

## Article

# Mesh-Type Magnetic Shielding for Audible-Frequency Magnetic Field Ripple Attenuation and NVH Improvement

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## Abstract

Magnetic field ripple in the audible-frequency range can induce magnetostriction in ferromagnetic components, causing vibration and noise even in non-rotating systems such as electric vehicle battery systems. Magnetic shielding can reduce such excitation; however, shielding materials used in this range are generally ferromagnetic and may themselves undergo magnetostriction, potentially degrading NVH performance. Therefore, magnetic shielding materials should provide effective field attenuation while suppressing their own vibration to improve system-level NVH performance. In this study, a magnetic shielding test setup and an electromagnetic finite-element model were developed. The electromagnetic model was compared with experimental plate-shield measurements and subsequently used for comparative investigations of the effects of shielding configuration, open-area ratio, and thickness, while the associated NVH performance was evaluated experimentally. A mesh-type structure with a continuous magnetic flux path achieved shielding performance comparable to that of a plate-type structure. Experiments using a 0.635 mm steel-wire mesh provided a magnetic shielding effectiveness of approximately 3.73 dB at 3 kHz and reduced the target vibration component at 6 kHz by 55.8% and system noise by 5 dB. These results demonstrate that mesh-type magnetic shielding can attenuate audible-frequency magnetic field ripple while improving system-level NVH performance, indicating potential application to electric vehicle battery systems and other electromagnetic systems.

**Keywords:** mesh-type magnetic shielding; NVH; magnetostriction; finite element analysis; audible-frequency magnetic field ripple



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## 1. Introduction

Noise and vibration in electric drive systems can generally be attributed to mechanical and electromagnetic sources. In particular, in devices that utilize strong magnetic fields, such as electric motors and electromagnetic actuators, Maxwell forces, torque ripple, and radial forces are considered major sources of structural vibration and audible noise. Accordingly, numerous numerical and experimental studies have investigated the prediction and reduction of noise, vibration, and harshness (NVH) in electric drive systems through electromagnetic force analysis, structural response analysis, and acoustic radiation analysis [1–8]. However, vibration in ferromagnetic components can arise not only from these electromagnetic forces but also from magnetostriction. Magnetostriction refers to the dimensional change of a ferromagnetic material caused by the reorientation of magnetic

domains when the material is exposed to a magnetic field. The magnitude of magnetostriction can vary depending on the magnetic field strength and the magnetic properties of the material, and repeated dimensional changes under time-varying magnetic fields can lead to structural vibration and noise. Under symmetric AC magnetic excitation, magnetostrictive strain generally exhibits an even-order dependence on the magnetic field or magnetization. In a simplified representation, the strain can be approximated as proportional to the square of the magnetic flux density,  $\lambda \propto B^2$ . Therefore, when the magnetic field varies sinusoidally at a frequency  $f$ , the magnetostrictive deformation can contain a dominant component at  $2f$ . Additional harmonic components may also arise owing to the nonlinear magnetic and magnetostrictive characteristics of ferromagnetic materials.

Accordingly, various studies have investigated the effects of magnetostriction and material properties on NVH to clarify and reduce the mechanisms of vibration and noise in ferromagnetic materials exposed to time-varying magnetic fields. Ekreem et al. reviewed the fundamental mechanisms of magnetostriction and compared various measurement techniques [9]. The influence of magnetostriction on the NVH characteristics of transformer and electric-motor cores has also been extensively investigated. Weiser et al. analyzed the contributions of magnetostriction and magnetic field strength to audible noise generated by transformer cores [10]. Cai et al. investigated the effects of magnetostriction on the NVH characteristics of motor stator cores through numerical and experimental analyses [11]. Cai et al. also compared interior permanent magnet synchronous motors (IPMSMs) with identical geometries but different core materials and investigated the deterioration of NVH performance associated with materials exhibiting greater magnetostriction [12]. These studies indicate that time-varying magnetic fields can induce magnetostriction in ferromagnetic materials and that reducing the resulting vibration is important for improving NVH performance.

One approach to reducing vibration associated with magnetostriction is to decrease the magnetic field reaching the ferromagnetic structure. Magnetic shielding can be applied for this purpose, and for static and low-frequency magnetic fields, magnetic flux shunting using high-permeability materials is a primary shielding mechanism. A high-permeability shield provides a lower-reluctance path than air, thereby redirecting magnetic flux through the shielding material and reducing the magnetic field reaching the target behind the shield. Liu et al. comprehensively reviewed techniques for improving magnetic shielding performance, including low-noise materials, magnetization control, and active compensation, and identified permeability, magnetic noise, and saturation characteristics as important factors in low-frequency magnetic shielding [13]. Kim et al. evaluated magnetic field penetration and attenuation from DC to 1 kHz using finite element method (FEM) analysis of cabinet-type shields composed of high-permeability materials such as mu-metal [14]. Clérico et al. experimentally investigated the magnetic shielding performance of an Al-steel-Al composite material [15].

In low-frequency magnetic shielding, shielding performance is affected not only by material properties such as permeability but also by geometric and installation parameters, including shield shape, thickness, number of layers, source-to-shield distance, openings, and contact conditions. Kornack et al. proposed the use of ferrite materials for low-frequency magnetic shielding and discussed their advantages compared with high-permeability metallic shields [16]. Olsen et al. compared the shielding performance of single- and multilayer plate-type magnetic shields [17], while Yang et al. evaluated the shielding performance of multilayer magnetically shielded rooms at frequencies below 100 Hz using finite element analysis [18]. In addition, the configuration of the experimental setup, installation method, and boundary conditions can significantly influence measured shielding performance. Koraqi et al. evaluated the magnetic shielding effectiveness of

plate-type materials over the frequency range of 9 kHz–10 MHz using both measurements and FEM analysis, demonstrating strong agreement between the numerical and experimental results. They also investigated the effects of the orientation and distance of the magnetic field source and measurement device, specimen dimensions, and mounting conditions using a shielding enclosure with an opening [19]. Marvin et al. evaluated plate-type magnetic shielding using a test configuration in which five sides of the measurement region were surrounded by absorbers and the shielding material was placed on the upper side [20]. More recently, Koraqi et al. proposed an H-t cell test configuration with a geometry similar to that of ducts used in acoustic experiments [21]. These studies demonstrate that accurate comparison of magnetic shielding performance requires consideration not only of the shielding material itself but also of the measurement system and evaluation method.

Although non-perforated plate-type magnetic shielding has been widely investigated, fully surrounding a target structure with shielding material can be difficult in practical systems because of requirements such as cooling and weight reduction. Accordingly, shielding structures containing openings have also been investigated. Sun et al. evaluated magnetic shielding performance by placing a magnetic field sensor inside a metallic enclosure with periodically arranged openings [22]. Al Achkar et al. proposed an equivalent electromagnetic finite-element model for a shielding material consisting of conductive wires, such as Cu and Al, arranged in a grid pattern within an epoxy matrix [23]. Elshami et al. analytically and experimentally investigated the low-frequency magnetic-field shielding behavior of wire-mesh structures and showed that shielding effectiveness is influenced by the aperture size, with smaller apertures providing higher shielding effectiveness [24]. Haddad et al. developed a low-frequency analytical model for braided and metallic grid shields based on periodic elementary patterns and established a relationship between sheet transfer impedance and shielding effectiveness, demonstrating good agreement with three-dimensional full-wave simulations [25]. These studies demonstrate that open and grid-type shielding structures can provide effective electromagnetic shielding and that their performance is strongly influenced by geometrical parameters. However, their influence on structural vibration and acoustic noise has received comparatively limited attention.

From this perspective, electric vehicle battery systems represent one potential application of open magnetic shielding structures. Power-electronic switching in battery systems can generate magnetic field ripple in the audible-frequency range, and the resulting time-varying magnetic field may excite nearby ferromagnetic components and induce vibration and noise. High-permeability magnetic shielding materials can reduce the magnetic field reaching these components by providing a low-reluctance path for magnetic flux. However, because such shielding materials are themselves generally ferromagnetic or ferrimagnetic, they may also undergo magnetostriction and electromagnetic excitation when exposed to time-varying magnetic fields, potentially becoming an additional source of vibration and noise. Therefore, magnetic shielding structures intended for NVH improvement should be designed to provide sufficient attenuation of audible-frequency magnetic field ripple while also considering the vibration characteristics of the shielding material itself.

To address these requirements, the present study proposes a mesh-type magnetic shielding structure composed of interwoven ferromagnetic wires. The interconnected ferromagnetic wires form continuous magnetic flux paths, enabling effective magnetic flux shunting. At the same time, small relative motions at the contact interfaces between adjacent wires may dissipate vibration energy through friction and thereby contribute to suppressing vibration of the shielding material itself. In addition, the open structure may offer potential advantages in terms of weight reduction and heat dissipation compared with conventional plate-type shielding.

To investigate the applicability of the proposed mesh-type magnetic shielding structure, an experimental magnetic shielding test setup and a corresponding electromagnetic finite-element model were developed. The electromagnetic finite-element model was first compared with experimental results obtained using plate-type shields with different thicknesses to assess whether it reproduced the overall thickness-dependent shielding trend. The model was then used as a comparative numerical tool to investigate the effects of shielding configuration, open-area ratio, and thickness on magnetic shielding performance. Based on the numerical results, steel-wire mesh shields were experimentally evaluated in terms of magnetic field attenuation, target-structure vibration, and system noise. Through these numerical and experimental investigations, this study examines whether mesh-type magnetic shielding can attenuate audible-frequency magnetic field ripple while simultaneously improving system-level NVH performance.

