Optimization of the design of radar-absorbing composite structures using response surface model with verification using scanning free space measurement

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ABSTRACT

In this paper, we propose an optimization method for the design of radar-absorbing structures (RAS) made of fiber reinforced plastic structures using a response surface model and a verification method using a scanning free space measurement (S-FSM) system. The two kinds structures designed were an RAS with a layer of carbon nanotubes (CNT) and an RAS with a periodic patterned carbon paste layer. In the optimal design, the objective function was set so that the absorbing frequency bandwidth had the maximum value, in order to have stealth functionality in the X-band. The RAS with CNT layer had a higher minimum reflection loss than that with carbon paste layer, and the absorbing frequency bandwidth was lower. Two specimens were fabricated on the basis of the analysis results, and the design results were verified by evaluating their electromagnetic performance using an S-FSM system capable of measuring reflection loss. As a result, it was confirmed that not only the electromagnetic performance of the specimen but also the defects caused by the manufacturing process could be detected using the S-FSM.

1. Introduction

To improve the survivability of fighters and reconnaissance aircrafts, stealth functions that evade detection by enemy radar are of utmost importance. The smaller the radar cross section (RCS) detected by the enemy radar, the better the stealth performance. Therefore, many researchers are studying various methods to reduce RCS [1–4].

Optimizing the shape of the object, using a radar absorbing material (RAM), or using radar absorbing structures (RAS) are methods for reducing the RCS. The goal of shape optimization is to scatter incident electromagnetic waves in the radar-free direction to reduce the RCS, but there are limitations to this application. A high impedance structure (HIS) proposed by Sievenpiper [5] in 1999 absorbed electromagnetic waves because it had the same characteristics as an artificial magnetic conductor (AMC) at a specific frequency; an HIS is one type of RAS. RAS includes not only HIS but also various structures with frequency-selective surfaces (FSS) or carbon nanotube (CNT) layers [6–9].

Recently, many researchers have proposed various types of RAS to reduce RCS. Filippo Costa [10] designed an RCS-reduction structure with multiple layers of FSS applied and predicted its performance using an equivalent circuit model. Lee [11] proposed a frequency selective fabric composite (FSFC), having characteristics similar to an FSS, formed by weaving a specific pattern of carbon fiber and dielectric fiber. In addition, since the absorption rate of the electromagnetic waves is highly dependent on the dielectric property of the nanocomposite [12], an optimal design for an RAS covered with one layer, considering both the dielectric property of the nanocomposite and the absorption characteristics of the electromagnetic wave, was performed [13]. Since RAS are mainly applied to fighters to implement stealth functionality, their mechanical rigidity must be ensured, in order for them to withstand the operating environments of the fighters. Therefore, it is necessary to design RAS that can satisfy both electrical and mechanical performance requirements by applying composite material having excellent mechanical properties inside the RAS.

In this study, two kinds of RAS based on glass fiber reinforced plastic (GFRP) were optimized using a response surface model; then, the specimens were fabricated, and their electromagnetic performance was measured using scanning free space measurement (S-FSM) [14]. The two kinds of structures designed were an RAS covered with a CNT layer and an RAS with a periodic-patterned carbon paste layer. In the case of the RAS covered with CNT, the optimum design was performed considering the CNT content and thickness, GFRP thickness, and
manufacturing tolerances. In the case of the RAS with the carbon paste, the optimum design for a rectangular pattern was performed using a response surface model for optimization, to intuitively and easily understand the relationship between the design variables and the objective function. Based on the optimum design results, the specimens were fabricated and their electromagnetic performance was evaluated and verified by F-SFM.

