Analysis of Radome Cross Section of an Aircraft Equipped with a FSS Radome

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ABSTRACT We study the radar cross section (RCS) property of an aircraft considering the electromagnetic (EM) characteristics of a frequency selective surface (FSS) radome, mounted on the aircraft. Instead of full-wave methods, we utilize high-frequency methods, such as the shooting and bouncing rays (SBR), physical theory of diffraction (PTD), and flat model, taking a significant computational efficiency. Based on the developed algorithm, we analyze monostatic and bistatic RCSs of the aircraft equipped with either single- and multi-layer dielectric, FSS, or PEC radomes in terms of frequency and polarization. Our calculations are validated by comparing with those of the commercial EM simulator with significant computational efficiency. The present numerical study indicates that including the radome EM characteristics into the overall aircraft RCS study is crucial for the accurate RCS estimate.

INDEX TERMS Frequency selective surface (FSS), FSS radome, radar cross section (RCS), shooting and bouncing rays (SBR), physical theory of diffraction (PTD), flat model

I. INTRODUCTION

Rapid technological advances in radar systems have made it possible for the real-time and early detection of the appearance of enemy aircraft with a higher probability. Inversely, the survivability of friendly aircraft has been threatened increasingly [1]. Hence, modern aircraft design requires a much smaller radar cross section (RCS), which measures how detectable an object is by radar, for better evading radar detection [3]–[5].

Current electromagnetic (EM) stealth technology primarily focuses on developing such RCS reduction capability. During this stealth-oriented design, it is crucial to evaluate and predict the RCS characteristics of a designed aircraft [1], [2]. Analytic formulae are often limited to calculate EM fields scattered from objects with arbitrary geometric complexity, one should have an accurate, reliable, and fast computational electromagnetic (CEM) algorithm for their RCS estimate. Some previous works evaluated the RCS of aircraft taking the full-wave approach, such as finite difference time domain (FDTD) [6], method of moments (MoM) [7]–[10], and multi-level fast multipole method (MLFMM) [11]–[15]. Although the full-wave EM analysis can yield quite accurate results, it may be too computationally expensive and have several non-trivial issues when handling electrically large structures. Specifically, differential equation solvers, such as FDTD and finite-element method (FEM), need the implementation of absorbing boundary conditions (e.g., perfectly matched layers) and the costly volumetric discretization over both scatterers and ambient space. In addition, the use of integral equation solvers requires the costly inversion of full matrices and preconditioners to treat the ill-conditioning issue. As an alternative, one can exploit high-frequency techniques based on the shooting and bouncing rays (SBR) to evaluate the RCS of aircraft much more efficiently. Several previous studies successfully showed the aircraft RCS study using the high-frequency methods [15]–[22]. The SBR method was used to analyze the RCS of various aircrafts including scale down models [15]–[17] and full-scale models [16]–[19], which were assumed as a perfect electric conductor (PEC). In addition, the RCS of aircrafts...
full- [20] and partially coated [21], [22] with radar absorbing materials (RAM) was evaluated using the SBR method.

However, most previous works on the RCS of aircraft assumed a radome, mounted on the fuselage, as a PEC. Such a naïve assumption may fail to capture the effects of state-of-the-art radomes on the overall RCS performance of an aircraft, leading to the significant deviation between numerical calculations and measured data. For example, recent studies showed that the use of multi-layered dielectric or frequency selective surface (FSS) radomes could achieve the considerable reduction of the RCS, caused by the antenna mounted on the front of the fuselage [23]–[29], instead of using a single-layered dielectric radome. This indicates that the explicit consideration of the EM characteristics of the radomes is essential for the accurate evaluation of the aircraft RCS property. Although more recent works conducted the RCS analysis of a hemispherical FSS radome mounted on a simple circular cylinder [28], [29], to our knowledge, the RCS study for an aircraft including complicated radome structures has not been performed yet.