## 2. Materials and Methods

### 2.1. Conceptual Application and Experimental Setup for Magnetic Shielding Evaluation

Figure 1 illustrates a conceptual application of magnetic shielding in an electric vehicle battery system. Power-electronic switching and current flow within the battery system can generate magnetic field ripple in the audible-frequency range. Steel structural components may be used in battery enclosures where mechanical strength and thermal protection are important design requirements. When these ferromagnetic components are exposed to time-varying magnetic fields, magnetostriction and electromagnetic excitation may induce structural vibration and consequently contribute to system noise. In this application concept, a magnetic shield is positioned between the magnetic field source and the steel battery enclosure to attenuate the magnetic field reaching the ferromagnetic structure, thereby reducing magnetostriction-related vibration and improving the NVH performance of the battery system.

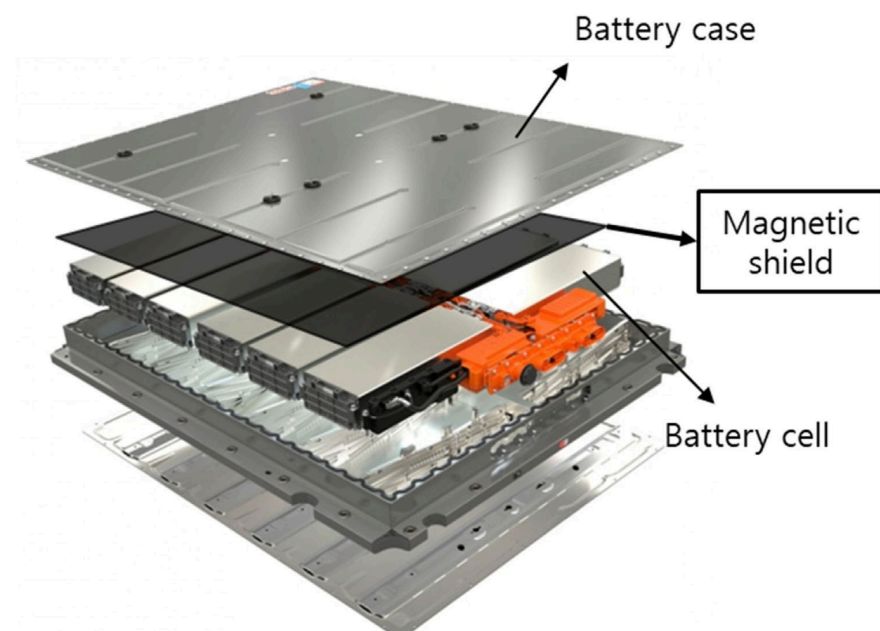


**Figure 1.** Conceptual application of magnetic shielding in an electric vehicle battery system.

Based on this application concept, a simplified experimental setup was constructed to evaluate magnetic shielding and NVH performance. The experimental configuration consists of a magnetic field source, a shielding material, and a ferromagnetic target, representing the basic magnetic interaction among the field source, shield, and structural

component in the application scenario. The setup was designed to generate an AC magnetic field capable of inducing magnetostriction-related vibration in the target structure and to concentrate the generated magnetic field toward the target region.

Figures 2 and 3 show the experimental setup and its schematic, respectively. The setup consists primarily of a magnetic field generation system and a magnetic field measurement system. In the magnetic field generation system, an AC signal at a specified frequency is generated by a function generator (KEYSIGHT EDU33211A, Keysight Technologies, Inc., Santa Rosa, CA, USA) and amplified using an amplifier (Real Master TA-1000, TJ Media Co., Ltd, Seoul, Republic of Korea). The amplified current is supplied to a copper winding around a laminated core, generating a time-varying magnetic field predominantly in the upward direction according to Ampère's law and the Biot–Savart law. The voltage applied to the coil is measured using an oscilloscope (GW INSTEK MSO-2104EA, Good Will Instrument Co., Ltd. (GW Instek), New Taipei City, Taiwan), while the current is simultaneously measured using a current probe (OWON CP-05+, Fujian Lilliput Optoelectronics Technology Co., Ltd. (OWON), Zhangzhou, China). The measured voltage and current signals are recorded to monitor the excitation conditions. The magnetic field is measured using a Hall-effect magnetic-field sensor (SNPHS-138, SNP, Hwaseong-si, Gyeonggi-do, Republic of Korea) connected to a dedicated signal-conditioning converter. The sensor has a specified measurement range of  $\pm 20$  mT, a sensitivity of 90 mV/mT, and a frequency response specification of 23 kHz (see Supplementary File S1). The converter supplies power to the sensor and provides an analog voltage output, which is acquired using an NI ELVIS II Series data acquisition system (National Instruments, Austin, TX, USA) equipped with a 16-bit analog-to-digital converter at a sampling rate of 100 kHz. The acquired magnetic-field signals are recorded on a PC for subsequent analysis. The magnetic-field measurements were used primarily to evaluate the relative change between the unshielded and shielded conditions under the same measurement configuration. Accordingly, the shielding performance was determined from the relative magnetic-field attenuation rather than from the absolute magnetic-flux-density value alone. A specimen fixture is installed between the core and the Hall-effect sensor to position the magnetic shielding specimens at a designated location.

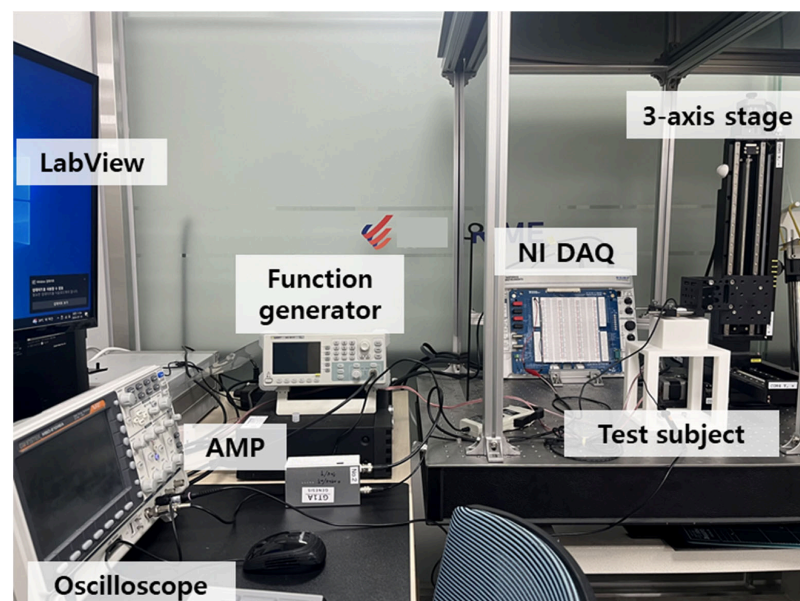


Figure 2. Experimental setup for magnetic shielding evaluation.

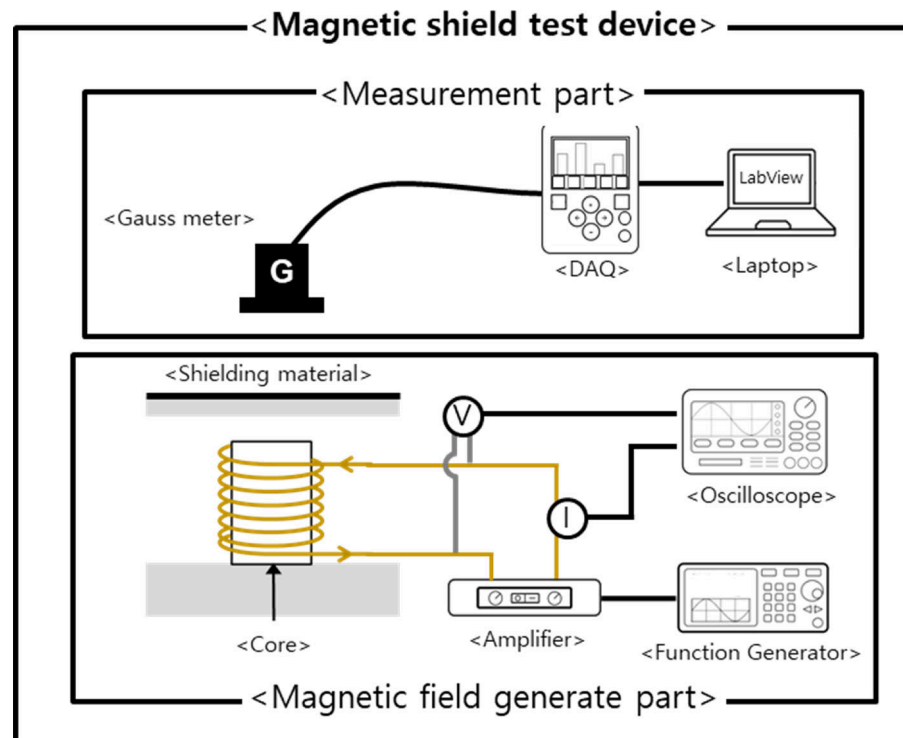


**Figure 3.** Schematic of the experimental setup for magnetic shielding evaluation.

The Gauss meter is mounted on a three-axis positioning stage to precisely control the sensor position, while the specimen fixture is fabricated from polylactic acid (PLA), which has negligible influence on the magnetic field. The three-axis stage is primarily constructed from aluminum, except for the lower base plate. To minimize the influence of the steel base plate on the magnetic field, the laminated core is positioned 200 mm above the base using a PLA fixture.