2. Modeling of radar absorbing structures

2.1. Radar absorbing structure using a CNT layer

In case of an RAS with a CNT layer, as shown in Fig. 1, a spacer is added between the CNT layer and the perfect electric conductor (PEC) to absorb the electromagnetic waves through wave cancellation caused by the phase difference between the incident electromagnetic wave and the electromagnetic wave reflected by the PEC [15,16]. The frequency at which the wave cancellation occurs depends on the dielectric constant and the thickness of the material. In the conventional method [17,18], the absorbing frequency is calculated using the relationship between the permittivity and the wavelength, as shown in eqs. 1 and 2. The equations express that the incident electromagnetic waves and the electromagnetic waves reflected by the PEC cancel each other. Using this method, the appropriate thickness of RAS was calculated, based on the CNT content, so that the absorbing frequency was 10 GHz. The reflection loss result is shown in Fig. 2. The spacer was made of GFRP. It was confirmed that the absorbing frequency was 10 GHz; however, the absorption efficiency markedly decreased as the CNT content increased. Generally, as the content of CNT increases, the tangent loss increases. However, because the absorption efficiency was calculated without considering the change in tangent loss, this method did not satisfy the desired electromagnetic performance. Additionally, since the method considered only the absorbing frequency, the absorbing frequency bandwidth was narrow. Therefore, it was necessary to design the RAS considering the electromagnetic properties of the material and the required electromagnetic performance.

\[ t_1 = \frac{1}{4} = \frac{\lambda_0}{4\sqrt{\varepsilon_{CNT}}} \]  

(1)

\[ t_2 = \frac{1}{2} = \frac{\lambda_0}{2\sqrt{\varepsilon_{GFRP}}} \]  

(2)

(where \(2(t_1 + t_2) = (n + 1/2)\lambda, \ n = 1\))

To evaluate the electromagnetic performance while considering the electromagnetic properties, the optimal design was performed using eqs. 3–5. The equations are reflected in transmission/reflection characteristics of plane wave when a uniform plane wave is incident on the boundary between regions composed of two different materials. Therefore, accurate reflection loss can be calculated because electromagnetic properties are considered. To calculate reflection loss, propagation constant (\(k_{CNT}\)) and the intrinsic impedance (\(Z_{CNT}\)) are needed and calculated using the permittivity (\(\varepsilon\)) and permeability (\(\mu\)) of materials. The objective function must be determined in order to define the optimization. If the objective function simply maximizes the absorption rate at the absorbing frequency, the absorption rate at the other frequencies could be lowered. Generally, an RAS, as shown in Fig. 1, is applied to the surfaces of aircrafts or warships for stealth functions. Since the frequency of the radar used by one’s enemies is unknown, it is necessary to absorb electromagnetic waves in a wide range of frequency bands. Therefore, the objective function was defined so that the frequency bandwidth was maximized based on -10 dB. The spacer, thickness of the CNT layer, and CNT content were used as constraint conditions. GFRP was used as the spacer material to ensure mechanical rigidity. Finally, the optimization problem can be defined as shown in Fig. 3. CNT layer was made by mixing CNT and matrix (PA66). And the dielectric constant and tangent loss of the CNT layer vary depending on their content. The electromagnetic properties of the CNT layer used for the optimum design in this study are shown in Fig. 4. Real part of permittivity (\(\varepsilon^r\)) increases linearly with increasing CNT content, and the imaginary part of permittivity (\(\varepsilon^i\)) increases quadratically with increasing CNT content. Diameters of CNT is 8–12 nm and lengths of the tubes range from 1 to 100 \(\mu\)m.

\[ \eta_\alpha = \eta_{GFRP}\tanh(\beta_{GFRP}t_{GFRP}) \]  

(3)

\[ \eta_\beta = \eta_{CNT}\cos(\beta_{CNT}t_{CNT}) + \eta_{CNT}\sin(\beta_{CNT}t_{CNT}) \]  

\[ \eta_\beta = \eta_{CNT}\cos(\beta_{CNT}t_{CNT}) + \eta_{CNT}\sin(\beta_{CNT}t_{CNT}) \]  

(4)

\[ \Gamma = \frac{\eta_\alpha - \eta_\beta}{\eta_\alpha + \eta_\beta} \]  

(5)

To analyze the relationship between the design variables and the objective function, an optimal design, according to the CNT content, was performed using a response surface model. The absorbing frequency bandwidth variations as related to the CNT content and thickness are shown in Fig. 5. Fig. 5(a) shows the optimal thickness, when the absorbing frequency bandwidth was maximal, as related to the CNT content. As the CNT content increased, the thickness of the CNT

