Paper

Int'l J. of Aeronautical & Space Sci. 17(1), 20–28 (2016)
DOI: http://dx.doi.org/10.5139/IJASS.2016.17.1.20

IJASS International Journal of Aeronautical and Space Sciences

Design Optimization of Composite Radar Absorbing Structures to Improve Stealth Performance

Byungwook Jang* and Myungjun Kim*

Graduate School of Aerospace and Mechanical Engineering, Korea Aerospace University, Goyang 10540, Republic of Korea

Jungsun Park and Sooyong Lee*****

Department of Aerospace and Mechanical Engineering, Korea Aerospace University, Goyang 10540, Republic of Korea

Abstract

In this study, an efficient method of designing laminate composite radar absorbing structures (RAS) is proposed with consideration given to the structural shape so as to improve aircraft stealth performance. The calculation of the radar cross section (RCS) should be decreased to enhance the efficiency of the stochastic optimization when designing an RAS. In the proposed method, RAS are optimized to match up the input impedance of the minimal RCS, which is obtained by using physical optics and the transmission line theory. Single and double layer dielectric RAS for aircraft wings are employed as numerical examples and designed using the proposed method, RCS minimization and reflection coefficient minimization. The availability of the proposed method is assessed by comparing the similarity of the results and computation time with other design methods. According to the results, the proposed method produces the same results as the stochastic optimization, which adopts the RCS as the objective function, and can improve RAS design efficiency by reducing the number of RCS analyses.

Key words: Radar absorbing structure (RAS), Radar cross section (RCS), Impedance matching, Design optimization

1. Introduction

A radar cross section (RCS) is an equivalent area that represents the intensity of an electromagnetic (EM) wave being reflected back to a radar from a target. It is the most important parameter to assess the survivability and stealth performance of military aircraft [1, 2]. A RCS can be decreased by utilizing shape designs and wave absorbers such as radar absorbing materials and structures (RAM/RAS) [3, 4]. Wave absorbers are applied to sections such as wings, where shape designs are restrictively adopted, and attenuate incident waves according to the EM properties of materials and the wave characteristics. RAM is produced by adding fillers with wave loss features to transformable materials like rubber sheets [5]. Recently, RAS have been employed in advanced stealth aircraft with the development of composite materials [6]. They are generally made of fiber reinforced composites, and fillers are added into the matrix [7, 8]. Therefore, RAS carry out two roles; they absorb waves and bear loads.

RAS wave absorbing performance is affected by EM characteristics such as the frequency, incident angle, and polarization, and structural characteristics such as EM properties, thickness, and structural shape [9]. Among these variables, the EM characteristics and the structural shape are set as design conditions, and the main design parameters are reduced to the permittivity, permeability, and thickness of the absorbing layers. RAS are usually designed to minimize the reflection coefficient, which is conventionally applied to the RAM [10-15]. The performance of the RAS-minimizing reflection coefficient is degraded when design results are applied to curved structures. This is because objects are regarded as a flat surface in the reflection coefficient. In recent

This is an Open Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (http://creativecommons.org/licenses/by-nc/3.0/) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

* Ph. D Student
** Professor, Corresponding author: jungsun@kau.ac.kr
*** Professor

Received: April 10, 2015 Accepted: June 10, 2015
Copyright ⓒ The Korean Society for Aeronautical & Space Sciences

years, optimizations have been interlocked with RCS analysis algorithms in order to sufficiently consider the structural shape [16]. Stochastic optimization methods, which have to calculate numerous objective functions, have been widely employed in RAS design to account for continuous design variables as well as discrete design variables [17]. Therefore, optimization in RAS design takes hours even if the RCS analysis needs only a few seconds.

In this study, an efficient method of designing composite RAS is proposed that gives consideration to the structural shape with a reduced RCS analysis. RAS are designed to satisfy the input impedance, which minimizes the RCS of the object, by utilizing discrete optimization after calculating the target input impedance via continuous optimization. A sequential quadratic program (SQP) and genetic algorithm (GA) are used to deal with the continuous and discrete optimizations, respectively. Physical optics (PO) and the transmission line theory are employed to obtain the RCS and input impedance. Single and double layer dielectric RAS for NACA-0012 and NACA-2412 wings are designed using three different methods– minimum reflection coefficient, min. RCS, and the proposed method – as numerical examples. Finally, the results are compared and evaluated to confirm the utility of the proposed method.

2. Theories on RAS design

2.1 RAS composition

Composite RAS are made of the absorbing layers and a perfect electric conductor (PEC), as shown in Fig. 1. They are classified as either single or multi-layer, depending on the number of absorbing layers. RAS absorbing layers are usually produced by adding electric conductive fillers into the matrix of glass fiber reinforced composites. Carbon fiber reinforced composites and metal plates are used for the PEC. RAS are generally dielectric, and the permittivity of the absorbing layers changes according to the filler content [18, 19]. RAS mechanical strength and stiffness can be adjusted via the PEC layer. Therefore, the permittivity and thickness of the absorbing layers are preferentially designed to maximize the wave absorbing performance of the RAS. The absorbing performance of the RAS can be evaluated via the reflection coefficient as well as the RCS.