## 2.2. Development and Numerical–Experimental Comparison of the Electromagnetic Model

Figure 4 compares the magnetic field generation and measurement configurations used in the experiment and the Maxwell electromagnetic finite-element model. In the experiment, an AC current is applied to the coil to generate a time-varying magnetic field. The core consists of electrical steel laminations stacked in the left-to-right direction in Figure 4a. A copper wire with a diameter of 1 mm is used for the coil, with a total of 100 turns. The Gauss meter is positioned such that the magnetic field passes through the sensor in the normal direction.

The Maxwell model uses the same number of coil turns as the experimental setup, and the excitation current is defined as a time-dependent input. To represent the electromagnetic characteristics of the laminated electrical steel core, the B–H curve of 25PNX1250 is assigned to the core material. Because the sensing element of the Gauss meter is sufficiently thin to have a negligible influence on the surrounding magnetic field, the sensor region in the electromagnetic finite-element model is represented by a cylindrical volume corresponding to the sensor dimensions and assigned vacuum properties. The magnetic flux density passing through this region is then evaluated. An open boundary condition is applied to the outer boundary of the electromagnetic model. To assess the thickness-dependent shielding trend reproduced by the electromagnetic finite-element model, numerical and experimental evaluations were conducted using plate-type ferromagnetic shields with different thicknesses.

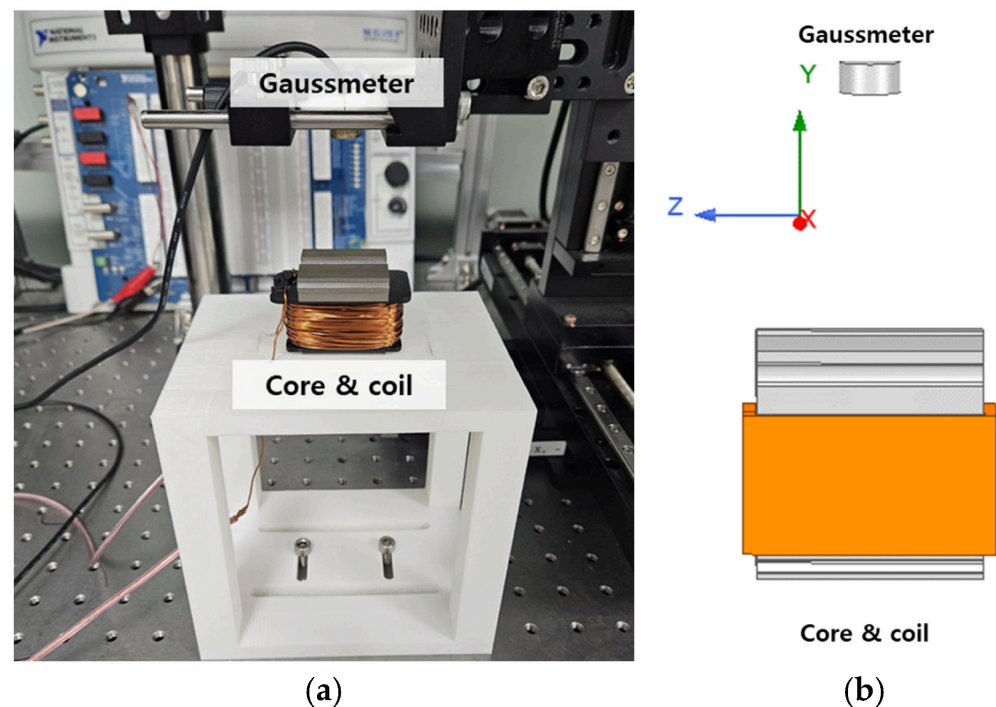


**Figure 4.** Magnetic field generation and measurement configurations: (a) experimental setup and (b) Maxwell electromagnetic finite-element model.

Figure 5 shows the schematic, experimental setup, and electromagnetic finite-element model used to evaluate the magnetic shielding performance of a plate-type ferromagnetic shield. Rather than completely enclosing the magnetic field source or target, a single-sided shielding configuration is employed, with the shielding material positioned between the core and the Gauss meter. The distance between the core and the Gauss meter is fixed at 40 mm, and the shielding plate is positioned midway between them, 20 mm above the core. The shielding plates were made of S45C carbon steel and had an area of  $200 \times 200 \text{ mm}^2$ . Five thicknesses of 0.5, 0.8, 1.0, 1.6, and 2.0 mm were evaluated. In this validation setup, the ferromagnetic plate serves solely as the shielding specimen, and no separate ferromagnetic target structure is included. The excitation current amplitude and frequency are fixed at 0.25 A and 3 kHz, respectively. Prior to the detailed evaluation, preliminary measurements were conducted at five excitation frequencies of 1, 2, 3, 4, and 5 kHz, considering the stable operating frequency range of the amplifier. Magnetic-field attenuation was observed under the investigated excitation conditions. Since the primary objective of this study was to compare the relative magnetic shielding performance of different shielding configurations and the associated NVH responses under consistent excitation conditions, 3 kHz was selected as the representative excitation frequency within the investigated range. Accordingly, the subsequent numerical and experimental evaluations were conducted at 3 kHz, and the quantitative findings are interpreted under this specified excitation condition.

In the electromagnetic finite-element model, the shielding structures were assigned the steel 1008 material from the system material library of ANSYS Electronics Desktop 2021 R2. The material was used without modification, with a bulk electrical conductivity of  $2.0 \times 10^6 \text{ S/m}$  and a nonlinear magnetic characteristic defined by the B–H curve provided in the ANSYS material database. Accordingly, the magnetic permeability was determined from the nonlinear B–H relationship rather than being assigned a constant value. No additional frequency-dependent magnetic properties or material characteristics fitted to the experimental specimens were introduced. Although the experimental shielding specimens were fabricated from S45C carbon steel, the applicability of the adopted numerical material

model was evaluated through a numerical–experimental comparison of magnetic-field attenuation using S45C plate specimens. This comparison provided a basis for the subsequent analyses of relative shielding performance across different configurations and geometrical parameters.

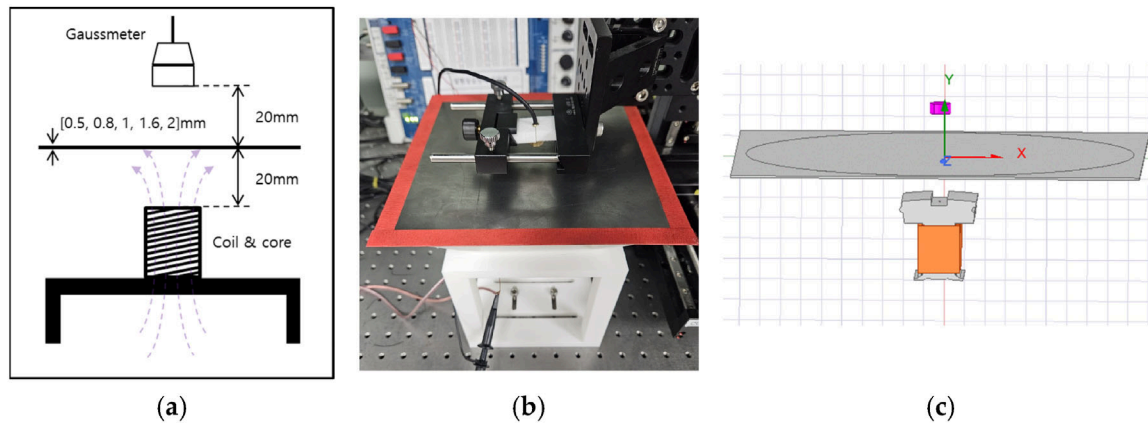


**Figure 5.** Evaluation of plate-type magnetic shielding performance: (a) schematic, (b) experimental setup, and (c) electromagnetic finite-element model.

Separately from the material model used in the FEM, an approximate skin-depth evaluation was conducted for the experimental S45C shielding specimens to support the interpretation of the measured mesh-shielding results. For a conductive ferromagnetic material subjected to a time-varying magnetic field, the skin depth can be expressed as  $\delta = \sqrt{2/(\omega\mu_0\mu_r\sigma)}$ , where  $\omega$ ,  $\mu_0$ ,  $\mu_r$  and  $\sigma$  denote the angular frequency, vacuum permeability, relative permeability, and electrical conductivity, respectively. For this approximate evaluation, representative material properties of AISI/SAE 1045, corresponding to S45C, were adopted. Using an initial relative permeability of  $\mu_{r,initial} = 300$  and an electrical resistivity of  $1.62 \times 10^{-7} \Omega \cdot \text{m}$ , the estimated skin depth at 3 kHz is approximately 0.214 mm, corresponding to  $3\delta \approx 0.641$  mm. Because the permeability of ferromagnetic steel varies with magnetic state, microstructure, and excitation conditions, this value is used only as an approximate penetration scale for interpreting the experimental S45C mesh results.