Maximize \[ |f_1 - f_2|, \ 20\log|\Gamma(f_1,f_2)| = -10\text{dB} \]

(Absorbing frequency bandwidth satisfying reflection loss < -10dB)

Subject to \[ 0.1<\text{thickness of CNT Layer}<10 \]  

0.5<thickness of GFRP<20 \n
1%<CNT wt.%<30% \n
8GHz<Absorbing frequency<12.5GHz

Fig. 3. Optimization problem definition.
decreased and the thickness of the GFRP increased. As the CNT content increases, the loss tangent increases, so the propagation constant ($\beta_{CNT}$) increases and the intrinsic impedance ($\eta_{CNT}$) decreases. As the propagation constant increases, the thickness of the CNT must be reduced, and as the intrinsic impedance decreases, the thickness of GFRP increases because $\eta_a$ (Eq. (3)) must increase. Fig. 5(b, c, and d) shows the absorbing frequency bandwidth related to CNT content and thickness. When the thickness of the CNT was greater than 1 mm or the thickness of the GFRP was greater than 4 mm, these data points were excluded from the graph because the absorbing frequency bandwidth was small. When the content of the CNT was 5%, the absorbing frequency bandwidth was greater than 1 GHz, for the range of 0.5 mm to 1 mm CNT thickness and 0.5 mm to 2 mm GFRP thickness. However, as the CNT content increased, the thickness range for the absorbing frequency bandwidth over 1 GHz gradually became narrower, and the absorbing

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Fig. 4. Electromagnetic properties of the CNT layer.

Fig. 5. Response surface models of RAS with CNT layer (a) optimization results (b) CNT 5%wt. (c) CNT 10%wt. (d) CNT 15%wt (The circles indicate maxima).

Fig. 6. Absorbing frequency bandwidth related to manufacturing tolerance.
frequency bandwidth increased. Therefore, in order to widen the absorbing frequency bandwidth, the CNT content should be increased, and CNT thickness should be less than 0.1 mm. However, when the CNT layer is thinned, the absorbing frequency bandwidth was drastically changed, even if the thickness of the CNT layer was slightly changed, as shown in Fig. 5(d). Since the thickness of the CNT layer is sensitive, a robust design is necessary by considering manufacturing tolerances to the CNT layer thickness.

To evaluate the sensitivity to the CNT thickness, it was necessary to know how the absorbing frequency bandwidth decreased in consideration of fabrication tolerances. The absorbing frequency bandwidth as related to the CNT content and manufacturing tolerance is shown in Fig. 6. The manufacturing tolerance for the thickness of CNT layer was assumed to be 0.01 mm, and the manufacturing tolerance for the GFRP thickness was assumed to be 0.03 mm through the conversation of manufacturer. As a result, it was confirmed that the absorbing frequency bandwidth increased as the CNT content increased if the influence of the manufacturing tolerances was not considered. However, when these manufacturing tolerances were considered, it was confirmed that the absorbing frequency bandwidth did not increase, even when the CNT content increased. In contrast, when the CNT content was 25% or greater, the absorbing frequency bandwidth was slightly decreased. Therefore, the best stealth performance was realized when the content of CNT having an almost similar absorbing frequency bandwidth was 10%–25%. When considering manufacturing in the design, the effect of the manufacturing tolerance should be minimized so that reliable performance can be ensured. Therefore, the difference between the absorbing frequency bandwidths with and without the tolerance should be small. The difference in the absorbing frequency bandwidth due to the tolerance is shown in Fig. 7. There was no effect due to the manufacturing tolerances of the GFRP, and when the CNT content was greater than 10%, the absorbing frequency bandwidth due to the tolerance of the CNT was greatly increased. Therefore, an optimal design, considering not only performance but also manufacturing tolerances, resulted when the CNT content was 10%, as the absorbing frequency bandwidth was the greatest. The reflection loss of this optimal design is shown in Fig. 8. In optimal design, CNT thickness is 0.25 mm and GFRP thickness is 2.3 mm.