This paper analyzes the RCS of an aircraft equipped with a tangent-ogive FSS radome, a curved FSS (hash-shaped slot FSS unit cells) embedded in a multi-layer radome. Taking the hybrid approach where both full-wave and high-frequency methods are utilized, we exploit the SBR method and flat model [27], [30] to account for scattered EM fields inside the airborne based on the ray physics. Furthermore, we consider diffraction fields generated at edges of the aircraft via physical theory of diffraction (PTD) [1] to improve the accuracy of the present method. On the other hand, we use a commercial full-wave EM solver (ANSYS HFSS [31]) to extract transmission and reflection behaviors of the inserted FSS layer at a given incident angle for parallel and perpendicular polarizations. Then, we incorporate them into the flat model for the subsequent use of the high-frequency methods.

Our first two calculations are the monostatic RCS of single-layer dielectric radome mounted on a PEC disk and multi-layer dielectric radome mounted on a missile. The results are compared with those of a commercial EM solver (microwave studio (MWS) of CST) [32] for validation. Then, we calculate the bistatic RCS of aircraft equipped with either the FSS, dielectric, or PEC radomes to understand the stealth performance. Based on the numerical results, we show the inclusion of the EM characteristics of the FSS radome into the aircraft RCS study results in a significant deviation from that of the PEC radome (about 40 dBsm difference at most).

II. ANALYSIS PROCEDURE

A. MODELING OF THE AIRCRAFT EQUIPPED WITH THE FSS RADOME

Fig. 1 depicts the problem geometry illustrating an aircraft equipped with a FSS radome. The aircraft is a simplified model of a stealth fighter whose fuselage is assumed to be a PEC. The length and wingspan of the aircraft are 18.97 m and 13.65 m, respectively. The antenna enclosed by the FSS radome is in the surface of the front of the fuselage. Here, we consider the same tangent-ogive FSS radome used in [27], which has a passband characteristic in the X-band. The base diameter and height of the FSS radome are 800 mm and 1060 mm, respectively. The FSS radome consist of seven layers: the innermost and outermost layers are E-glass/epoxy (skin), second and sixth layers are foam, third and fourth layers are adhesive films, and a FSS layer (hash- shaped slot unit cells) is sandwiched by the adhesive films. A detailed configuration and dimension of the FSS radome can be found in [27].

B. NUMERICAL METHOD FOR RCS ESTIMATE

The problem geometry under this study consists of a PEC fuselage equipped with the multi-layer radome, which embeds a curved FSS layer. To calculate the RCS of the aircraft, we use the SBR method, PTD, and the flat model. The SBR method and PTD are well-known high-frequency techniques that can efficiently analyze the RCS of electrically large objects such as naval ships and aircrafts [33], [34]. The SBR method is based on the ray tracing technique and physical optics (PO), which can quantify the multiple reflections by determining the equivalent current densities induced on the surface of illuminated PEC planes, whereas PTD can calculate the diffraction fields based on the determination of the filamentary currents induced on illuminated of PEC edges. In addition, the ray tracing technique and flat model are useful for identifying the EM characteristics of a multi-layer radome [27], [30]. In the high-frequency regime, the curved radome can be looked locally flat via the tangent plane approximation where the phase matching condition fulfills locally. Note that “flat model” refers to a flat multi-layer radome with the same structure as an original curved radome. This method uses a look-up table including the pre-computed reflection and transmission coefficients of the flat model, which can significantly reduce the costly computational loads. Therefore, the present method is highly suitable for the EM analysis of a multi-layer radome embedding a curved FSS layer. Fig. 2 shows the analysis procedure to calculate the RCS of the
aircraft equipped with the FSS radome based on the SBR method, PTD, and flat model.

1) Ray Tracing with Flat Model
An incident plane wave illuminating the aircraft is modeled by numerous rays. Then, the intersection points where the rays hit the aircraft are determined, and the perpendicular($\hat{e}_\perp$) and parallel vector($\hat{e}_\parallel$) are calculated by using the ray direction vector($\vec{k} = (k_x, k_y, k_z)$) and the radome surface normal vector($\hat{n} = (n_x, n_y, n_z)$) in eqs. (1).

$$\hat{e}_\perp = \hat{n} \times \vec{k}$$  \hspace{1cm} (1)

The electric field can be decomposed by using normalized perpendicular($\hat{e}_\perp$) and parallel vector($\hat{e}_\parallel$) in eqs. (2).

$$\vec{E}_\perp = \vec{E} \times \hat{e}_\perp$$  \hspace{1cm} (2)