Figure 6 shows the peak-to-peak magnetic field amplitude at the measurement position as a function of shield thickness. Without a shielding material, the magnetic field amplitude is approximately 190  $\mu\text{T}$ , whereas the introduction of a plate-type shield results in a substantial reduction in the magnetic field. In the numerical results, the shielding effect increases with increasing plate thickness, with a particularly pronounced reduction occurring between thicknesses of 0.8 and 1.0 mm. For thicknesses greater than approximately 1.0 mm, the magnetic field amplitude converges to approximately 30  $\mu\text{T}$ , indicating that further increases in thickness provide only limited improvement in shielding performance.

The experimental results show a similar trend. For shielding thicknesses of 0.8 mm and above, the measured magnetic field amplitude remains approximately 20–25  $\mu\text{T}$ . The magnetic-field reduction ratio was defined as  $R = (B_{unshielded} - B_{shielded})/B_{unshielded} \times 100$ , where  $B_{unshielded}$  and  $B_{shielded}$  denote the magnetic-field amplitudes without and with the shielding material, respectively. The reduction ratios were calculated independently for the numerical and experimental results using their corresponding unshielded conditions, and the difference between the two reduction ratios was within approximately 3 percentage points. These results demonstrate that shield thickness is an important design parameter for magnetic field attenuation; however, once a sufficient low-reluctance path for magnetic flux is established within the shielding material, further increases in thickness provide only limited improvement in shielding performance. Although differences are present between

the absolute magnetic-field amplitudes obtained numerically and experimentally, both results exhibit a consistent thickness-dependent attenuation trend. In particular, the shielding performance increases with increasing shield thickness and approaches a converged level above a certain thickness. The magnetic-field reduction ratios, calculated independently using the corresponding unshielded conditions, differed by approximately 3 percentage points. Based on this consistency in the relative attenuation trend, the electromagnetic model was subsequently used as a comparative tool to investigate the effects of shielding configuration and geometrical parameters rather than as a material-specific predictor of the absolute magnetic-field amplitude. The electromagnetic finite-element model developed in this study was limited to the electromagnetic domain and was used to evaluate magnetic-field distribution and magnetic shielding performance. Structural vibration and acoustic radiation were not included in the numerical model; therefore, the vibration response of the mesh shielding structure itself was not predicted numerically. The structural vibration and acoustic responses associated with the application of the mesh shield were instead evaluated experimentally, as described in Section 3.3.

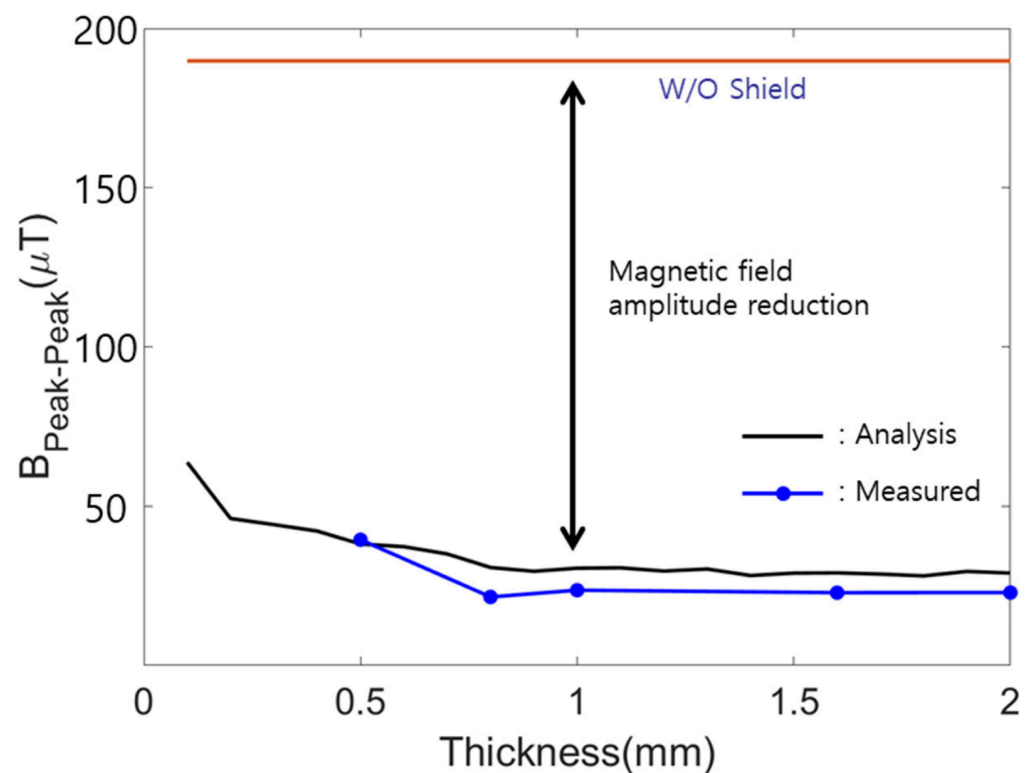


**Figure 6.** Numerical and experimental comparison of magnetic field attenuation with plate-type shields of different thicknesses.

### 3. Results and Discussion

#### 3.1. Comparison of Magnetic Shielding Performance for Different Shielding Configurations

Magnetic shielding performance is affected by various material and structural parameters, including shielding configuration, open-area ratio, material properties, and shield thickness. In this study, the electromagnetic finite-element model described in Section 2.2 was used as a comparative numerical tool to investigate the effects of shielding configuration, open-area ratio, and shield thickness on magnetic shielding performance under consistent material and excitation conditions.

As shown in Figure 7, six shielding configurations were considered to compare the effect of shield placement on magnetic shielding performance. The configurations include

an unshielded condition, a single-sided plate shield positioned between the magnetic field source and the target, five-sided shielding surrounding either the source or the target, and fully enclosed shielding surrounding either the source or the target. The shield thickness was set to 1 mm for all configurations, and the distance between the core and the Gauss meter was fixed at 40 mm. For the single-sided configuration, the shielding material was positioned midway between the core and the Gauss meter, 20 mm above the core. The excitation current amplitude and frequency were set to 0.25 A and 3 kHz, respectively.

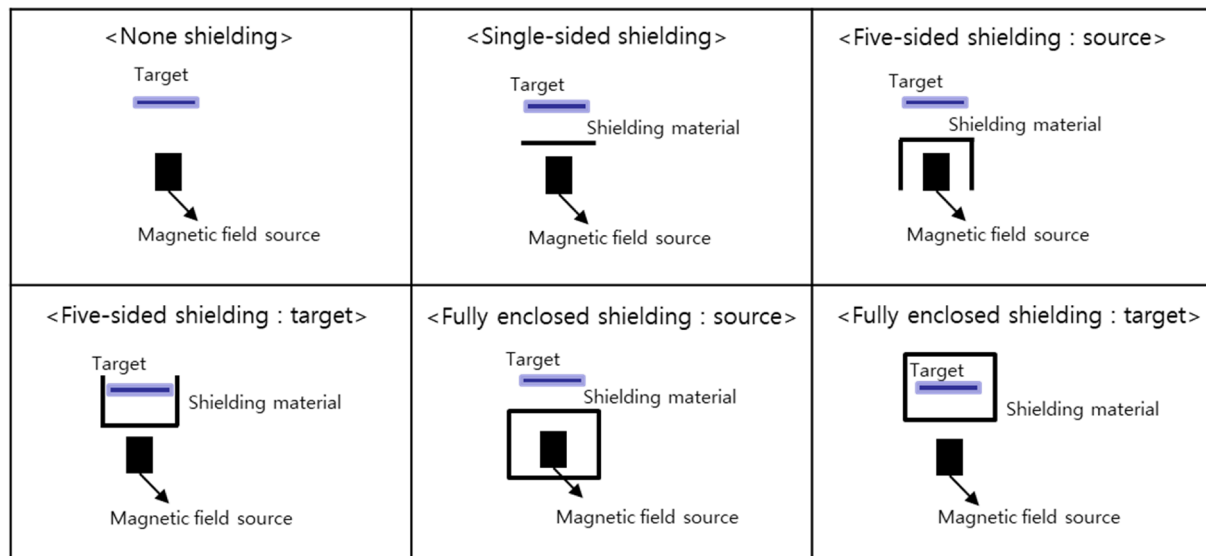


**Figure 7.** Schematic of the investigated magnetic shielding configurations.

Figure 8 compares the time-domain magnetic fields obtained from the electromagnetic analysis for the six shielding configurations shown in Figure 7, with a uniform shield thickness of 1 mm applied to all shielded configurations. The left panel presents the magnetic field over approximately 700  $\mu\text{s}$ , corresponding to two excitation cycles. The right panel provides an enlarged view over the ranges of 200–300  $\mu\text{s}$  and 0–15  $\mu\text{T}$  to facilitate comparison among the shielded configurations.