2.2. Radar absorbing structure using the periodic patterned carbon paste

An RAS is used to absorb electromagnetic waves by applying a CNT layer or an FSS. The FSS has the characteristic of transmitting or reflecting electromagnetic waves in a specific frequency band with its designed periodic-pattern shape. In generally, FSS is used as a RAS with a dielectric inserted between PEC and FSS. The electromagnetic waves passing through the FSS repeat the reflection inside the dielectric due to the FSS and the PEC, and the electromagnetic waves are absorbed or canceled in this process. In this study, an RAS was designed by applying a cyclic pattern using carbon paste having electromagnetic characteristics similar to an FSS, as shown in Fig. 9. To analyze the electromagnetic characteristics of the periodic patterns of the carbon paste, an electromagnetic analysis was performed using a commercial electromagnetic analysis software, HFSS. A simple square shape was used as the pattern of the carbon paste, and the analysis model is shown in Fig. 9(b). A unit cell model was used, and a periodic boundary condition was applied. The PEC layer was replaced by a perfect electric boundary condition without modeling, and the incident wave was modeled using a Floquet port. The design parameters of the carbon paste pattern included the size of the square shapes and the interval between the shapes. To compare the electromagnetic performance when the periodic patterned carbon paste layer replaced the CNT layer, the analysis was performed by applying the same thickness (2.3 mm) as an RAS covered with the CNT layer.

The absorbing frequency bandwidth and peak value of reflection loss according to pattern shape are shown in Fig. 10. As a result, it was confirmed that the trends of the absorbing frequency bandwidth and peak value of reflection loss in the X-band were different from each other. Therefore, as discussed previously, it can be confirmed that the absorbing frequency bandwidth may not be maximized when the conventional method [17,18] is applied to the absorbing frequency. The results for the largest absorbing frequency bandwidth and the largest peak value of reflection loss are shown in Fig. 11. Since the absorbing frequency bandwidth should be wide in the case of stealth performance, a pattern with the largest absorbing bandwidth would be more suitable than a pattern with the largest peak value of reflection loss. However, when these patterns are actually applied, the performance is sensitive to the number of unit cells [19]. Since the analysis model assumed an infinitely arranged unit cell was used, it is necessary to design the pattern considering the actual number of unit cells. The easiest method to reduce the influence of the number of unit cells is to reduce the size of the unit cell. Therefore, a constraint condition on the size of the unit cell was added to the analysis, limiting the size of the unit cell to 8 mm. The constraint condition of the unit cell size depends on the curvature of object or size of the shape [19,20]. When the constraint condition of the unit cell size was added, a pattern with a 5-mm square shape and an interval of 3 mm between the shapes had the widest absorbing frequency bandwidth. The reflection loss of the optimal design in the X-band is shown in Fig. 12.
3. Measurement of RAS specimens using s-fsm

Based on the optimal design results, RAS specimens with a CNT layer and a periodic patterned carbon paste were fabricated. For the RAS with the CNT layer, the layer was made of a mixture of resin and CNT and then attached to GFRP. The periodic-patterned carbon paste layer was made by printing with masking metal onto a PI film, then co-
cured by laminating with a glass fiber prepreg. The PEC layer was made by adhering copper tape to the back of both specimens. The specimens were 990 mm × 990 mm and are shown in Fig. 13.

The electromagnetic performance of an RAM and RAS are usually measured using a waveguide or free space measurement (FSM) system. Because of the difficulty with measuring patterned specimens using the waveguide method, electromagnetic performance is often evaluated...
using FSM. Since, in conventional FSM, the reflection loss is measured for the specific area corresponding to a microwave spot size, the full-field electromagnetic performance cannot be measured for full-scale parts. Therefore, even if there are incorrect design areas, manufacturing defects, or damage to the specimen, it is difficult to detect them. Consequently, in this study, we proposed a design verification method using S-FSM, which is capable of scanning an entire area at an interval of 25 mm, as shown in Fig. 14. The S-FSM can scan the complete area of the specimen while moving the specimen on the X-Y scan stage, and can record the electromagnetic characteristics according to the position of the specimen. The spot diameter of the focused horn antenna was 60 mm, the measurement area was 950 mm × 700 mm, and the measurement interval was 25 mm. The measurement conditions are summarized in Table 1.

