Broadband Radar Absorbing Structures with a Practical Approach from Design to Fabrication

Won-Ho Choi¹ · Woon-Hyung Song¹ · Won-Jun Lee^{2,*}

Abstract

In this study, a novel broadband radar absorbing volume structure (RAVS) is proposed and demonstrated with a practical point of view from design to fabrication. The proposed RAVS uses a design concept of repeatedly stacked carbon nanotube (CNT) composites and foam cores of the same thickness to improve the applicability to real structures while maintaining absorption performance. The repeatedly stacked CNT composites, which act as electrically lossy materials, result in the multiple scattering of incident electromagnetic waves trapped inside the structure. The trapped incident waves then lose their energy by multiple scattering. Based on this design concept, the RAVS designed through field analysis and parametric study achieved a -10 dB absorption performance from 4 GHz to 16 GHz. With reference to the design values, RAVS was fabricated for verification, and the absorption performance was measured using a free space measurement system. The measurement result showed excellent absorption performance that satisfied -10 dB from 5.8 GHz or less to 14 GHz.

Key Words: Low Observable Aircraft, Multi-Functional Composites, Radar Absorbing Structure, Smart Structures.

I. INTRODUCTION

A radar absorbing structure (RAS) is a multifunctional composite structure that simultaneously has load-bearing and electromagnetic (EM) wave absorption functions. The goal of RASs is to reduce the radar cross-section (RCS) of the target and increase its survivability [1].

In recent years, RASs have been actively researched and implemented in various forms with various types of absorbing materials. Although previously reported RASs can effectively reduce RCS through their unique absorbing materials and/or by changing the lay-up structure to optimize the absorption performance [2–12], most of the proposed RASs have been focused on the X-band (8.2–12.4 GHz).

When the radar absorber is designed for a narrowband application and radar frequencies other than the design frequency, the design values deviate from the optimal values, significantly degrading the absorption performance. Moreover, the performance of narrowband designs is sensitive to fabrication tolerance. Therefore, a robust design considering the changes in radar frequencies and fabrication tolerance is required.

The Jaumann absorber is the representative broadband absorbing structure [1, 13–15]. It is a multilayered structure that consists of dielectric spacers and resistive sheets. Although the Jaumann absorber can perform broadband absorption, the dielectric thickness and resistance of each layer should have different design values for optimal performance. Despite its excellent absorption performance, such a structure is burdensome at the

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time of fabrication because there are many design parameters to be controlled. In addition, although the absorption performance in the planar structure is excellent, the absorption performance on a planar structure cannot be fully achieved when applied to curved structures [16]. Choi and Kim [17] reported a broadband radar absorbing honeycomb structure with a design concept that uses the transverse direction of the hexagonal passages to increase the effective thickness. The researchers have presented a design concept that utilizes the entire volume of a leading-edge structure. However, when the full-depth honeycomb core is applied to such a leading-edge shape, the additional composite materials should be laminated for fastening with other parts. In this case, the bonding strength at the interface between the honeycomb core and the additional laminated composite is likely to be weak because of the small contact area. Although the proposed broadband radar absorbing honeycomb structure shows an outstanding absorption performance, there is limited applicability to the leading-edge shape, which is essential for reducing RCS over a wide frequency range.

To resolve such issues, this study proposes a broadband radar absorbing volume structure (RAVS) that uses the entire volume of the structure for EM wave absorption. To improve applicability and manufacturability, the proposed RAVS uses a structure in which the carbon nanotube (CNT) composites and foam cores are repeatedly stacked with the same thickness. The repeatedly stacked CNT composites, which act as electrically lossy materials, trap the multiple scattering of incident EM waves inside the structure. The trapped incident waves then lose their energy by multiple scattering.