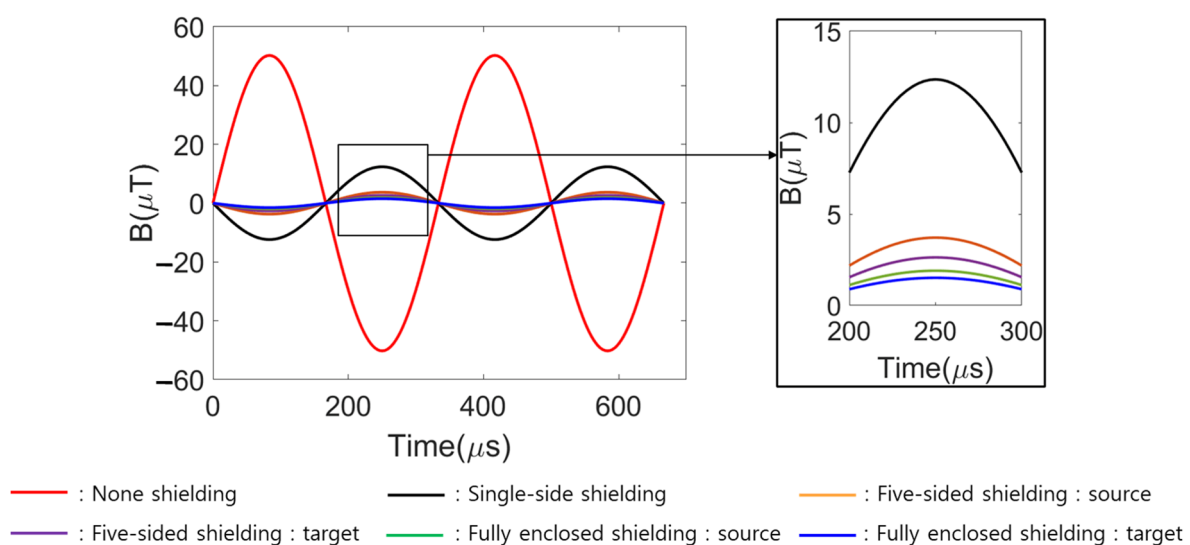


**Figure 8.** Comparison of magnetic shielding performance for different shielding configurations with a shield thickness of 1 mm.

In the unshielded condition, the maximum magnetic field amplitude is approximately 50  $\mu\text{T}$ . When a single plate-type shield is placed between the source and the target, the maximum amplitude decreases to approximately 12  $\mu\text{T}$ . For configurations with five-sided or fully enclosed shielding, the magnetic field amplitude is reduced to below approximately 4  $\mu\text{T}$ . Thus, even a single-sided plate-type shield can reduce the magnetic field to approximately one-fifth of that obtained under the unshielded condition.

Among the multi-sided shielding configurations, the shielding performance follows the order of fully enclosed target shielding, five-sided target shielding, fully enclosed source shielding, and five-sided source shielding. The relatively lower performance of source-side shielding may be associated with a higher concentration of magnetic flux in the shielding material, which can increase the possibility of local magnetic saturation and consequently reduce the effectiveness of magnetic flux shunting. These results indicate that an appropriate shielding configuration should be selected by considering the geometry and installation constraints of the target electromagnetic system.

### *3.2. Effect of Open-Area Ratio and Thickness on the Shielding Performance of Mesh-Type Magnetic Shields*

As discussed in Section 3.1, magnetic shielding performance varies depending on the shielding configuration. However, in practical applications such as electric vehicle battery systems, fully enclosing the target ferromagnetic structure is often difficult. Therefore, among the shielding configurations investigated in Section 3.1, the single-sided configuration was selected because of its simple structure and sufficient shielding effect compared with the unshielded condition. A mesh-type magnetic shielding structure was then applied to this configuration.

Figure 9 shows the three shielding structures considered to investigate the influence of ferromagnetic-path continuity on magnetic shielding performance. The plate-type structure represents a fully continuous shield with an open-area ratio of 0%. The total shielding area was  $200 \times 200 \text{ mm}^2$ . For the mesh-type structure, 100 square openings were arranged in a  $10 \times 10$  pattern. Each opening had dimensions of  $14.14 \times 14.14 \text{ mm}^2$ , and the width of the ferromagnetic grid was 5.33 mm, resulting in an open-area ratio of approximately 50%. The spot-type structure was defined as the geometrical complement of the mesh-type structure: the  $14.14 \times 14.14 \text{ mm}^2$  square regions were assigned as discrete ferromagnetic spots, while the 5.33 mm wide interconnected grid regions were treated as open areas. Thus, the mesh- and spot-type structures had the same open-area ratio of 50% but differed in the continuity of the ferromagnetic material. In the mesh-type structure, the ferromagnetic regions formed continuous interconnected paths across the shielding plane, whereas those in the spot-type structure were physically separated. The spot-type structure was introduced solely as a numerical reference configuration to isolate the effect of ferromagnetic-path continuity and was not fabricated as a physical specimen in the present study. Therefore, the comparison involving the spot-type structure should be interpreted as a numerical result only. Each shielding structure was applied to the electromagnetic finite-element model shown in Figure 5c. The open-area ratio is defined as the ratio of the open area to the total area of the shielding plane. The shield thickness was 1 mm. The distance between the core and the Gauss meter was fixed at 40 mm, with the shielding material positioned midway between them, 20 mm above the core. The excitation current amplitude and frequency were 0.25 A and 3 kHz, respectively.

Figure 10 compares the magnetic field amplitudes obtained using the plate-, mesh-, and spot-type shielding structures. The plate- and mesh-type structures exhibit similar magnetic field amplitudes of approximately 15  $\mu\text{T}$ , indicating that the mesh-type structure with a 50% open-area ratio can provide shielding performance comparable to that of the solid plate under the investigated conditions. In contrast, the spot-type structure, which has

the same open-area ratio as the mesh-type structure but consists of disconnected ferromagnetic regions, exhibits a substantially higher magnetic field amplitude of approximately 37  $\mu\text{T}$ . These numerical results indicate that magnetic shielding performance depends not only on the open-area ratio but also on the continuity of the ferromagnetic path. A continuous ferromagnetic path provides a low-reluctance route for magnetic flux shunting, whereas discontinuous ferromagnetic regions limit effective flux redirection. From a magnetic-circuit perspective, the magnetic reluctance can be expressed as  $R_m = l/(\mu A)$ , where  $l$ ,  $\mu$  and  $A$  denote the magnetic path length, permeability, and cross-sectional area, respectively. Thus, the disconnected ferromagnetic regions in the spot-type structure increase the effective magnetic reluctance because the magnetic flux must cross high-reluctance air gaps. Based on these results, the mesh-type structure was selected for further investigation.

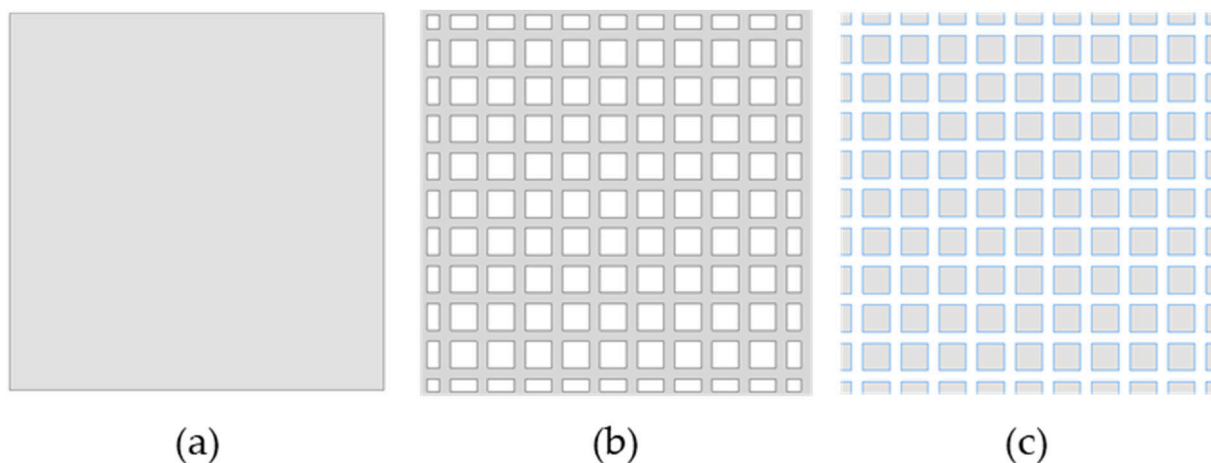


**Figure 9.** Shielding structures used to investigate the effect of ferromagnetic path continuity on magnetic shielding performance: (a) plate type with a 0% open-area ratio, (b) mesh type with a 50% open-area ratio, and (c) spot type with a 50% open-area ratio.