The vector network analyzer (VNA) of the S-FSM system was triggered at each scan point to measure the reflection loss and report the data back to the PC. The measurements were stored in a three-dimensional array with one dimension each for height, width, and frequency. These data could be viewed in a frame-wise fashion in terms of frequency, which can be thought of as slicing the three-dimensional array across the frequency axis. The reflection loss map versus the frequency

Table 1
Measurement conditions of S-FSM.

<table>
<thead>
<tr>
<th>Scan Area (mm)</th>
<th>950 × 700-25</th>
<th>Frequency range</th>
<th>8.2–12.4 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweep points</td>
<td>401</td>
<td>Spot diameter</td>
<td>60 mm</td>
</tr>
<tr>
<td>Focal length</td>
<td>430 mm</td>
<td>Scan interval</td>
<td>25 mm</td>
</tr>
</tbody>
</table>

Fig. 13. (a) RAS specimen applied with CNT layer (b) RAS specimen applied with carbon paste.

Fig. 14. Scanning Free Space Measurement system.

Fig. 15. Results of RAS covered with CNT (a) Scanning image (b) Reflection loss.
carbon paste was not uniform in its reflection loss. On the other hand, as shown in Fig. 16(a), the RAS with the CNT layer had a minimum reflection loss of $-35$ dB and an absorbing frequency bandwidth of $3.15$ GHz. When designing radar-absorbing structures (RAS) for the X-Band, previous researchers used a design method that simply tuned to the frequency to be absorbed. In many cases, since the absorption rate in other frequency bands was not considered, the required stealth performance may not have been optimized. Therefore, in this study, a novel RAS development process was proposed, to improve the optimum design/performance evaluation/design improvement, as shown in Fig. 17. To improve the stealth performance, an optimal design that maximized the absorbing frequency bandwidth was performed and an optimal design method, using a response surface model, was proposed. In addition, for design verification, a scanning free space measurement (S-FSM) system was proposed to evaluate the full-field electromagnetic performance. The scanning is necessary to predict how the electromagnetic performance varies depending on the manufacturing process or shape and so that these results can be reflected in further design improvements.

To verify the proposed process, the optimal design of two types of RASs based on glass fiber reinforced plastic (GFRP) was performed and was verified by S-FSM. The first structure type, the RAS covered with the CNT layer was optimized by considering the CNT content and thickness, GFRP thickness, and manufacturing tolerances. For the second type of RAS, the CNT layer was replaced with a periodic-patterned carbon paste layer and the optimal design of the pattern was performed. In the optimal design, the objective function was set so that the absorbing frequency bandwidth had the maximum value, in order to have the stealth functionality in the X-band. Based on the optimal design, an RAS with the CNT layer had a minimum reflection loss of $-35$ dB and an absorbing frequency bandwidth of $3.15$ GHz. The RAS with carbon paste had a minimum reflection loss of $-32.4$ dB and an absorbing frequency bandwidth of $3.75$ GHz. Based on the analysis results, two specimens were fabricated and their electromagnetic performances were evaluated using S-FSM to measure the reflection loss. Based on these measurements, uniform reflection loss values were obtained for all regions of the RAS with the CNT layer because the optimal design considered the manufacturing tolerances. However, non-uniform measurement results were obtained for the RAS with carbon paste, due to manufacturing problems, because the specimen was not designed considering the manufacturing tolerances. Therefore, in future, it is necessary to study the optimum design method using reliability-based design optimization (RBDO) in order to consider the manufacturing tolerances of the RAS with carbon paste.
Through the process proposed in this study, it is possible to improve the optimum design and design to further improve the stealth performance. In addition, S-FSM was able to detect not only the electromagnetic performance but also the defects caused in the manufacturing process.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.compstruct.2017.11.075.

References
