Research on Influencing Factors of Magnetic Shielding Effectiveness of Finite Length Cylinder

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Abstract. The article mainly studies the shielding effectiveness (SE) inside a cylinder with a finite-length metal shell. Since the SE inside an infinite-length cylinder is equal everywhere, this article focuses on exploring the SE of a finite-length metal shell cylinder. The article simulates the influence of the cylindrical shape factor (the ratio of the height to the inner diameter of the cylinder) on the SE at different frequencies; the influence of the frequency of the external magnetic field on the SE of the cylinder; the change of the SE on the central axis of the cylinder; the change in the SE on the central axis of the cylinder when a small hole is opened at the centre of the bottom of the cylinder; the change in the SE on the central axis of the cylinder when small holes are opened at the centre of the upper and lower surfaces of the cylinder.

1. Introduction

Low frequency magnetic shielding can be an indispensable part of many applications such as ultrasensitive atomic sensors [1], electric vehicles [2]-[3], and wireless power transmission systems [4]-[5]. Usually, a metallic shell is employed as the shielding enclosure. The magnetic shielding effectiveness (SE) of a shielding enclosure is defined as the ratio of the magnetic field intensity observed at a given position with the enclosure removed to that observed at the same point with the enclosure loaded. The shielding effectiveness of the shielding cavity under the low-frequency magnetic field is an issue worthy of attention. At present, there are precise analytical formulas for the magnetic field shielding effectiveness of spherical and infinite cylindrical shields [6].

2. Model and theory

As shown in figure 1, it is a conductive cylindrical shell with an inner diameter r, an inner height h, and a wall thickness t. The conductivity, permeability and permittivity of the metal shell are σ, μ and ε respectively. The cylindrical shell is in an external uniform time-harmonic magnetic field B₀ with a frequency f in the z direction.

Figure 1. Cylindrical model
2.1. Cylindrical Magnetic Conducting Shield in a Parallel
For an infinite cylindrical shell placed in a uniform magnetic field, the magnetic field is parallel to the z-axis, as shown in figure 2:

![Figure 2. Infinite cylinder](image)

The thickness of the cylindrical shell is Δ, the outer diameter is b, and the inner diameter is a. It can be seen from the literature [6] that the shielding effectiveness formula is as formula (1):

\[
SE = \frac{(ay)^2}{2} \left[ I_n(\gamma b)K_2(\gamma a) - K_n(\gamma b)I_2(\gamma a) \right] - \left( \frac{ay}{2} \right) \left( \frac{\mu - 1}{\mu} \right) \left[ I_n(\gamma b)K_0(\gamma a) - K_n(\gamma b)I_0(\gamma a) \right]
\]

where \( I_q(\cdot) \) and \( K_q(\cdot) \) are the qth-order modified Bessel functions of the first and second kind, respectively.

If the shield is a good conductor (i.e., the product of the frequency and the dielectric permittivity can be assumed to be small enough with respect to the conductivity, \( \omega \varepsilon_0 \varepsilon_r \ll \sigma \)), then the propagation constant \( \gamma \) can be expressed as

\[
\gamma = \sqrt{\omega \mu \mu_i \sigma} = (1 + j) \sqrt{\frac{\omega \mu \mu_i \sigma}{2}} = \frac{(1 + j)}{\delta}
\]

where \( \delta \) is the frequency-dependent skin depth

\[
\delta = \sqrt{\frac{2}{\omega \mu \mu_i \sigma}}
\]

3. Results and discussion
3.1. The effect of the ratio of the height to the inner diameter of a finite-length cylinder on the SE of a cylindrical metal shell
Use COMSOL software to explore the influence of the ratio of the height of the cylinder to the inner warp (h/r) on its shielding effectiveness through simulation. The observation point is selected as the position of 1/4 on the central axis of the cylinder. The result is shown in figure 3:

![Figure 3. the influence of h/r](image)
The different colours of the curve in the figure represent different frequencies. It can be observed from the figure that when the ratio of height to inner diameter (h/b) increases to 3, the SE inside the cylinder basically no longer changes.

3.2. Influence of Frequency of External Magnetic Field on SE of Cylindrical Shell

Explore the impact of different frequencies on the SE. The measuring point is 1/4 of the central axis of the cylinder. The result is shown in figure 4:

![Figure 4. Influence of Frequency of External Magnetic Field](image)

It can be seen from the figure that the shielding effectiveness basically increases with the increase of frequency.

