Wideband Shielding Effectiveness of Laminated Sheet using Copper and Magnetic Materials

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Abstract: This paper presents conditions of a laminated sheet composed of copper and magnetic sheets for obtaining wideband shielding effectiveness below 10 MHz. The following two conditions are clarified: (1) the optimum thickness ratio of the copper sheet to the laminated sheet is 0.5–0.7, (2) the loss factor (tan δ) of the relative permeability of the magnetic sheet is above 1 for increasing reflection losses of the laminated sheet. These conditions are validated by measuring the shielding effectiveness of the laminated sheet. The shielding effectiveness of the laminated sheet is higher than that of the copper sheet in the frequency from 0.1 MHz to 10 MHz.

Keywords: radiation noise, shielding sheet, lamination

Classification: Electromagnetic compatibility (EMC)

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1 Introduction

Clean power generation is demanded owing to increasing energy consumption and greenhouse gas emission [1]. Power electronics equipment such as electric vehicles and photovoltaic power systems are expected as the technologies to meet the demand. Recently, switching frequencies of power semiconductors in the equipment have been increasing for the higher power conversion efficiency. Accordingly, the switching devices radiate high frequency and wideband noise whose levels are so high [2, 3]. The semiconductors such as insulated gate bipolar transistor (IGBT) and metal-oxide-semiconductor field-effect transistor (MOSFET) operate in low frequency (LF: 30-300 kHz) band, and the noise frequencies are up to high frequency (HF: 3-30 MHz) band. Currently, electromagnetic compatibility standards for radiation noises do not cover below 30 MHz, but suppression of the radiation noises is needed because of the above reason.

Metallic materials are mostly used for suppressing the radiation noises from LF and HF bands. Although the materials should be thin for workability and functionality, the materials are required to be thick for shielding magnetic field effectively in the wideband frequency [4]. The authors focus on laminated sheets to solve the above problem. Laminated sheets which are composed of copper and magnetic materials are expected to obtain higher shielding effectiveness than that of the metallic materials [5, 6]. However, optimum conditions of laminated sheets for obtaining wideband shielding effectiveness from LF to HF bands were not reported.

This paper presents optimum conditions of a laminated sheet for obtaining wideband shielding effectiveness below 10 MHz and discusses the thickness ratio of the copper sheet to the laminated sheet and the relative permeability of the magnetic sheet. Since material thicknesses are quite thin against the wavelength in the above target frequency, attenuation losses of the laminated sheet are negligibly small. Therefore, the discussion is focused on reflection losses of the laminated sheet.
2 Shielding effectiveness analysis

2.1 Evaluation method

Fig. 1 shows (a) a magnetic shield measurement system called Kansai Electronic Industry Development Center (KEC) method [7, 8] and (b) its electromagnetic simulation model. As shown in Fig. 1 (a), this system is composed of two shielded loop antennas embedded in two metal cavities. A part of the antenna is arranged in the center of metal cavity, and a shielding sheet is set in between the cavities. A signal generator, a spectrum analyzer and an amplifier are used for the measurement. Shielding effectiveness is defined as the received power normalized to that without shielding sheet. As shown in the Fig.1 (b), the shielded loop antennas and the metal cavity are modeled for the simulation that 3D electromagnetic simulator HFSS [9] is used. The ends of each shielded loop antenna are terminated with 50 Ω.

Fig. 1. KEC method to evaluate shielding effectiveness.
2.2 Evaluation results

First, a shielding effectiveness of a laminated sheet is simulated in order to clarify the optimum thickness ratio of the copper sheet to the laminated sheet. The laminated sheet, of which the total thickness is 53 µm, is composed of copper (conductivity $5.8 \times 10^7$ S/m) and magnetic sheets. Here, real part $\mu'_r$ and imaginary part $\mu''_r$ of the relative permeability of the magnetic sheet are assumed to be 1000 and 0, respectively. Fig. 2 (a) shows the shielding effectiveness against the thickness ratio of the copper sheet to the laminated sheet. The thickness ratio at maximum shielding effectiveness is also shown with large symbols in the Fig. 2 (a). The shielding effectiveness decreases with decreasing frequency; therefore, improving the shielding effectiveness in the lower frequency is required. The thickness ratio at the maximum shielding effectiveness is 0.5-0.7 in the frequency from 0.1 MHz to 10 MHz, and the shielding effectiveness at 0.1 MHz is 7 dB higher than that of copper sheet. Therefore, the optimum ratio of the copper sheet to laminated sheet is 0.5-0.7 for obtaining wideband shielding effectiveness.