If the intersection point is placed on PEC surfaces, such as the metal tip, the enclosed antenna, and the fuselage, there are only reflected waves phase reversed in eqs. Otherwise, the reflected and transmitted waves are calculated using reflection($\Gamma$) and transmission($T$) coefficients pre-computed from the flat model. We determined the reflection($\vec{E}_r$) and transmission electric field($\vec{E}_t$) at intersection point in eqs. (3).

$$\vec{E}_r = \Gamma \vec{E}_\perp + \Gamma \vec{E}_\parallel$$
$$\vec{E}_t = T \vec{E}_\perp + T \vec{E}_\parallel$$  \hspace{1cm} (3)

For example, when a transmitted wave pass through the FSS, it is reflected by the enclosed antenna and then the reflected wave is traced until it reaches the outermost surface (see Fig. 3).

2) Physical Optics
We obtained the electric field($\vec{E}_a$) and magnetic field($\vec{H}_a$) at the intersection point of the outer radome and PEC body by using the ray tracing technique. The induced equivalent electric($\vec{J}_s$) and magnetic surface current ($\vec{M}_s$) on the outer radome given by

$$\vec{J}_s = \hat{n} \times \vec{H}_a$$
$$\vec{M}_s = -\hat{n} \times \vec{E}_a$$  \hspace{1cm} (4)

Similarly, for a PEC body with a reflection coefficient of -1, the induced equivalent electric($\vec{J}_{PO}$) and magnetic surface current ($\vec{M}_{PO}$) in the PEC body are given by

$$\vec{J}_{PO} = 2\hat{n} \times \vec{H}_a$$
$$\vec{M}_{PO} = 0$$  \hspace{1cm} (5)

In the far-field condition that the distance between the source and a target is so far enough, the scattering Electric field can be approximated as

$$\vec{E}_s = \frac{j\beta}{4\pi r} \int \hat{r} \times \vec{M} - (\hat{r} \times \eta \hat{n} \times \hat{r}) e^{j\beta r \cdot \hat{r}} \partial S$$  \hspace{1cm} (6)

where $r$ is the distance from scattering point to observation point, $\hat{r}$ is the observation position vector, $\beta$ is wavenumber, $S$ is the surface of the facet and $\hat{r}$ is the unit position vector in $S$ (See Fig. 4).

3) Physical Theory of Diffraction
We applied PTD technique to consider the diffraction at the point where the PEC edge and the ray intersect point. We defined the filamentary electric ($I_a$) and magnetic current ($I_m$) as in [1] and calculated the diffraction wave as given by

$$\vec{E}_d = \frac{j\beta}{4\pi r} \int_c (\eta I_a \hat{k}_d \times (\hat{k}_d \times \hat{z}_l) + I_m \hat{k}_d \times \hat{z}_l) e^{-j\beta r \cdot \hat{r}} dl'$$  \hspace{1cm} (7)
where $\vec{r}'$ is the position of a point on $C$, $\hat{k}_d$ is the unit vector in the direction of diffraction and $\hat{z}_i$ is the tangent unit vector to the edge. Fig. 5 show a locally tangent wedge for diffracted field configurations.

4) RCS Estimate
The total scattered electromagnetic field can be calculated as the sum of the previously calculated PO scattered field($\vec{E}_s$) and PTD scattered field($\vec{E}_d$). In [35], we can calculate RCS($\sigma$) as the ratio of the total scattered electric field to the incident electric field at a given observation point as

$$\sigma = \lim_{r \to \infty} 4\pi r^2 \frac{|\vec{E}_s + \vec{E}_d|^2}{|\vec{E}_i|^2}$$

(8)

C. VALIDATE AND NUMERICAL RESULTS
We designed three models matched in the X-band for analyze as shown in Table 1. The single dielectric layer consists of one skin layer with half wavelength thickness. The multi dielectric layer and FSS flat model was designed previous works [31]. The multi-layer implements the 3rd and 5th layer of FSS flat model are combined into one adhesive film.

