Prediction and validation of electromagnetic performance of curved radar-absorbing structures based on equivalent circuit model and ray tracking method

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ABSTRACT

In this study, an equivalent circuit model and ray tracking method were used to predict the electromagnetic characteristics of curved radar-absorbing structures (RASs) applied with a frequency selective surface (FSS). After performing an electromagnetic analysis of FSS using a unit cell model, an equivalent circuit model reflecting the characteristics of the FSS was constructed. The equivalent circuit model of the FSS was applied to an equivalent circuit model for the RAS to evaluate the absorption performance as a function of the curvature and incident angle. Electromagnetic characteristics of the curvature structure were predicted by estimating the path of the electromagnetic wave using the ray tracking method. The calculated results were compared with the experimental results using free space measurements. Through this study, it was possible to estimate an equivalent circuit model reflecting the electromagnetic characteristics of the RAS with respect to the incident angle and curvature of the FSS. In addition, the electromagnetic performance of the entire curved structure was evaluated using the ray tracking method.

1. Introduction

A frequency selective surface (FSS) can transmit or reflect a specific frequency band. Therefore, many studies are being conducted, especially in the microwave engineering and optics fields, with a particular focus on topics like radio wave absorption, RCS reduction, and stealth radome [1–6]. The FSS is determined by various parameters, such as the shape and dimensions of the pattern, the permittivity of the surrounding material, its thickness, and the angle of the incident wave. The FSS has the same characteristics as a circuit with capacitance and inductance, and an equivalent circuit model can be used to analyze the electromagnetic characteristics of the FSS [7].

Various methods have been proposed to obtain the required electromagnetic performance and to analyze the electromagnetic characteristics. The electromagnetic performance of a multi-layer structure is predictable using simple equations [8]. The electromagnetic analysis of structures with specific patterns is performed by using electromagnetic simulation software [9]. Optimal design has been performed to satisfy the required electromagnetic performance using these analysis methods [10]. Filippo Costa [11] proposed a method for predicting the electromagnetic performance of a multi-layered structure with FSS using an equivalent circuit model. An FSS was proposed where the resonance frequency of the FSS can be changed using a PIN [12] and varactor diode [13]. Lee [14] proposed a frequency selective fabric composite fabricated by woven carbon and dielectric fibers. In the previous studies, the electromagnetic characteristics of a flat plate were analyzed. However, since applied shapes have curvature, it is necessary to analyze the electromagnetic characteristics in structures with curvature. B. Philips [15] used the ray tracking method to predict the transmission loss in structures with curvature. Z. Sipus [16] analyzed the structural curvature by approximating the curvature as a set of overlapping subarrays. Dazhi Ding [17] evaluated the curved structure by applying the multilevel fast multipole algorithm (MLFMA) to the volume-surface integral equation.

To analyze the FSS, numerical analysis techniques like finite-difference time-domain method and finite element method are primarily used. These techniques have high degrees of freedom for approximating complex shapes, but they require significant computational cost or are often impossible if the model to be analyzed is large. Therefore, to improve computational efficiency, an equivalent circuit model consisting of capacitance or inductance induced by the FSS shape can be constructed, and the electromagnetic characteristics can be analyzed more easily and quickly. In addition, if transmission line theory is applied to the equivalent FSS circuit model, it is possible to analyze the
electromagnetic characteristics of the structure applied with FSS, such as a radar-absorbing structure (RAS). However, most of the RAS is applied to the curved structural configuration, and since electromagnetic waves are incident at various angles, the equivalent circuit model should be designed by considering the incident angle.

In this study, an RAS applied with an FSS was designed and its electromagnetic characteristics were predicted by using an equivalent circuit model. An equivalent circuit model considering the incident angle was proposed. Electromagnetic analysis of the structural curvature was performed by applying the equivalent circuit model to the ray tracking method. In previous research into the ray tracking method [15], curved structural analysis was performed by simply applying the transmission/reflection coefficient at the transmitting/reflecting interface between each layer. This method is difficult to use when considering changes in the transmission/reflection coefficient due to thickness and curvature. Therefore, in this study, by using an equivalent circuit model and the ray tracking method, the electromagnetic characteristics of a curved RAS applied with an FSS were predicted in a structure with known curvature.