3.3. Influence of Frequency of External Magnetic Field on SE of Cylindrical Shell

Explore the effect of shielding effectiveness on the central axis of a finite-length cylinder. The result is shown in figure 5. z is the coordinates of the measuring point (take the centre of the bottom as the origin of the coordinates), h is the height of the cylinder. It can be seen from the figure that the shielding effectiveness on the central axis is symmetrical about the cylinder midpoint; the SE is uniform in the middle area of the cylinder; the more the measuring point is closer to the cylindrical shell, the smaller the SE; the figure also shows that the shielding effectiveness increases with the increase of the frequency of the applied magnetic field.

![Figure 5. The SE on the central axis](image)

3.4. Changes in SE when a small hole is opened at the bottom of the cylinder

Explore the change in shielding effectiveness on the central axis of the cylinder when a small hole is opened at the bottom of the cylinder. As shown in figure 6, z is the coordinates of the measuring point (take the centre of the bottom as the origin of the coordinates), h is the height of the cylinder.
Figure 6. SE changes when a hole is opened at the bottom of the cylinder
Different colours represent different frequencies. It can be seen from the figure that, near the hole, the frequency of the applied magnetic field basically has no effect on the SE. In places far away from the hole, the SE increases with increasing frequency. At the same time, it can be observed that when the frequency is 30kHz, a phenomenon similar to "oscillation" occurs.

3.5. Changes in SE when holes are opened on the center of the upper and lower surfaces of the cylinder
When small holes are opened at the centre of the upper and lower surfaces of the cylinder, the change in the shielding effectiveness on the central axis is explored. As shown in Figure 7, z is the coordinates of the measuring point (take the centre of the bottom as the origin of the coordinates).

Figure 7. SE changes when holes are opened on the upper and lower surfaces of the cylinder
It can be seen from the figure that the shielding effectiveness on the central axis of the cylinder is symmetrical about the centre point; near the two holes, the shielding effectiveness has nothing to do with the frequency; in the place far away from the two holes, the greater the frequency, the higher the shielding effectiveness. This is consistent with the conclusion drawn in section 3.5.

4. Conclusion
1. The simulation result shows that when the ratio of height to inner diameter (h/r) increases to 3, the SE at the 1/4 position on the central axis of the cylinder basically no longer changes.
2. The SE inside the finite cylindrical shell increases with the increase of the frequency of the external magnetic field.
3. On the central axis of the cylinder, the SE is symmetrical about the midpoint.
4. When a small hole is opened at the centre of the bottom of the cylinder, the SE at the position close to the small hole basically does not change with the change of frequency. The SE far away from the small hole increases with the increase of the frequency of the applied magnetic field.

5. When small holes are opened at the centre of the upper and lower surfaces of the cylinder, the SE on the central axis of the cylinder is symmetrical about the centre point; near the two holes, the shielding effectiveness has nothing to do with the frequency; in the place far away from the two holes, the greater the frequency, the higher the shielding effectiveness.

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References
[1] Ma, D., Ding, M., Lu, J., Yao, H., & Han, B. (2019). Study of shielding ratio of cylindrical ferrite enclosure with gaps and holes. IEEE Sensors Journal, 19: 6085-6092.
[2] Frikha, A., Bensetti, M., Duval, F., Benjelloun, N., Lafon, F., Pichon, L. (2015) A new methodology to predict the magnetic shielding effectiveness of enclosures at low frequency in the near field. IEEE Transactions on Magnetics, 51: 1-4.
[3] Frikha, A., Bensetti, M., Pichon, L., Lafon, F., Duval, F., Benjelloun, N. (2015) Magnetic shielding effectiveness of enclosures in near field at low frequency for automotive applications. IEEE Transactions on Electromagnetic Compatibility, 57: 1481-1490.
[4] Lee, S., Kim, D. H., Cho, Y., Kim, H., Song, C., Jeong, S., et al. (2018) Low leakage electromagnetic field level and high efficiency using a novel hybrid loop-array design for wireless high power transfer system. IEEE Transactions on Industrial Electronics, 66: 4356-4367.
[5] Zhang, L., Zhou, Y., Xiu, S., Hao, W. (2019) Design and analysis of platform shielding for wireless charging tram. IEEE Access, 7: 129443-129451.
[6] King, L. V. (1933) Electromagnetic shielding at radio frequencies. Phil. Mag. J. Sci., VII, 15: 201–223.