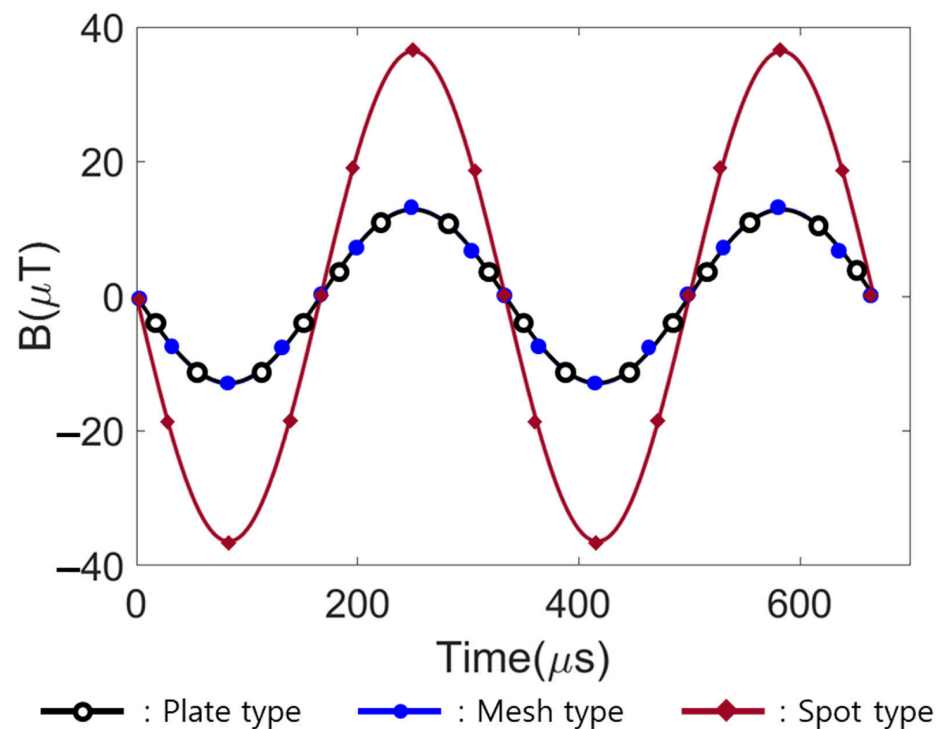


**Figure 10.** Comparison of magnetic field amplitudes for plate-, mesh-, and spot-type shielding structures.

The open-area ratio and thickness are major design parameters governing the performance of mesh-type magnetic shielding. In general, increasing the shield thickness or decreasing the open-area ratio increases the amount and cross-sectional area of ferromagnetic material available for magnetic flux shunting, which can improve shielding performance. However, once a sufficient low-reluctance path for magnetic flux is established, further increases in the amount of shielding material may provide only limited improvement. Therefore, numerical analysis was performed to identify the range in which the shielding performance begins to converge, thereby providing a basis for reducing the amount of shielding material while maintaining the required shielding performance. In this analysis, the total shielding area and thickness were fixed at  $200 \times 200 \text{ mm}^2$  and 1 mm, respectively, while the mesh spacing was varied to investigate the effect of the open-area ratio.

Figure 11a shows the magnetic shielding performance of the mesh-type structure as a function of mesh spacing and open-area ratio. The open-area ratio was geometrically calculated from the dimensions of a repeating square mesh cell as  $\phi = L_a^2 / (L_a + L_b)^2 \times 100$ , where  $L_a$  is the width of the square opening and  $L_b$  is the width of the ferromagnetic grid. Since the mesh pitch is  $L_c = L_a + L_b$ , the open-area ratio can equivalently be expressed as  $\phi = L_a^2 / L_c^2 \times 100$ . Thus, the mesh spacing and open-area ratio shown in Figure 11 represent geometrically related parameters rather than independent variables. The mesh spacing was varied from approximately 0.4 to 100 mm, corresponding to open-area ratios of approximately 8–98%. The magnetic shielding performance is evaluated using Equation (1).

$$S_{dB} = 20 \log_{10} \left( \frac{B_0}{B_s} \right) \quad (1)$$

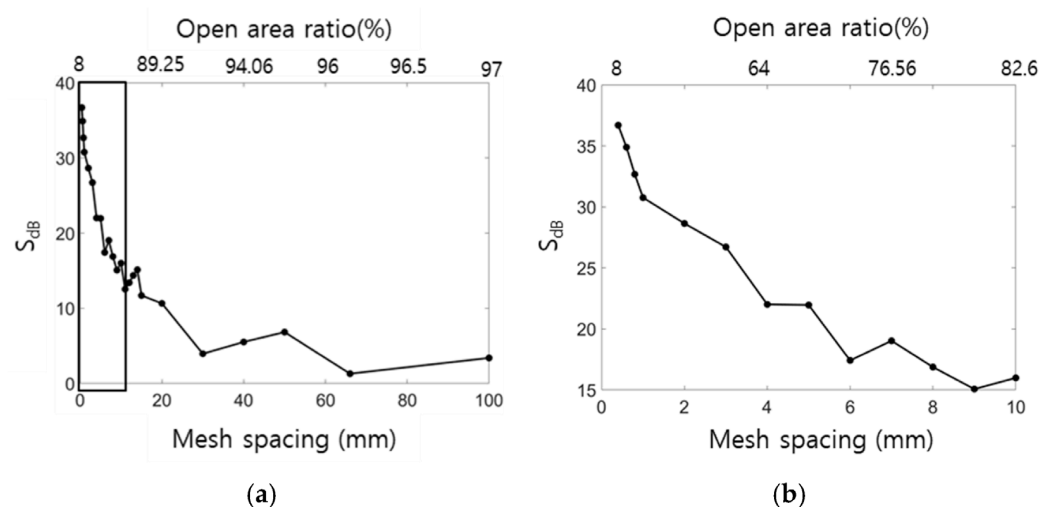


**Figure 11.** Magnetic shielding performance as a function of the open-area ratio of the mesh-type shield: (a) overall mesh-spacing range and (b) enlarged view for mesh spacings of 0.4–10 mm, corresponding to open-area ratios of approximately 8–82.6%.

In Equation (1), the shielding performance is determined from the magnetic field amplitudes obtained with and without the magnetic shielding material.

Figure 11 shows that the shielding performance remains at a similar level when the open-area ratio exceeds approximately 90%. Under these conditions, the large openings allow a substantial portion of the magnetic flux to pass through the mesh rather than being redirected through the shielding material. In contrast, when the mesh spacing decreases below approximately 10 mm, corresponding to an open-area ratio of approximately 82.6% or lower, the shielding performance increases rapidly as the mesh spacing decreases.

For the 1 mm thick mesh considered in this analysis, no clear convergence in shielding performance was observed as the open-area ratio decreased. This suggests that shield thickness should also be considered together with the open-area ratio. When sufficient thickness is provided, a larger portion of the magnetic flux can be redirected through the shielding material, allowing the shielding performance to approach a converged level.

Figure 12 shows the magnetic shielding performance of a mesh-type structure with an open-area ratio of 80% as a function of shield thickness. Six excitation conditions with the same frequency but different current amplitudes are compared. For shield thicknesses below approximately 1 mm, the shielding performance increases as the thickness increases. However, above approximately 1 mm, the improvement becomes limited and the shielding performance tends to converge. This result indicates that once a sufficient low-reluctance path for magnetic flux shunting is established within the shielding material, further increases in thickness provide only limited improvement in magnetic shielding performance. As discussed in Section 2.2, the numerical analysis employed the electrical conductivity and nonlinear B–H characteristic of ‘steel 1008’. Because the effective magnetic permeability varies with the magnetic operating point, the convergence observed above approximately 1 mm represents the thickness-dependent shielding response under the adopted material model and excitation conditions, rather than a fixed skin-depth threshold.

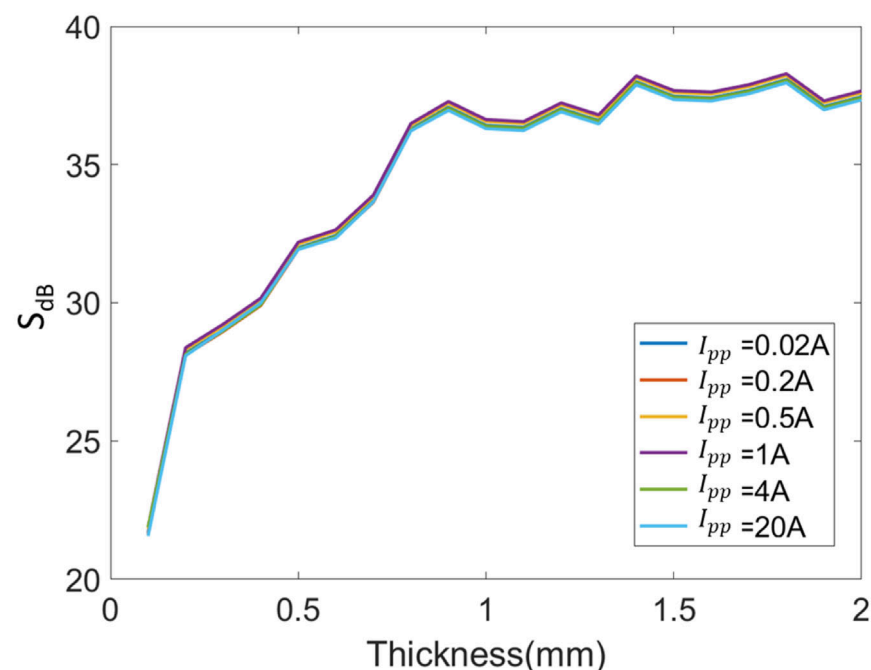


**Figure 12.** Effect of thickness on the shielding performance of a mesh-type shield with an open-area ratio of 80%.

In addition, similar shielding performance is obtained when the excitation current amplitude is varied from 0.02 to 20 A. The close agreement among the results obtained under different excitation levels indicates that, within the range investigated in this study, the shielding performance defined by Equation (1) is relatively insensitive to variations in excitation current amplitude. No clear degradation in shielding performance associated with magnetic saturation was observed within the investigated current range. However, the present current-sweep analysis was not intended to determine the absolute saturation boundary of the mesh shielding material. Determination of this boundary requires material-specific nonlinear magnetic characterization and further evaluation under higher magnetic-field conditions.

### 3.3. Magnetic Shielding and NVH Performance of Mesh-Type Magnetic Shields

In the preceding section, the performance of mesh-type shielding was investigated using the electromagnetic finite-element model. Subsequently, steel-wire mesh specimens were experimentally evaluated to investigate their effects on both magnetic shielding and NVH performance.