2. Analysis of curved radar-absorbing structures

2.1. Radar-absorbing structural design

To analyze the electromagnetic characteristics of an RAS depending on the curvature, an RAS with a square-loop-shaped FSS was designed, as shown in Fig. 1(a). Fig. 1(b) shows how a perfect electrical conductor (PEC) layer, a spacer layer, and a FSS are stacked, and the absorption frequency is 10.5 GHz. The analysis was performed using commercially available analysis software (HFSS), and a unit cell model was used to analyze the FSS using the Floquet theorem. The result is shown in Fig. 1(c).

2.2. Equivalent circuit model of FSS

An equivalent circuit model for an FSS with a square loop pattern is composed of a simple LC circuit. Since the designed FSS consists of two square loops, it is possible to convert an equivalent circuit model with two LC circuits connected in parallel, as shown in Fig. 2. The impedance of this equivalent circuit model can be calculated using Eq. (1). It has two reflection frequencies \( f_1, f_2 \), determined by two square loops, and it has one transmission frequency \( f_3 \) due to the interaction between the two square loops. Since the equivalent circuit model has the same electromagnetic characteristics as the FSS, it can be used as an analytical model that reflects the electromagnetic characteristics of the FSS.

\[
\eta_{\text{FSS}} = \frac{1}{j\omega C_1} \left( 1 - \omega^2 L_1 C_1 \right) \left( 1 - \omega^2 L_2 C_2 \right) \left[ \frac{L_1 L_2 (f_1 - \omega^2) (f_2 - \omega^2)}{j\omega (L_1 + L_2) (f_3 - \omega^2)} \right]
\]

\[
\eta_{\text{FSS}} = \frac{1}{j\omega C_1} \left( 1 - \omega^2 L_1 C_1 \right) \left( 1 - \omega^2 L_2 C_2 \right) \left[ \frac{L_1 L_2 (f_1 - \omega^2) (f_2 - \omega^2)}{j\omega (L_1 + L_2) (f_3 - \omega^2)} \right]
\]

\[
\left\{ \begin{align*}
  f_1 &= \frac{1}{\sqrt{L_1 C_1}}, \\
  f_2 &= \frac{1}{\sqrt{L_1 C_1 + L_2 C_2}}, \\
  f_3 &= \frac{1}{\sqrt{L_2 C_2}}
\end{align*} \right.
\]

The proposed equivalent circuit model can be compared with the HFSS results to calculate the value of the LC component according to the incident angle. However, in the case of FSS, the electromagnetic characteristics are determined by the dielectric constant and the permeability of the adjacent materials. According to previous research
2.3. Analysis of RAS applied with the FSS

Equivalent circuit model of the RAS applied with the FSS is shown in Fig. 5(a). Eqs. (2)–(5) can be obtained by applying transmission line theory to this equivalent circuit model. \( \eta_{\text{FSS}} \) is the equivalent impedance value calculated from the equivalent circuit model of the FSS obtained above. Impedance (\( \eta \)) and propagation constant (\( \beta \)) changes were considered according to incident TE and TM radiation at various angles. The unit cell model shown in Fig. 5(b) was used to compare the results of the equivalent circuit model and the unit cell model. Fig. 6 shows good agreement between the two models.

\[
\begin{align*}
\Gamma &= \frac{\eta_{\text{in}} - \eta_{\text{out}}}{\eta_{\text{in}} + \eta_{\text{out}}} \\
\eta_{\text{in}} &= \frac{\eta_{\text{FSS}} \eta_0}{\eta_{\text{FSS}} + \eta_0} \\
\eta_{\text{out}} &= \eta_{\text{FSS}} \eta_0 (\beta p + j \eta_{\text{FSS}}) \\
\eta_b &= \eta_{\text{FSS}} \eta_0 \eta_{\text{FSS}} (\beta p + j \eta_{\text{FSS}}) \\
\eta &= \eta_{\text{FSS}} \eta_0 \eta_{\text{FSS}} \tanh(\beta p + j \eta_{\text{FSS}}) \\
\end{align*}
\]

