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

Dae-Sung Son, Jong-Min Hyun, Jung-Ryul Lee*

Department of Aerospace Engineering, Korea Advanced Institute of Science and Technology, Daejeon, South Korea

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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 tacking 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

* Corresponding author.
E-mail address: leejrr@kaist.ac.kr (J.-R. Lee).

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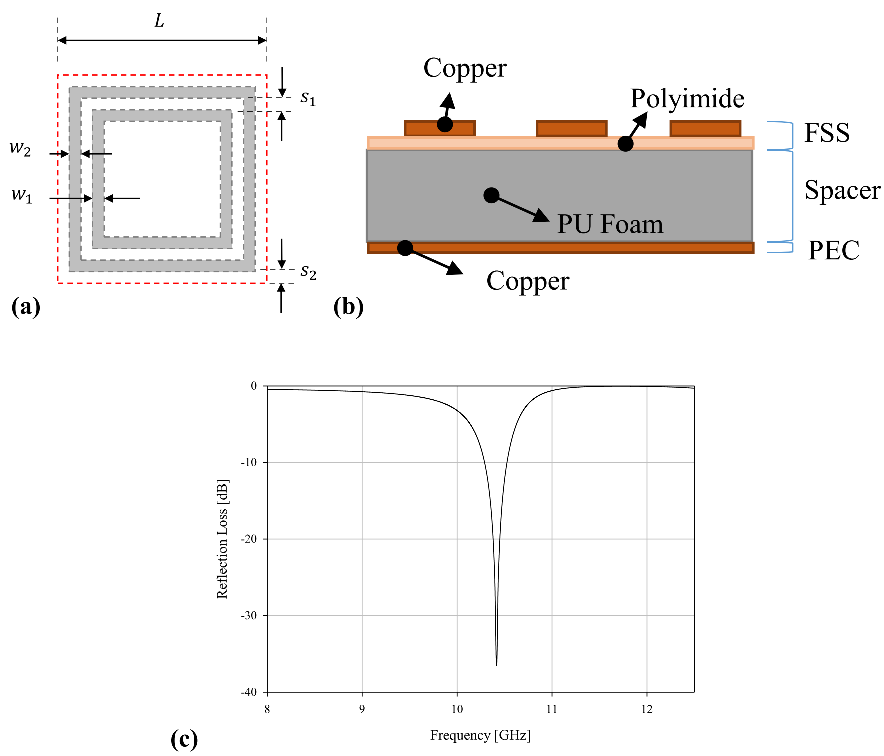

Fig. 1. (a) FSS shape, (b) RAS cross section, and (c) RAS analysis result.

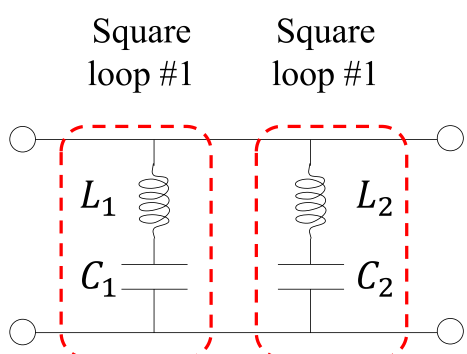

Fig. 2. Equivalent circuit model of the FSS with two square loops.

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_3) determined by two square loops, and it has one transmission frequency (f_2) 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.

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

$$\left(Where,\quad f_1 = \frac{1}{\sqrt{L_1 C_1}},\quad f_2 = \sqrt{\frac{C_1+C_2}{C_1 C_2 (L_1+L_2)}},\quad f_3 = \frac{1}{\sqrt{L_2 C_2}}\right) \qquad (1)$$

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