellation and flux shunting respectively [3]. Therefore, the contributions of flux shunting and eddy current cancellation can be calculated respectively.

Fig. 4 shows the calculated and measured results of the copper foil with a thickness of 0.05 mm. The dashed line represents the SE only considering the contribution of the last term of the logarithmic function in Eq. (2), and they are almost equal to zero in the whole band. The solid line shows the SE only including the first two terms, which is much higher than that of the dashed line. Thus, it can be inferred that the contribution of eddy current cancellation to SE is dominate. In the band from 10 to 100 kHz, the approximate SE with the first two terms almost coincide with the measured results. In the band from 100 to 500 kHz, the deviation increases while is still below 3 dB. Generally, the approximate SE without considering flux shunting matches well with the measured results by the Helmholtz coil method. Therefore, it can be concluded that, for a high-conductivity material, the contribution of flux shunting can be ignored in the band from 10 to 500 kHz. In addition, due to the same reason mentioned above, the slope of the measured results with frequency of Permalloy is also smaller than that of the calculated.

![Figure 4](image_url)

**Figure 4.** The calculated and measured shielding effectiveness of a 0.05 mm thick copper foil

For the high-permeability material (Permalloy 1J85), the SE considering the first two terms of the logarithmic function in Eq. (2) and that considering the last term were also calculated respectively with \( \mu \) of 10, and the results are shown in Fig. 5. Similar to the situation of copper, the approximate SE with first two terms is much higher than that with the last term. And the variation tendency of the approximate SE with first two terms agrees well with that of the experimental values. Therefore, for a magnetic material, the contribution of flux shunting can be ignored in the band from 10 to 500 kHz. In addition, due to the same reason mentioned above, the slope of the measured results with frequency of Permalloy is also smaller than that of the calculated.
3.2. Shielding effectiveness analysis of an open-cell nickel foam

3.2.1. Eddy current shielding model. It has been confirmed that in the band from 10 to 500 kHz, eddy current cancellation is the primary shielding mechanism. Although an eddy current shielding model of a finite flat plate has been established by Payne [15], a shielding model of foamed materials has not been found. Therefore, we considered utilizing the model of Payne to establish one applying to foamed materials. In Fig. 6 (a), a plate is placed in a magnetic field whose direction is perpendicularly to a side of the plate, and t, w and l are the thickness, width and length of the plate respectively. The eddy current is induced by the magnetic field and flows along the direction as shown by the red arrow. In such case, the plate behaves like a coil. The magnetic SE at the center as shown in Fig. 6(a) can be expressed as

$$SE = 20\log\left|\frac{B_0}{B_r}\right| = 20\log\left|1 + j\mu_0\mu_r f_w R\right| = 20\log\left|1 + j\mu_0\mu_r f_l t\sigma/2k\right|$$

(3)

Where $f$ is the frequency, $B_0$ is the magnetic field intensity at the center of the opening without the plate, $B_r$ is the resultant magnetic field intensity with the plate placed, $\sigma$ is the conductivity of a fully dense material, $R$ is the equivalent resistance of the plate along the current loop:

$$R = L/\left(\sigma A\right) = 2w/\left(\sigma l t/k\right)$$

(4)

Where $k$ is the equivalent coefficient of the distribution of eddy currents. When the direction of magnetic field is perpendicularly to a plane with an area of $A$, the eddy current gradually decreases from edges to the center, and the uneven distribution of current will make the calculation difficult. Therefore, as an approximation, the plane can be equivalent to one with the current evenly distributed, and the area is $A/k$. For a plate, $k$ is 8 [15].
Based on the assumption of equivalent coil, a shielding model was established to calculate the SE of foam structure. As shown in Fig 1(a), nickel foam has a kind of periodic structure. Generally, the tetrakaidecahedron can be treated as a periodic structure of nickel foam [17]. In Fig. 6(b), the edges of quadrilateral and hexagonal are ligaments of open-cell nickel foam, which provide the conductive paths represented by red arrows. These conductive paths end to end construct one single conductive circle perpendicular to the direction of magnetic field. As shown in Fig. 6(b), there is a certain interval between the circles, which is different from the continuous distribution in a fully dense plate. The interval distance is determined by the pore size $d$, and averagely it can be assumed that there are $l/d$ and $t/d$ loops respectively in the direction of the length $l$ and thickness $w$. In addition, compared to the length of a straight conductive circle in a fully dense plate, that of a curved circle in a foam structure is longer, approximately double[17] due to the structure of tetrakaidecahedron. Finally, the total resistance can be expressed as

$$R = 2 \cdot \frac{2w}{\sigma_s A \left( \frac{l}{d} \cdot \frac{t}{d} \cdot \frac{1}{k} \right)} = 2 \cdot \frac{2w}{\sigma_s \frac{\sqrt{3}}{4} \left( r_0^2 - r_1^2 \right) \frac{l}{d} \cdot \frac{t}{d} \cdot \frac{1}{k}}$$

(5)

Where $r_1$ and $r_0$ are the inner and outer widths of ligaments respectively, $A$ is the area of the cross-sectional of ligament, then $A$ is equal to $\sqrt{3} \left( r_0^2 - r_1^2 \right) / 4$, $d$ is the average pore size. The SE can be expressed as

$$SE = 20 \log \left| 1 + j \frac{\sqrt{3}}{4} \left( r_0^2 - r_1^2 \right) \mu_0 \mu_r \mu_0 \mu_r / \left( 16 kd^2 \right) \right|$$

(6)

The above formula is the low-frequency magnetic SE expression of a flat opening-foam structure based on the assumption of the equivalent coil.