Where, \( \beta = \frac{\omega}{c_0} \sqrt{\mu \epsilon} \), \( \eta = \sqrt{\frac{\mu}{\epsilon}} \)

2.4. Curved structural analysis

To understand the electromagnetic characteristics of the curved structure, it is necessary to consider the influence of the curvature as well as the incident angle. A schematic of incident wave propagation in the curved structure is shown in Fig. 7. The wave incident at \( \theta_1 \) is transmitted at \( \theta_2 \) at the first interface, but the angle of incidence changes to \( \theta_2^f \) due to the curvature at the second interface. Therefore, \( \theta_1 \) and \( \theta_2 \) are different in the curved structure. Eqs. (6)–(9) are used to calculate the reflection coefficient of the curved structure. The values of \( L \) and \( \theta_2^f \) in the reflection coefficient equation can be simply expressed as functions of curvature and thickness. To confirm the effects of the incident angle and curvature, electromagnetic characteristics of the curved RAS can be obtained by applying the equations for the curved structure to the equivalent circuit model of the RAS.

\[
\begin{align*}
\Gamma_{\text{TE}} &= \frac{\eta_{\text{TE}} - \eta_{\text{L}}}{\eta_{\text{TE}} + \eta_{\text{L}}} \\
\eta_{\text{TE}} &= \eta_1 \cos(\beta_1 L \cos \theta_1) + j \eta_1 \sin(\beta_1 L \cos \theta_1) \\
\eta_{\text{TM}} &= \frac{\eta_{\text{TM}} - \eta_{\text{L}}}{\eta_{\text{TM}} + \eta_{\text{L}}} \\
\eta_{\text{TM}} &= \eta_2 \cos(\beta_2 L \cos \theta_2) + j \eta_2 \sin(\beta_2 L \cos \theta_2) \\
\end{align*}
\]

Where, \( \eta_1 = \eta \text{ sec } \theta_1 \), \( \eta_2 = \eta \text{ sec } \theta_2 \), \( \eta_3 = \eta \text{ sec } \theta_3 \), \( \beta = \frac{\omega}{c_0} \sqrt{\mu \epsilon} \), \( \eta = \sqrt{\frac{\mu}{\epsilon}} \), \( \beta_1 = \frac{\sin \theta_1}{\cos \theta_1} \)

\[
\begin{align*}
\eta_{\text{L}} &= \eta_1 \cos \theta_1, \quad \eta_{\text{L}} = \eta_2 \cos \theta_2, \quad \eta_{\text{L}} = \eta_3 \cos \theta_3, \\
\eta_{\text{L}} &= \eta_1 \cos \theta_1, \quad \eta_{\text{L}} = \eta_2 \cos \theta_2, \quad \eta_{\text{L}} = \eta_3 \cos \theta_3 \\
\end{align*}
\]
3. Ray tracking method

In this study, the electromagnetic performance of a curved structure is measured using a reflection loss measurement setup with a standard horn antenna. Therefore, the ray tracking method is required to understand the electromagnetic performance of the curved structure because the analysis in the previous sections was only able to obtain results for a single unit cell. Before performing the ray tacking method, it is necessary to understand how the electromagnetic waves from the standard horn antenna propagate. Therefore, near field analysis was performed using electromagnetic software (FEKO), and the results are shown in Fig. 8. As a result, it can be confirmed that the emitted radiation spreads radially, and it is possible to calculate the incident angle of the electromagnetic wave on the specimen. As shown in Fig. 8 (b), the energy density of the incident electromagnetic wave can be obtained from the Poynting vector. The incident angle and the energy density of the electromagnetic wave incident on the specimen were obtained by near field analysis, and the results were applied to the ray tracking method. The electromagnetic wave incident on the specimen was divided and applied to the ray tacking method. Also, the

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<th>TE Mode</th>
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<th>Equivalent circuit model</th>
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Fig. 4. Comparison between the unit cell model (HFSS) and the equivalent circuit model of the FSS.