Fig. 1 shows the application concept of the proposed RAVS using the leading-edge shape. As shown in Fig. 1(a), first, a core block in which foam cores and CNT composites are repeatedly stacked is fabricated, and the fabricated core block is machined according to the shape to be applied. Finally, the machined core block is stacked with other composite materials for autoclave cure. Fig. 1(b) shows the final form of the RAVS applied to the leading-edge shape. As shown in Fig. 1(b), because the interface between the core block and the composite shear web is bonded face-to-face, the bonding strength can be increased compared with the radar absorbing honeycomb core.

II. MATERIAL PREPARATION

To design a broadband RAVS, CNT prepreg, foam core, and glass fiber reinforced polymer (GFRP) were prepared. Here, CNT prepreg refers to the prepreg coated on the glass fabric with CNT-dispersed epoxy resin. The role of a CNT is to increase the loss tangent of resin. The CNT is a multi-walled design purchased from Carbon Nanotech, Pohang, Korea. Carbon purity was greater than 95%, and the average diameter was 15

Fig. 1. Schematic diagram of the application concept of the RAVS: (a) fabrication of the core block and (b) final form of the RAVS in a leading-edge shape.

nm. To fabricate the CNT prepreg, the prepared CNT powder was dispersed in epoxy resin using a planetary mixer. The final CNT content of the mixed constituent material was 3.0 wt%. Using a prepreg manufacturing machine, the mixed constituent materials were coated on a dry glass fabric. The GFRP and foam core used for the RAVS were purchased from Cytec (Cycocom), Brussels, Belgium and Evonik (Rohacell), Essen, Germany, respectively.

A free space measurement system was used to measure the permittivity of the prepared composite materials [18, 19]. The free space measurement system consists of two spot-focusing horn antennas, a sample holder, and a network analyzer. The role of the spot-focusing horn antennas is to minimize measurement inaccuracies caused by scattering at the edge of the specimens. By replacing the focusing horn antennas with different frequency bands, the system can measure in the frequency range of 5.8–18 GHz. The through-reflect-line (TRL) calibration technique and time-domain gating were used to eliminate undesirable reflections. The free space measurement system was controlled using a computer connected with a general-purpose interface bus cable.

Fig. 2 shows the measurement results for the broadband permittivity characteristics. As shown in Fig. 2(a) and (b), the permittivity of the GFRP and foam core did not significantly depend on the frequencies. However, in the case of the CNT-composite, the change in permittivity exhibited a frequency de-

pendence due to the effects produced by the dispersion of the conductive CNT fillers in epoxy resin.

III. DESIGN PRINCIPLES

To design a radar absorber, the theoretical relationship between thickness and material properties should be understood. Rozanov and his colleagues [20, 21] reported the theoretical bandwidth limitations of radar absorbers for a given thickness and set of material properties. In the case of a multi-layer absorber, the largest possible bandwidth for a given physical thickness and permeability can be written as:

$$|\ln \rho_o| \Delta \lambda < 2\pi^2 \sum_j \mu_{s,j} d_j \quad (1)$$

where ρ_o is the desired reflection coefficient, $\Delta \lambda$ is the bandwidth defined by $\Delta \lambda = \lambda_{max} - \lambda_{min}$ (λ_{max} and λ_{min} are the wavelengths at the lower and upper band edge, respectively), and $\mu_{s,j}$ and d_j are the static permeability and thickness at each layer, respectively. As described in Eq. (1), to enlarge the bandwidth of the radar absorber, the permeability and thickness of each layer should be large. Generally, magnetic materials are beneficial for implementing broadband absorbing performance. However, in the case of the radar absorber using magnetic materials, a large number of magnetic particles should be impregnated in the matrix for a sufficient absorption performance in the high-frequency ranges. This approach is accompanied by a weight increase. Moreover, because having too many magnetic particles negatively impacts the mechanical properties, magnetic absorbers are not suitable as a load-bearing composite structure [22]. However, in the case of non-magnetic materials, according to Eq. (1), the absorption bandwidth is only controlled by thickness; that is, if the total thickness increases, the weight increases. Therefore, to minimize the weight increase, a low-density foam core was used as the primary material.