In order to analyze the EM reflection and transmission behaviors of these models, we extract the reflection and transmission coefficients at a given incident angle and frequency for both polarizations using the ANSYS HFSS [31], and configure the look-up table. Fig. 6 shows the transmission characteristics of the flat model versus frequencies. We confirmed that all models matched with free space about 10 GHz. Moreover, in the case of the FSS flat model in Fig. 6 (c), it confirmed that all models matched with free space about 10 GHz. Moreover, in the case of the FSS flat model in Fig. 6 (c), it shows that band-pass characteristic was distinct compared to other models.

As shown in Table 2, we calculated the RCS of 5 cases to analyze the effect of the radome and validate our numerical methods. Radome and Missile models were constructed with single and multi dielectric layers, and our method was validated by comparing simulation time, number of meshes,
FIGURE 6. Reflection and transmission characteristic of the (a) Single-layer dielectric flat model, (b) multi-layer dielectric flat model, (c) FSS flat Model

and root mean square error (RMSE) with commercial EM software results. RMSE is defined as

$$\text{RMSE [dB]} = \sqrt{\frac{1}{N} \sum_{n=1}^{N} (\sigma_{\text{our}} - \sigma_{\text{cst}})^2}$$  (9)

where $\sigma_{\text{our}}$ [dBsm] is the RCS result by the our method, and $\sigma_{\text{cst}}$ [dBsm] is the RCS output by CST I-solver. RCS is computed with N sampling points in terms of frequency and angle range. Next, we analyzed the RCS reduction effect of the FSS radome by calculating the RCS of the Aircraft equipped with various radomes.

For the single-layer dielectric radome mounted on a PEC disk firstly, our calculations are compared with MWS of CST I-solver [32] results. The PEC disk has a radius of 390 mm and is surrounded by a tangent-ogive radome with a radius of 400 mm and a height of 1058 mm. Fig. 7 shows the monostatic RCS calculations via our method and MWS of CST at $\theta_i = 0^\circ$ and $\phi_i = 0^\circ$ for horizontal and vertical
FIGURE 8. Monostatic RCS of the multi-layer dielectric radome mounted on the missile at $\phi = 0^\circ$ for HH polarization

FIGURE 9. Bistatic RCS of the multi-layer dielectric radome mounted on the missile at $\theta = 0^\circ$ and $\phi = 0^\circ$ for HH polarization

TABLE 3. Summary of comparing results between our method and MWS of CST

| Target Model | Analyze Type | Simulation Time | Number of Meshes | RMSE [dB] |
|--------------|--------------|-----------------|------------------|-----------|
| Radome Monostatic RCS | Our Method: 181 s CST: 32.6 h | 137,103 | 1.622 (HH) |
| | CST: 1,181,282 | | 1.690 (VV) |
| Monostatic RCS | Our Method: 193 s CST: 55.1 h | 151,695 | 6.039 |
| | * Average time per each point | | |
| | Missile Bistatic RCS | Our Method: 123 s CST: 79.1 h | 151,695 | 7.853 |
| | * Total Calculation Time at Normal Incidence | | |

FIGURE 10. Monostatic RCS of the aircraft equipped with the FSS radome at $\theta_i = 0^\circ$ and $\phi_i = 0^\circ$ for (a) HH polarization, (b) VV polarization.

polarizations in the frequency range of 5 to 15 GHz. The RMSE of monostatic RCS between CST and our method are 1.662 and 1.690 dB within the frequency range, which is a good agreement in both calculation. The computation time at 10 GHz in our method took about 181 seconds using a PC (dual Intel Xeon CPU E5-2640v4 at 2.40 GHz and DDR4 512 GB memory), whereas CST took more than a day to simulate the same. Our method has a total number of meshes of 137,103 and CST 1,181,282 (10 GHz) respectively. In our method, the mesh is determined according to the shape of geometry regardless of frequency, whereas the l-solver of CST increases the number of mesh surfaces in proportion to the electrical size, which takes a long time to calculate. Therefore, these results clearly show that our proposed method is a time-efficient method for analyzing electrical large objects.