Figure 13 shows the mesh-type magnetic shielding specimens used in the experiment. The specimens consist of interwoven S45C carbon-steel wires with diameters of 0.635 and 0.254 mm. Unlike a conventional solid plate, the interwoven mesh structure contains numerous contact interfaces between adjacent wires. When the shielding material undergoes vibration, small relative motions at these contact interfaces may dissipate vibration energy through friction, thereby helping to suppress vibration of the shielding material itself. This frictional energy dissipation is considered a potential NVH advantage of the mesh-type structure; however, its contribution was not independently quantified in the present study and will be quantitatively investigated in future work.

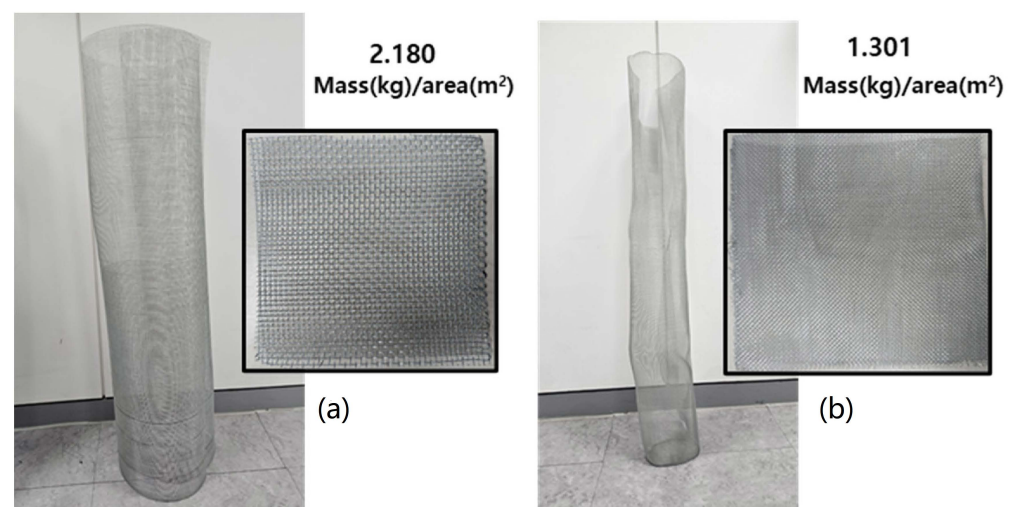


**Figure 13.** Mesh-type magnetic shielding specimens used in the experiment: (a) 0.635 mm wire diameter with a 56.9% open-area ratio and (b) 0.254 mm wire diameter with a 57.6% open-area ratio.

Two commercially available steel meshes were selected for the experiments. The meshes with wire diameters of 0.635 and 0.254 mm have similar open-area ratios of 56.9% and 57.6%, respectively. These specimens were used to evaluate the magnetic shielding and NVH performance of the mesh-type structure. From a multi-physics perspective, the system can be described as a sequential coupling process in which the time-varying magnetic field produces magnetostrictive and electromagnetic excitation in the ferromagnetic components. The resulting structural response can be conceptually expressed by the dynamic equilibrium relation  $M\ddot{x} + C\dot{x} + Kx = F_{em} + F_{ms}$ , where  $M$ ,  $C$  and  $K$  are the mass, damping, and stiffness matrices, respectively, and  $F_{em}$  and  $F_{ms}$  represent the equivalent electromagnetic and magnetostrictive excitations. The resulting structural vibration subsequently contributes to acoustic radiation. In the present study, these coupled responses were evaluated experimentally rather than through a fully coupled electromagnetic–structural–acoustic numerical model.

The experimental setup shown in Figure 14 was configured to simultaneously evaluate the magnetic shielding and NVH performance of the two mesh specimens. Under the same excitation condition, the magnetic field reaching the target structure, the resulting structural vibration, and the system noise were measured together. This configuration enables the effect of the mesh shield to be assessed in terms of both magnetic field attenuation and system-level NVH performance.

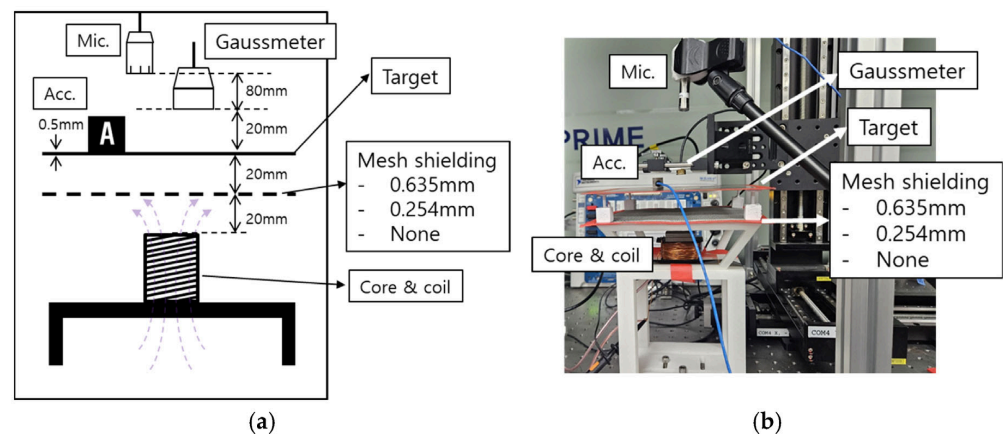


**Figure 14.** Experimental setup for evaluating the magnetic shielding and NVH performance of mesh-type shields: (a) schematic and (b) experimental setup.

Figure 14 shows the schematic and experimental setup used for these measurements. The distance between the magnetic field-generating core and the mesh shield is fixed at 20 mm. A steel plate with a thickness of 0.5 mm and an area of  $200 \times 200 \text{ mm}^2$  is positioned 20 mm above the mesh shield and used as the target structure. Unlike the plate used as the shielding specimen in the model-validation setup of Figure 5, this steel plate serves as the ferromagnetic target structure whose vibration response is evaluated. In the unshielded reference condition, the target structure and all measurement positions are maintained, and only the mesh shielding specimen is removed. An accelerometer is attached to the target structure to measure its vibration response. A Gauss meter is positioned 20 mm above the center of the target structure to measure the magnetic field, while a microphone is placed 100 mm above the target structure to measure the system noise. The Gauss-meter position in this setup differs from that in Figure 5 because the present configuration includes the ferromagnetic target structure to enable simultaneous evaluation of magnetic shielding and NVH responses. Therefore, the absolute magnetic-field amplitudes obtained from Figures 5 and 14 are not directly compared; instead, the shielding performance in Figure 14 is evaluated from the relative change between the unshielded and mesh-shielded conditions under the same measurement geometry. The excitation current amplitude and frequency are fixed at 0.25 A and 3 kHz, respectively, consistent with the preceding numerical and experimental conditions.

Figure 15 presents the FFT results of the magnetic field measured with and without the mesh-type magnetic shielding materials. Under the unshielded condition, the magnetic field amplitude at 3 kHz is  $88.23 \mu\text{T}$ . When the mesh shields with wire diameters of 0.254 and 0.635 mm are applied, the magnetic field amplitudes decrease to 76.82 and  $57.42 \mu\text{T}$ , respectively. According to Equation (1), these values correspond to magnetic shielding effectiveness values of approximately 1.20 and 3.73 dB for the 0.254 and 0.635 mm meshes, respectively.

Although the two mesh specimens have similar open-area ratios, the mesh with a wire diameter of 0.635 mm exhibits higher magnetic shielding performance. However, the two specimens differ not only in wire diameter but also in associated geometrical parameters, including the effective ferromagnetic cross-sectional area and material amount. Therefore, the observed difference in shielding performance cannot be attributed solely to wire diameter. Under the investigated conditions, the 0.635 mm mesh, which provides a larger effective ferromagnetic cross-sectional area, exhibited greater magnetic-field attenuation. The independent contributions of these coupled design parameters require further quantitative investigation. Based on the approximate skin depth of 0.214 mm estimated in Section 2.2, the wire diameters of the two S45C mesh specimens, 0.254 and 0.635 mm, correspond to

approximately  $1.2\delta$  and  $3\delta$ , respectively. In particular, the 0.635 mm wire diameter is close to the commonly referenced  $3\delta$  penetration criterion, at which the field amplitude within a homogeneous conductor is substantially attenuated. This relationship suggests that the skin-depth effect may contribute to the higher magnetic shielding effectiveness observed for the 0.635 mm mesh. However, the two mesh specimens also differ in the available ferro-magnetic cross-sectional area, material amount, and associated mesh geometry. Therefore, the experimentally observed difference in shielding performance should be interpreted as the combined effect of electromagnetic penetration and magnetic-flux shunting associated with the mesh geometry, rather than being attributed to skin depth alone.