For the design of the RAVS, the transmission line Eq. (1) was used and is written as Eqs. (2) and (3) as follows:

$$\eta_{n+1} = \eta_n \frac{\eta_{n-1} + j\eta_n \tan(k_n d_n)}{\eta_n + j\eta_{n-1} \tan(k_n d_n)} \quad (2)$$

$$\rho = \frac{\eta_{n+1} - \eta_o}{\eta_{n+1} + \eta_o} \quad (3)$$

Using Eqs. (2) and (3), the input impedance and reflection coefficient of the multilayered structures were calculated. Here, η_{n+1} is the input impedance on the surface of the absorber; η_n and η_{n-1} are the impedances in the n^{th} and $n-1^{\text{st}}$ layer, respectively; k_n is the wave number in the n^{th} layer; and d_n is the thickness in the n^{th} layer.

Unlike conventional radar absorbers, the proposed design concept uses the attenuations of EM waves by multiple scattering. Fig. 3 shows the principles of the design concept of the

Fig. 2. Permittivity measurement results: (a) GFRP, (b) foam core, and (c) CNT composite.

Fig. 3. Principles of the RAVS: (a) ray interactions and (b) field intensity distribution.

RAVS through ray interaction analysis and field analysis. Note that although Fig. 3(a) illustrates the case of oblique incidence differently from Fig. 3(b), this is only for convenience of explanation because the ray trajectory is visible at the oblique incidence. In Fig. 3(a) when the incident wave impinges on the surface of the RAVS, the EM waves are trapped inside the RAVS. These trapped EM waves proceed to lose their energy by successive transmissions and reflections by the repeatedly stacked CNT composites. As a result, the field intensity decreases as the EM waves propagate from the surface to the bottom of the RAVS as shown in Fig. 3(b). Here, the small peaks denoted in the field intensity graph as triangle symbols indicate the presence of reflections and transmissions due to the difference in the wave impedance of the foam core and the CNT composite.

As shown in Figs. 1 and 3, the proposed RAVS has a structure stacked with the same thickness of CNT composites and foam cores. Such a design approach is different from the design concept of the conventional RAS in which the thickness of each layer is different for an optimal design. As the RAVS has few

design variables, it has the advantage of design simplicity and hence manufacturability.

IV. DESIGN OF THE RAVS

Fig. 4 shows the schematic diagram of the initial design configuration of the RAVS. Note that the number of CNT composite layers is $N-1$, where N is the number of foam cores.

First, to determine the design range, the absorption bandwidth for the change in thickness of the CNT composite and foam core was analyzed (Fig. 5).

Fig. 5(a) shows the -10 dB bandwidth for the change in thickness of the CNT composite and foam core. The target zone was set to a bandwidth greater than 10 GHz. However, there was no information on which frequency band the -10 dB bandwidth should cover. Therefore, as the X-band is the most important frequency band for RCS reduction, the return loss for the design variables within the target zone at 10 GHz was analyzed as shown in Fig. 5(b). The return loss distribution shows that the best performance for the foam core thickness at 10 GHz was approximately 4 mm. To determine the number of foam cores, the return loss was analyzed depending on the number of foam core layers. Fig. 6 shows the return loss vs. the number of foam core layers at each frequency. As shown in the figure, the return loss converges at more than 10 layers of foam cores.

Return loss convergence can also be confirmed in the field distribution depending on the number of foam core layers. To simulate the field distribution in the RAVS, CST Microwave Studio [23] was used.

Fig. 7(a) shows the analysis unit-cell model of the RAVS

Fig. 4. Initial configuration for the design of the RAVS.

Fig. 5. Design procedures of the RAVS: (a) setup for the design target zone and (b) selection of design parameters.

