Composite Structures 186 (2018) 106–113

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

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

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ARTICLE INFO

Keywords:
Radar absorbing structure
Optimization design
Free space measurement
Carbon nanotube
Response surface model

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

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https://doi.org/10.1016/j.compstruct.2017.11.075
Received 22 August 2017; Received in revised form 31 October 2017; Accepted 24 November 2017
Available online 26 November 2017
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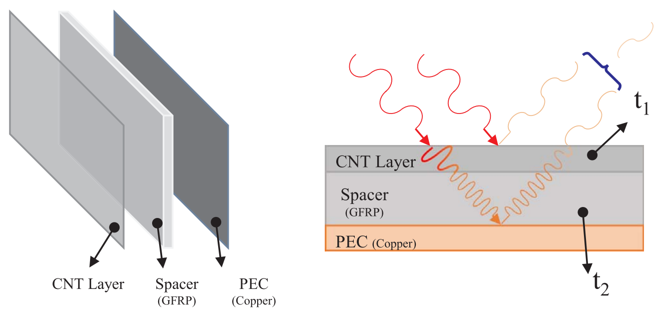

Fig. 1. RAS with CNT layer.

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 S-FSM.

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

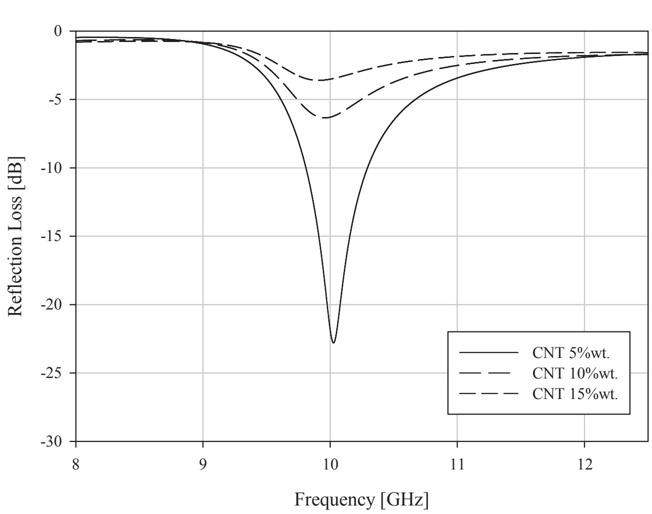

Fig. 2. Results of RAS with a CNT layer using conventional method [16,17].

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.

$$t_1 = \frac{1}{4}\lambda = \frac{\lambda_0}{4\sqrt{\varepsilon_{\mathrm{CNT}}}} \quad (1)$$

$$t_2 = \frac{1}{2}\lambda = \frac{\lambda_0}{2\sqrt{\varepsilon_{\mathrm{GFRP}}}} \quad (2)$$

(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 (β_{CNT}) and the intrinsic impedance (η_{CNT}) are needed and calculated using the permittivity (ε) and permeability (μ) 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 (ε') increases linearly with increasing CNT content, and the imaginary part of permittivity (ε'') increases quadratically with increasing CNT content. Diameters of CNT is 8–12 nm and lengths of the tubes range from 1 to 100 µm.

$$\eta_a = \eta_{GFRP}\tanh(j\beta_{GFRP}t_{GFRP}) \quad (3)$$

$$\eta_{in} = \eta_{CNT}\frac{\eta_a\cos(\beta_{CNT}t_{CNT}) + j\eta_{CNT}\sin(\beta_{CNT}t_{CNT})}{\eta_{CNT}\cos(\beta_{CNT}t_{CNT}) + j\eta_a\sin(\beta_{CNT}t_{CNT})} \quad (4)$$

$$\Gamma = \frac{\eta_{in}-\eta_0}{\eta_{in} + \eta_0} \quad (5)$$

(where $\beta = \frac{\omega}{c_0}\sqrt{\mu_r\varepsilon_r}$, $\eta = \sqrt{\frac{\mu}{\varepsilon}}$)

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 $|f_1 - f_2|$, $20log|\Gamma(f_1, f_2)| = -10\mathrm{dB}$

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

Subject to 0.1<thickness of CNT Layer<10
0.5<thickness of GFRP<20
1%<CNT %wt.<30%
8GHz<Absorbing frequency<12.5GHz

Fig. 3. Optimization problem definition.