![Fig. 2. Simulated shielding effectiveness of laminated sheet.](image)

Secondly, the relative permeability of the magnetic sheet is treated. The thickness of the copper sheet is set to 35 µm (total thickness of 53 µm) to satisfy the optimum thickness condition. Fig. 2 (b) shows the shielding effectiveness of the laminated sheet against $\mu'_r$ at $\mu''_r = 0$. The shielding effectiveness of copper sheet with 53 µm
thickness is also shown for comparison. The shielding effectiveness increases with increasing $\mu'$. This result means the reflection loss contributes to the shielding effectiveness. The color values in Fig. 2 (b) indicate $\mu'$, at the intersection points of the shielding effectiveness of the laminated sheet and that of the copper sheet. The values are minimum conditions of the magnetic sheet for obtaining higher shielding effectiveness than that of the copper sheet. Fig. 2 (c) shows the shielding effectiveness of laminated sheet against tan$\delta (=\mu''/\mu')$. The shielding effectiveness increases drastically as tan$\delta$ of the magnetic sheet exceeds 1. In order to interpret the simulated results, the relationship between tan$\delta$ of the magnetic sheet and the reflection loss of the laminated sheet is examined. Characteristic impedance $Z_S$ of a material is expressed by Eq. (1).

$$Z_S = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}} \quad (1)$$

where, $\sigma$, $\mu$, and $\varepsilon$ are the conductivity, permeability and permittivity of the material and $\omega$ is the angular frequency. On the assumption that $\sigma = 0$, and $\varepsilon$ is constant, the real part of $Z_S$ is given by Eq. (2). Here, $Z_0$ is impedance of free spaces.

$$Re(Z_S) = Z_0\sqrt{\frac{\mu'}{2}}(1 + \sqrt{1 + tan^2\delta}) \quad (2)$$

Eq. (2) exhibits the drastic increase in $Z_S$ with tan$\delta$ above 1. The high shielding effectiveness is due to increasing the reflection loss by the impedance mismatch between the low-impedance copper sheet and high-impedance magnetic sheet. Therefore, the magnetic sheet with tan$\delta$ over 1 should be selected for increasing the reflection loss of the laminated sheet.

3 Measurements

Shielding effectiveness of the laminated sheet is measured to validate the above discussions. From the conditions obtained in previous section, the magnetic sheet of amorphous ribbon containing iron as a main component is selected. Thickness of the magnetic sheet is 18 $\mu$m. Fig. 3 shows (a) $\mu'$, and (b) tan$\delta$ of the magnetic sheet. The conditions of relative permeability of the magnetic sheet are also shown with dotted lines. The $\mu'$, is smaller than the conditions over 4 MHz, but the laminated sheet would have higher shielding effectiveness than the copper sheet because its tan$\delta$ meet the conditions in the frequency from 0.1 MHz to 10 MHz. Fig. 3 (c) shows the measured and simulated shielding effectiveness of the laminated sheet. The shielding effectiveness of the copper sheet with 53 $\mu$m thickness is also shown for comparison. The measurement results are consistent with the simulation within 5 dB errors. The shielding effectiveness of the laminated sheet at 0.1 MHz is 26 dB higher than that of the copper sheet. Additionally, the shielding effectiveness of the laminated sheet is higher than that of the copper sheet in the frequency from 0.1 MHz to 10 MHz. The conditions are validated by the measurement results.
4 Conclusions

This paper presents conditions for obtaining wideband shielding effectiveness of the laminated sheet below 10 MHz by using electromagnetic simulation. As a result, the following conditions were clarified: (1) the optimum thickness ratio of the copper sheet to the laminated sheet is 0.5-0.7; (2) tanδ of the relative permeability of the magnetic sheet is above 1 for increasing reflection losses of the laminated sheet. To validate the above discussions, the shielding effectiveness of the laminated sheet satisfying these conditions was measured. As a result, the shielding effectiveness of the laminated sheet at 0.1 MHz was 26 dB higher than that of the copper sheet. Moreover, the shielding effectiveness of the laminated sheet is higher than that of the copper sheet in the frequency from 0.1 MHz to 10 MHz. Therefore, the conditions were validated by the measurement results.

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