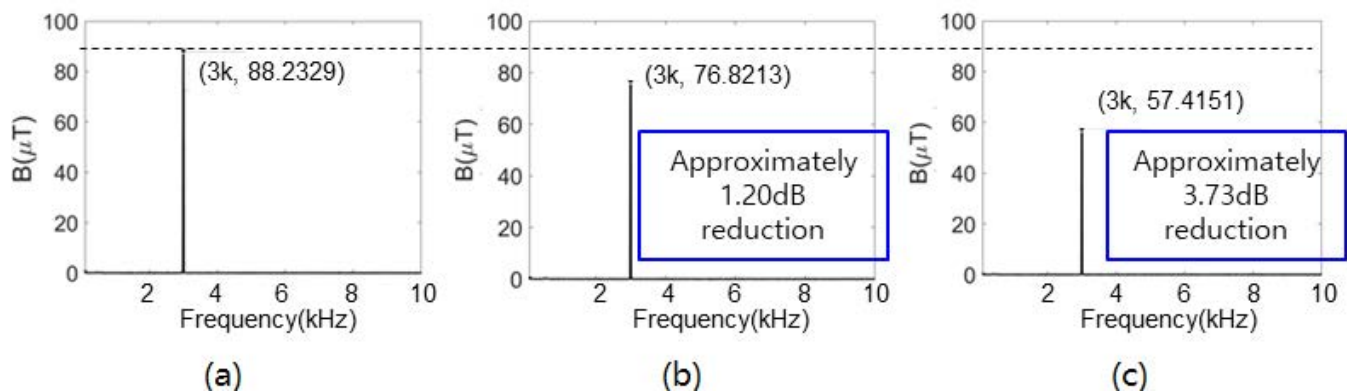


**Figure 15.** Magnetic field attenuation achieved by mesh-type shields with different wire diameters: FFT results for (a) unshielded, (b) 0.254 mm wire diameter, and (c) 0.635 mm wire diameter.

Figure 16 shows the FFT results of the vibration response of the target structure and the system noise for different mesh shielding conditions. Although the excitation current frequency is 3 kHz, the dominant vibration component of the target structure is observed at 6 kHz, corresponding to twice the excitation frequency. This frequency relationship is consistent with the even-order characteristic of magnetostrictive deformation described above. However, electromagnetic forces can also contain second-order field-dependent components; therefore, the observed 6 kHz response should be interpreted as being consistent with magnetostrictive and electromagnetic excitation rather than as evidence of magnetostriction alone.

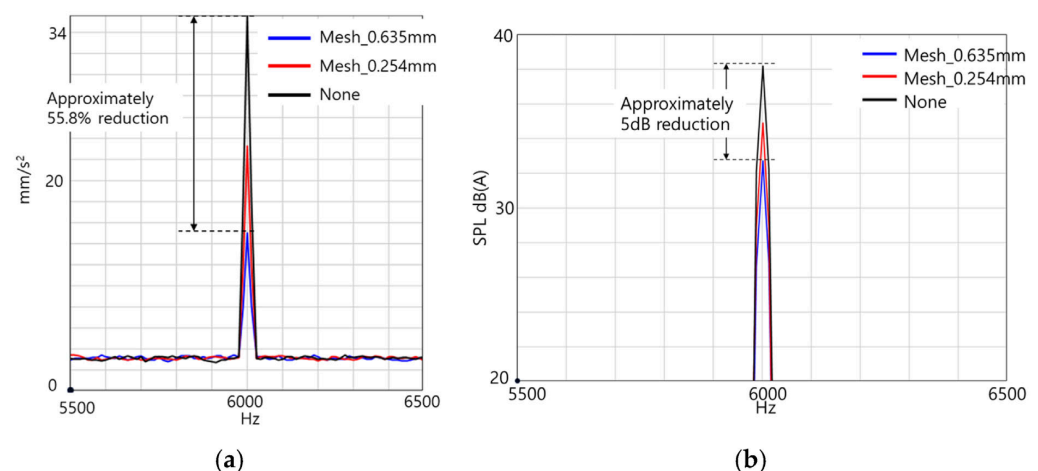


**Figure 16.** NVH improvement achieved by applying mesh-type magnetic shielding: (a) vibration acceleration of the target structure and (b) system noise.

When the mesh shield with a wire diameter of 0.635 mm is applied, the vibration amplitude of the target structure at 6 kHz decreases by approximately 55.8% compared

with the unshielded condition. The system noise is also reduced by approximately 5 dB, demonstrating a clear improvement in NVH performance. Accordingly, rather than interpreting the NVH response solely on the basis of a nominal skin-depth estimate, the results are considered together with the directly measured magnetic shielding effectiveness of each mesh specimen. Under the investigated conditions, the higher shielding effectiveness of the 0.635 mm mesh was accompanied by reduced magnetic excitation of the target structure and consequent reductions in the dominant vibration component and system noise.

The observed NVH improvement can be interpreted as resulting from the reduction in the magnetic field reaching the target structure after the mesh shield is introduced, which consequently reduces magnetic-field-induced vibration of the target. In addition, frictional energy dissipation between the interwoven wires may also contribute to suppressing vibration of the mesh shielding material itself.

#### 4. Conclusions

This study evaluated magnetic shielding materials not only from the conventional perspective of magnetic field attenuation but also from an NVH perspective that considers system vibration and noise. A magnetic shielding test setup and an electromagnetic finite-element model were developed, followed by numerical–experimental comparison and comparative and parametric analyses. In addition, a mesh-type magnetic shielding material composed of steel wires was experimentally evaluated to investigate magnetic field attenuation and the resulting changes in target-structure vibration and system noise.

First, a magnetic shielding test setup consisting of a core and coil for generating an AC magnetic field and a Gauss meter for magnetic field measurement was developed. A corresponding electromagnetic finite-element model with the same geometry was then established. The magnetic field attenuation associated with different plate-shield thicknesses was compared between the numerical and experimental results. Both approaches showed similar trends with increasing shield thickness, and the difference between the numerical and experimental magnetic-field reduction ratios, calculated relative to their corresponding unshielded conditions, was within approximately 3 percentage points. These results provided a comparative basis for using the electromagnetic model to investigate the relative effects of shielding configuration and geometrical parameters under consistent numerical conditions.

The electromagnetic model was subsequently used to comparatively investigate the effects of shielding configuration and the structural parameters of mesh-type shields. Configurations surrounding either the magnetic field source or the target provided higher shielding performance than the single-sided plate configuration, with target-side shielding showing particularly effective magnetic field attenuation. Comparison of the plate-, mesh-, and spot-type structures showed that the mesh structure, in which the ferromagnetic material forms a continuous magnetic flux path, achieved shielding performance comparable to that of the plate structure under the investigated conditions. In contrast, the spot-type structure, in which the ferromagnetic regions were disconnected, exhibited lower shielding performance. These results indicate that, for low-frequency magnetic shielding, establishing a continuous low-reluctance path for magnetic flux shunting is an important design consideration in addition to the total amount of shielding material.

The parametric analysis of the mesh-type shielding material showed that magnetic shielding performance generally improved as the open-area ratio decreased and the shield thickness increased. For a mesh structure with an open-area ratio of 80%, the shielding performance increased as the thickness approached approximately 1 mm, whereas further increases in thickness resulted in only limited improvement and the performance tended to converge. These results suggest that, from an engineering design perspective, mesh-type

shields should maintain continuous ferromagnetic paths, while the open-area ratio and thickness should be selected to provide sufficient magnetic flux-shunting capacity without unnecessary material usage. Under the investigated conditions, increasing the thickness beyond approximately 1 mm provided only limited additional shielding benefit for the 80% open-area mesh. Although a larger effective ferromagnetic cross-sectional area may improve shielding performance, the independent effect of wire diameter could not be isolated in the present experiments and should therefore be considered together with the open-area ratio and the amount of ferromagnetic material. Finally, two steel-wire mesh shields with similar open-area ratios but different wire diameters were experimentally evaluated in terms of both magnetic shielding and NVH performance. The meshes with wire diameters of 0.254 and 0.635 mm provided magnetic shielding effectiveness values of approximately 1.20 and 3.73 dB at 3 kHz, respectively, compared with the unshielded condition. In particular, when the 0.635 mm wire mesh was applied, the dominant 6 kHz vibration component of the target structure decreased by approximately 55.8%, while the system noise was reduced by approximately 5 dB.

These results demonstrate that appropriately designed magnetic shielding can reduce not only the magnetic field reaching a target structure but also the associated structural vibration and system noise. Therefore, the design and evaluation of magnetic shielding structures for electric drive and other electromagnetic systems should consider the coupled relationship among magnetic field, structural vibration, and noise rather than focusing solely on magnetic shielding performance. These findings highlight the potential of mesh-type magnetic shielding to attenuate audible-frequency magnetic field ripple while improving system-level NVH performance, providing a basis for its application to electric vehicle battery systems and other electromagnetic systems.

Future work will focus on developing a coupled electromagnetic–structural–acoustic multi-physics model to quantitatively distinguish the effects of key mesh design parameters, including wire diameter, open-area ratio, and thickness, on magnetic shielding and NVH performance, thereby establishing a systematic design methodology for mesh-type magnetic shielding structures. In parallel, a standardized magnetic shielding–NVH evaluation procedure should be established by measuring magnetic-field attenuation, structural vibration, and acoustic response under identical excitation and geometric conditions and by reporting these responses using consistent evaluation metrics.

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## Abbreviations

The following abbreviations are used in this manuscript:

|       |                                             |
|-------|---------------------------------------------|
| AC    | Alternating Current                         |
| DAQ   | Data Acquisition                            |
| DC    | Direct Current                              |
| FEM   | Finite Element Method                       |
| FFT   | Fast Fourier Transform                      |
| IPMSM | Interior Permanent Magnet Synchronous Motor |
| NVH   | Noise, Vibration and Harshness              |
| PLA   | Polylactic Acid                             |
| PMSM  | Permanent Magnet Synchronous Motor          |

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