We also analyze and validate the multi-layer dielectric radome mounted on the missile, which has width and length of 2.34 m and 8.05 m, respectively. The monostatic RCS
simulation was performed at a frequency of 10 GHz with angles of incidence $\theta_i$ from 0 to 180° and $\phi_i$ is 0°. The bistatic RCS was also simulated at a frequency of 10 GHz with observation angles $\theta_s$ ranging from 0 to 360°. The results shown in Fig. 8 and 9, respectively. The surface mesh of the missile is divided into 151,695 surfaces when analyzed using our method, whereas the CST is divided into 5,501,279 surfaces. The monostatic and bistatic RCS computation times took about 193 s and 123 s for our method and 55.1 hours and 79.1 hours for CST. The RMSE with our method with CST shows an approximate good fit of 6.039 dB for monostatic and 7.853 dB for bistatic RCS. Table 3 summarizes the comparison between the proposed technique and CST results.

Now, we consider the FSS radome mounted on the aircraft (see Fig. 1 for the problem geometry). Utilizing the flat model results (in Fig. 6), we calculate the monostatic RCS of the aircraft equipped with the FSS radome versus frequency at $\theta_i = 0^\circ$ and $\phi_i = 0^\circ$, as shown in Fig. 10. Furthermore, we also calculate the monostatic RCS of the multi-layer dielectric radome and PEC radome and compare the performance of three different kinds of radomes mounted on the aircraft. Due to the broadband transmission characteristics and high reflection from the enclosed antenna, the multi-layer dielectric radome shows a higher RCS over the entire bandwidth. On the other hand, the RCS of the FSS radome is much lower than that of the dielectric radome except for the X-band due to its passband characteristic. However, PEC radome shows completely different results because the original EM properties of the radome and enclosed antenna are not considered. The results including the EM characteristics of the FSS radome into the aircraft RCS have a significant deviation from that of the PEC radome, which is about 40
dBsm difference at most. In addition, we consider bistatic RCS of the aircraft at the stopband and passband when $\theta_i$ is 0° and $\phi_i$ is 0°. Fig. 11 shows the bistatic RCS of the aircraft equipped with the FSS radome at 5, 10, and 15 GHz, respectively. In the bistatic RCS results at 5GHz and 15GHz (see Fig. 11 (a), (b), (e) and (f)), compared to the multi-layer dielectric radome, the FSS radome remarkably decreases the RCS (about 25.6 dBsm at most) in front of the aircraft, while it slightly increases the RCS (about 8.4 dBsm at most) around the observation angles of about 120 and 240. This is because the incident wave is mostly reflected on the surface of the FSS radome due to its stopband characteristic. On the other hand, since the incident wave is hardly reflected on the surface of the FSS radome due to its passband characteristic at 10GHz, and is mostly through the FSS radome and is reflected by the enclosed antenna, the RCS of the aircraft equipped with the FSS radome is very similar with that of the aircraft equipped with the multi-layer dielectric radome (see Fig. 11 (c), (d)). In contrast, in the cross polarization bistatic RCS, it can be seen in Fig. 12 that the significant difference due to the FSS radome is small.

We confirmed that the FSS radome can efficiently reduce the RCS in front of the aircraft over a wide frequency range due to its passband or stopband characteristics. Moreover, in order to accurately calculate the RCS of the radome mounted on the fuselage, the EM characteristics of the radome have to be considered. Our method can efficiently calculate the RCS of the aircraft equipped with the FSS radome, and these results can be usefully used for stealth design.

III. CONCLUSION

We calculated the RCS of the tangent-ovige FSS radome onboard the fighter. Multiple reflections inside the radome were considered using the SBR technique. In addition, the reflected and transmitted EM fields were calculated using a flat model. The scattered EM field was calculated by applying the PO and PTD method to the outermost part of the radome, the surface of the conductor, and the edge of the conductor, respectively. Our proposed method was verified using a commercial analysis program, MWS of CST, and was shown to be very efficient about the required number of meshes and calculation speed.

The RCS of the FSS radome mounted on the fuselage was smaller than that of the dielectric radome mounted on the fuselage. We have observed that the FSS radome can reduce the RCS of the aircraft over a wide frequency range except for the pass band due to its pass band characteristic. Importantly, we have shown that the RCS results were erroneous if the EM characteristics of the radome was not considered properly; thus, the EM characteristics of the radome mounted on the fuselage should be considered to obtain the correct RCS results of the aircraft. Our method is useful to analyze the RCS of the FSS radome mounted on fuselage such as aircrafts and missiles, and these results can be used for the stealth design.

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