Fig. 6. Change in absorption performance vs. the number of foam core layers.

with boundary conditions. Tangential fields, E_t and H_t , were set to 0 for the periodic boundary characteristic of the unit-cell. As shown in Fig. 7(b), compared with the foam cores with 7 and 13 layers, the foam cores with 10 layers were sufficient for the attenuation of field intensity. As the absorption mechanism of

Fig. 7. (a) Simulation model for field analysis with a boundary condition and (b) a field distribution depending on the number of foam core layers.

the RAVS is field attenuation trapped inside the structure by multiple scattering, no additional layers were found to be necessary when the RAVS was designed with sufficient layers. With reference to the analysis results, the thicknesses of the foam core and CNT composite were determined to be 4 mm and 0.3 mm, respectively, and the total numbers of foam cores and CNT composites were set to 10 and 9, respectively. In the following section, the proposed RAVS was verified through fabrication and measurement using the determined design parameters.

V. FABRICATION AND MEASUREMENT OF THE RAVS

The fabrication process flow for the RAVS is summarized in Fig. 8. With reference to the design values, the foam cores were machined to the designed thickness using a composite trim router. The thickness tolerance of the machined foam cores was less than 0.15 mm. In the lay-up step, two plies of GFRP were laid up on the tool, and then the CNT prepreps and foam cores were repeatedly stacked. As a ground material, a flexible copper clad laminate was laid up for fabrication simplification. After finishing the lay-up step, curing accessories, such as a non-perforated release film, breather, and bagging film, were placed onto the stacked RAVS specimen. The layered RAVS specimen was cured in an autoclave with the curing accessories for 120 minutes at 130°C. The cured specimen was cut to the di-

Fig. 8. Fabrication process flow of the designed RAVS: (a) GFRP and foam core lay-up, (b) CNT composite prepreg, (c) repetition of foam core and CNT composite prepreg, (d) lay-up of ground material, (e) vacuum bagging with curing accessories, and (f) auto-clave cured specimen.

mensions of $180 \text{ mm} \times 180 \text{ mm}$ to measure its absorption performance.

The absorption performance of the fabricated specimen was measured using the free space measurement system. Fig. 9(a) shows the free space measurement system with spot-focusing

horn antennas and a specimen inserted into the sample holder. In Fig. 9(b), the results of the measurement of absorption performance and the simulation in the frequency range of 5.8–18 GHz were compared. As shown in Fig. 9, the overall tendency of the measurement result was in good agreement with the simulation result, even though there was a small shift in the frequency at approximately 1 GHz from the simulation result due to the permittivity variation depending on the dispersibility of the CNT in epoxy. Furthermore, the fabricated RAVS satisfied the -10 dB absorption bandwidth at frequencies greater than 8.6 GHz. The proposed RAVS showed excellent absorption performance in terms of the absorption bandwidth. Although the proposed RAVS has a smaller absorption bandwidth of about 5 GHz than previously reported broadband radar absorbers [17], which utilize similar application concepts, the proposed RAVS is meaningful in that it improved the applicability by simplifying the structure and proposed a specific application concept.

VI. CONCLUSION

This study proposes a broadband RAVS to improve applicability and manufacturability. The proposed RAVS has a stacked structure of CNT composites and foam cores of the same thickness to simplify the structure by minimizing the design variables. The absorption mechanism of the RAVS is explained using multiple scattering by the CNT composite walls. The repeatedly stacked CNT composites, which act as electrically lossy materials, trap the multiple scattering of incident EM waves inside the structure. The trapped incident waves then lose their energy by multiple scattering. As an application concept of the RAVS,

Fig. 9. (a) Free space measurement system and (b) return loss measurement result of the fabricated specimen.

a core block is machined into the shape to be applied. The proposed RAVS has a smaller absorption bandwidth than previously reported broadband radar absorbers. However, it has an absorption performance of -10 dB or more in the C-band and X-band, which are important frequency bands at the radar frequency. From a practical point of view, this study provides an important concept and application method for the RAVS.

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