Fig. 5. (a) Equivalent circuit model of RAS, (b) Unit cell model of RAS (HFSS).
electromagnetic characteristics of the curved RAS were predicted by calculating the reflection loss of the electromagnetic wave that returned to the standard horn antenna. The electromagnetic wave reflected from the RAS was calculated using the analytical method of the curved RAS proposed above.

4. Comparison of experimental and calculated results

To verify the calculated results for the curved RAS, a specimen was manufactured, as shown in Fig. 9. The size of the specimen was larger than that of the standard horn antenna. The FSS was fabricated by a photolithography process using a thin copper-coated polyimide film. Copper tape was used for the PEC. Fig. 10 shows the reflection loss measurement setup using a standard horn antenna. If the curvature specimen is measured in the far field, it is difficult to accurately measure the reflected electromagnetic waves because the amount of electromagnetic waves returns to the receiver antenna is small because of the curvature. Therefore, the electromagnetic performance according to the curvature was measured by reducing the measurement distance in the near field. Fig. 11 shows the results of the analysis and the experimental results. As shown in Fig. 11(a), it was confirmed that the absorption frequency increased with as the curvature increased. A curvature increase means that the ratio of the electromagnetic wave with large incident angles is increased. As the incident angle increased,
the absorption frequency increased, as shown in Fig. 6. Therefore, the absorption frequency increased as the curvature increased. In addition, it was confirmed that the reflection loss reduced as a whole because the electromagnetic wave returning to the standard horn antenna was reduced due to the curvature. As shown in Fig. 11(b), the calculated results show the same characteristics as the experimental results. As the curvature increased, the absorption frequency increased and the reflection loss decreased.

5. Conclusion

In this study, a novel analysis method using an equivalent circuit model and ray tracking method was proposed, as shown in Fig. 12. This method was used to estimate the electromagnetic performance of curved RAS with FSS. To analyze the FSS, it is necessary to predict the electromagnetic characteristics according to the incidence angle, because the resonance frequency of the FSS changes with the incident angle. Therefore, the electromagnetic analysis of the FSS was performed using electromagnetic software (HFSS). Since the electromagnetic...
characteristics of the FSS vary depending on adjacent materials, the FSS was analyzed by reflecting the electromagnetic properties of adjacent materials. Then, the equivalent circuit model of the FSS was applied to the equivalent circuit model of the RAS, and the electromagnetic performance was predicted using transmission line theory. Near field analysis was also performed to understand how electromagnetic waves interact with a standard horn antenna. The results were applied to the ray tracking method to predict the electromagnetic performance of the entire curved RAS.

To verify the predicted electromagnetic performance of the curved RAS with an FSS, three specimens with different curvatures were fabricated and the electromagnetic performance was measured using a reflection loss measurement setup with a standard horn antenna. The results of the magnitude and direction of the incident electromagnetic waves on the specimen were applied to the proposed method to predict the electromagnetic performance of the entire curved structure. As a result, it was confirmed that as the curvature increased, the absorption frequency increased and the reflection loss decreased as a whole. These characteristics agreed well with the experimental results, which shows that the developed electromagnetic performance prediction method for the curved RAS with an FSS is effective and accurate.

The analytical method proposed in this study has the advantage of reducing the analysis time by using a unit cell model instead of analyzing the entire curved structure. In addition, since the equivalent circuit model of the RAS reflects the electromagnetic characteristics according to the curvature and incident angle, it is possible to analyze complex and large shapes. Therefore, it is expected that the proposed method can shorten the existing computational time and analyze a large curved structure that is physically impossible with the existing software.

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