3.2.2. Analysis of calculated results. The electromagnetic and structural parameters of the open-cell nickel foam for calculating the SE have been given in Section 2.1. The average outer width and the
thickness of the wall of ligaments are 100 μm and 10 μm respectively. The calculated results are shown in Fig. 7, in which the solid line represent the theoretical values calculated based on the assumption of equivalent coil. This figure also shows the measured results by shielding enclosure, and test frequencies are 14, 150 and 500 kHz. It can be seen that the SE is enhanced with the increasing frequency. Because when the frequency increases, the frequencies of the magnetic field passing through the material increase, resulting in the induced electric field enhanced. Then the induced current flowing along the ligament are enhanced and the ability to suppress the original magnetic field is strengthened. It is important to note that, in the actual test, the magnetic field passes vertically through the side of the nickel foam plate and the induced currents flow perpendicular to the magnetic field, which means there are no currents flowing along the ligaments parallel to the magnetic field. Therefore, it should be considered the direction of the magnetic when calculating the equivalent resistance of the foam structure.

\[ SE = 20 \log \left( \frac{B_0(x)}{B_1(x)} \right) \sim 20 \log \left( \frac{x}{x^{0.7}} \right) \sim 20 \log \left( x^{0.3} \right) \]

When \( x \) is 0.45 m, the error is 2 dB. When the shield exists, the magnetic induction \( B \) attenuates faster, which makes the test results slightly larger. But it affects the test results little. The second reason is when the test samples were prepared, the edge of the open-cell nickel foam left some holes and that caused the magnetic field leakage, which unavoidably made the test results decline. Besides,
in the actual test, the direction of the magnetic doesn’t pass through perpendicular to the side of the sample precisely, which results in the real equivalent resistance of the foam structure higher than the theoretical. But in general, the trend of the calculated results is in good agreement with that of the experimental values.

Fig. 8 shows the calculated SE of 6 mm thick open-cell nickel foam with 70, 80, 90 and 100 ppi (corresponding to the pore size of 0.36, 0.32, 0.28 and 0.25 mm, respectively), and the measured SE of the 6 mm thick samples with 80 and 90 ppi. As shown in Fig. 8, similar to the situation of 3 mm thick nickel foam with 90 ppi, the calculated results of samples with 80 and 90 ppi are higher than the experimental results due to the test errors. The calculated SE of 6 mm thick sample with 90 ppi is in the range from 25 to 60 dB from 10 to 500 kHz, which is higher than that of 3 mm thick. This is because as the thickness increases, the area that the magnetic field can pass through increases, then the SE can be enhanced. As the average pore size decreases, the SE also increases, and the SE of the sample with 100 ppi is the highest. This is because according to the equivalent coil assumption, the reduction of the average pore size leads to the increasing the number of circles in the directions of length and thickness of the plate, which reduces the total resistance.

![Figure 8. Effect of pore size on shielding effectiveness of nickel foam](image)

In addition, the SE of 3 mm thick nickel foam with 110 ppi was calculated and it is in the range from 23 to 56 dB, which is equal to that of 6 mm thick sample with 80 ppi. However, the areal density of the former is doubled. Besides the increase of areal density, if the average pore size becomes too small, that will make porous media difficult for free convection heat transfer [18]. Therefore, although the reduction of pore size can enhance the SE of open-cell nickel foam, it is necessary to be combined with practical applications to design structural parameters. In order to analyze the difference in shielding performance between the open-cell nickel foam and the fully dense material, we calculated the SE of open-cell nickel foam with a thickness of 3 mm, average pore size of 0.32 mm and a nickel strip with a thickness of 0.05 mm. The areal densities of them are approximately equal to 0.45 kg/m². The calculated results indicate that the SE of open-cell nickel foam is half of that of the fully dense nickel strip in the band from 10 to 500 kHz. The main reason is that, although the areal densities of the two materials are equal, the number of conductive paths with currents is different. That is because in the foam structure, there are no currents in a part of ligaments which are parallel to the direction of the magnetic field.
4. Conclusion
Through the calculation and measurement of the SE of copper foil and Permalloy, the dominance of eddy current cancellation was confirmed in the band from 10 to 500 kHz. And a shielding model of open-cell nickel foam was established and verified. Both the calculated and experimental results reveal that, under the same thickness the SE of open-cell nickel foam is enhanced with the increased frequency or the reduction of the average pore size, respectively. The former makes the induced electric field elevated, and the latter increases the number of the conductive paths, which results in the enhancement of the magnetic induction. Although reducing the average pore size and increasing the thickness of the material can improve the shielding performance, the areal density is also increased. As a result, the practical application should be taken into consideration when designing the structure parameters.

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