The Effective Design Approach of Radar Absorbing Leading Edge Structure of Airfoil

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1. Introduction

Since radar absorbing structures function simultaneously as electromagnetic waves absorbing and load bearing structures, many structural elements such as horizontal and vertical stabilizers, wing skins, fuselage, and various structural elements can be replaced with radar absorbing structures to reduce the radar cross section (RCS). The key design parameters of radar absorbing structure are the thickness of layers for given permittivities, because the thickness is directly related to the impedance matching [1]. In most reported literatures, a planar interface between free space and a semi-infinite medium was used for the design of radar absorbing structures, in the context of electromagnetic wave reflections [2-5]. However, although the design approach is simple, it does not take into account curved surfaces and wave polarizations. Therefore, another design approach is necessary to design curved surfaces like the leading edge of an airfoil.

In this study, the planar surface approach and cylindrical layer approach to reduce the monostatic RCS of an airfoil was investigated by replacing the leading edge with RAS.

2. Material Preparation

To design the radar absorber, the implementable material properties should be known. 6 samples were fabricated to obtain the material properties or permittivities. Fig. 1(a) shows the fabricating process flow for the composite material. Multi-Walled Carbon Nanotubes (MWCNTs) were used as conductive fillers to increase the loss tangent. The weight % (wt %) of MWCNTs in the prepregs was split into 0, 0.4, 0.7, 1.0, 1.3, and 1.6 wt%. The mixed constituent materials were dispersed by a three-roll-mill, which uses shear force to disperse nanoparticles, producing uniformly dispersed composite materials. The prepregs were fabricated by using hand impregnated, and its thickness was controlled by the number of plies. Specimens were cured and vacuum bagged in an autoclave. After curing, composites were cut to the dimensions of an X-band rectangular waveguide, 22.86×10.16 mm. To reduce the errors by air-gap between the specimen and waveguide, the gap was sealed up with silver paste. To measure and calculate the material properties, HP 8722ES network analyser was used. The measured relative permittivities are shown in Fig. 1(b). Fig. 1(b) shows the dependence on the weight fraction of MWCNTs.

To design the multi-layered radar absorber, permittivities of 0.4 wt% and 1.6 wt% were used as shown in Fig. 1(b). The design code was linked with a genetic algorithm to obtain the optimum thickness of each layer. A center frequency of 10 GHz in the X-band was used for the design.

3. Results and Discussion

To design the radar absorbing structure for the leading edge of an airfoil, two different design approaches were used. One is the planar surface approach (Fig. 2(a)) using the transmission line impedance equation [6], and another is the cylindrical layer approach (Fig. 2(b)) using the
analytical solution of a cylindrically layered absorber [7]. For the planar surface approach, transmission line impedance equation written as

\[ Z_{n+1} = Z_n \frac{Z_{n+1} + jZ_n \tan(\beta_n d_n)}{Z_n + jZ_{n-1} \tan(\beta_n d_n)} \]  

(1)

was used. Eq. (1) gives the input impedance of layered media seen from the free-space to the absorber. Here, \( Z_{n+1} \) is the input impedance, \( Z_n \) and \( Z_{n-1} \) is the impedance of each layer from ground plane, \( \beta_n \) is the propagation constant of \( n \)-th layer, and \( d_n \) is the thickness of \( n \)-th layer. Finally, the reflection coefficient of the multi-layered absorber is calculated from Eq. (2) by using input impedance from Eq. (1). The \( Z_0 \) is the free space impedance in Eq. (2).

\[ \Gamma = \frac{Z_{n+1} - Z_0}{Z_{n+1} + Z_0} \]  

(2)

As another approach of the absorber design, backscattering solutions for a metallic cylinder layered with absorbing materials were used. For parallel polarization to the cylinder, the backscattered field from the layered cylinder is written as

\[ E_{\text{back-scatter}} = E^o \left( \frac{a}{2r} e^{ikr(2\pi d)} \left[ R - \frac{1}{k_o a} \zeta_E \right] \right) \]  

(3)

and the backscattered field for the vertical polarization to the cylinder is written as

\[ H_{\text{back-scatter}} = H^o \left( \frac{a}{2r} e^{ikr(2\pi d)} \left[ -R - \frac{1}{k_o a} \zeta_H \right] \right) \]  

(4)

Here, \( a \) is the outer radius of the cylinder, \( R \) is the reflection coefficient of the layered absorbing layer, and \( k_o \) is the free-space wave number. The expressions for \( \zeta_E \) and \( \zeta_H \) can be found in [7]. To calculate monostatic RCS, eq. (3) and (4) can be written as

\[ \sigma^E_{\text{back-scatter}} = \pi a \left[ R - \frac{1}{k_o a} \zeta_E \right]^2 \]  

(5)

\[ \sigma^H_{\text{back-scatter}} = \pi a \left[ -R - \frac{1}{k_o a} \zeta_H \right]^2 \]  

(6)

Fig. 3 shows the NACA0025 airfoil shape [8]. The leading edge of the perfectly conducting airfoil structure was replaced with radar absorbing materials as shown in Fig. 3. Fig. 4 is the calculated thickness of each layer by using calculation code linked with optimization code. Flat-plate optimum values calculated with eq. (2) show constant values, but cylindrical optimum value calculated with eq. (5) (parallel polarized to the cylinder was more effective) depends on its outer radius. It can be inferred that because the leading edge is not a planar surface but a curved surface, its optimum value will be different from the flat-plate optimum values, and it will depend on the wave polarizations.

To calculate the monostatic RCS of the airfoil, the commercial software package CST Microwave Studio was used [9]. The calculated monostatic RCS of the airfoil shape for the normal incidence on leading edge with the obtained combination of layer thicknesses in Fig. 4 is shown in Fig. 5. In case of using flat-plate optimum values, the monostatic RCS with H-pol was lower than that of V-pol. On the other hand, in case of using cylinder optimum values, the magnitude of the
monostatic RCS showed different behaviors from the flat-plate optimum values used. As shown in Fig. 5, when cylinder-optimum values obtained from large radius are used, the magnitude of RCS approached to that of RCS calculated with flat-plate optimum values in both polarizations. When small curvature is used for the calculation of optimum thicknesses, the optimum thicknesses approached to that of flat-plate optimum values as shown in Fig. 4. This is the cause behind the magnitude of the RCS approaching that of the RCS with flat-plate optimum values in both polarizations. As shown in Fig. 5, the planar-surface with Eq. (3) is simple, but, when the optimum-values are used in curved surfaces, this approach could not control effects of the wave polarizations. However, the cylindrical layer approach could control both polarizations, and the specific values can be chosen, which are more considered in wave polarizations.

4. Conclusion

In this study, planar surface approach and cylindrical layer approach were investigated to reduce the monostatic RCS of NACA0025 airfoil. Although the planar-surface approach is simple, it could not control both polarizations, and was only effective on one polarization. However, the cylindrical layer approach could control both polarizations and was more effective in controlling the absorbing performance for the wave polarizations.

Acknowledgments

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**Reference**