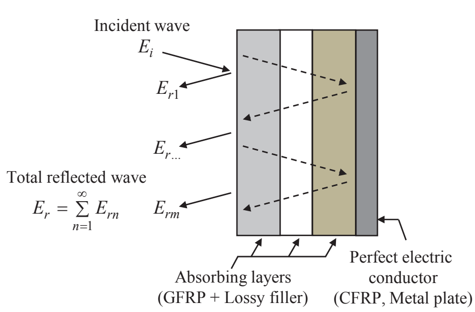


Fig. 1. Schematic drawing of a composite RAS

2.2 Reflection coefficient

Incident waves are reflected and transmitted at the outer surface of the RAS. The transmitted wave is transformed into thermal energy according to loss mechanisms in the absorbing layers [20]. The reflection coefficient (Γ) is defined as the ratio of the reflected field (E_r) to the incident field (E_i) as follows, and is used to represent reflected wave amounts for a flat surface [21].

$$\Gamma = \frac{E_r}{E_i} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \tag{1}$$

where Z_{in} is the input impedance at the outer surface and Z_0 is the characteristic impedance of the free space (377). Input impedance, which is a complex number, can be obtained by using the transmission line theory [22]. It is formulated as follows for a single layer dielectric RAS with the complex permittivity (ε_r=ε'-jε"), the thickness of the absorbing layer (t), and the wave length (λ).

$$Z_{in} = \frac{Z_0}{\sqrt{\varepsilon_r}} \tanh(j\frac{2\pi t}{\lambda}\sqrt{\varepsilon_r}) \tag{2}$$

The complex permittivity should be increased to augment the energy absorption of the RAS. Since unconditional increments in the permittivity bring about increased reflection and performance deterioration, the RAS is designed to enlarge the transmitted wave by minimizing the reflection coefficient. The reflection coefficient is minimized when the input impedance is close to the characteristic impedance of the free space.

2.3 RCS and physical optics (PO)

The RCS represents the intensity of the EM energy reflected back to the radar, and is defined as the ratio of the scattered electric field (E_s) to the incident electric field (E_i) [23].

$$\sigma(m^2) = \lim_{R\to 0} 4\pi R \frac{\left|\overline{E_s}\right|^2}{\left|\overline{E_i}\right|^2} \tag{3}$$

where σ is the RCS in square meters, and R is the range to the object. The RCS is also expressed in decibel square meters (σ(dBsm)=10logσ(m^2)); advanced stealth aircraft show values lower than -20dBsm. The RCS of some simple objects can be calculated using analytical solutions. Analysis methods are generally applied to obtain the RCS of complicated objects and incident wave conditions.

Physical optics (PO) is an RCS analysis method that uses an approximation of the surface current (J_s) caused by the incident electric field and boundary conditions. The object is divided into the illuminated portion and shadowed portion in the PO, as shown in Fig. 2. The surface current is approximated by using the Stratton-Chu equation, which is the integral of the Maxwell equation [24]. The surface current for the PEC is as follows with the surface normal vector ($\hat{n}$) and incident magnetic field (H_i).

$$\overline{J_s} \approx \begin{cases} 2\hat{n} \times \overline{H_i}, & \text{for illuminated portion} \\ 0, & \text{for shadow portion} \end{cases} \tag{4}$$

Also, it can be calculated by adapting the reflection coefficient (Γ) for the RAS, as shown in following figure.

3. Proposed RAS design method

An RAS can be designed by minimizing the reflection coefficient or RCS for target frequencies. The number of target frequencies increases depending on the number of absorbing layers used to expand the wave absorbing performance to a wider frequency range. It is difficult to account for the structural shape by using a reflection coefficient because objects are regarded as flat surfaces. On the other hand, a RCS can appraise a structural shape since it is calculated based on analysis models. A RCS analysis requires a lot of computations and makes optimization inefficient. In this study, an efficient method of designing a dielectric RAS is proposed. In this method, the RAS is not flat like aircraft wing leading edges, and consideration is given to structural shapes with a reduced RCS analysis. The RAS is designed via optimizations that match up the input impedance, thereby minimizing the RCS for target frequencies, as follows.

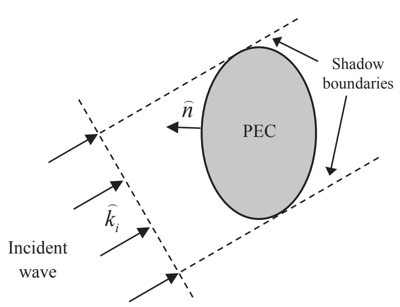


Fig. 2. Surface parts for the PO approximation application [20]

$$\begin{aligned} &\text{Minimize } \sum_{i=1}^{n} w_i \left| Z_{in,f_i}(\varepsilon_i', \varepsilon_i'', t_i) - (Z_{in})_{\min\_\sigma, f_i} \right| \\ &\text{S.T. } 1)\ \varepsilon'_{\min} \le \varepsilon_i' \le \varepsilon'_{\max} \\ &\qquad 2)\ t_{\min} \le t_i \le t_{\max} \end{aligned} \tag{5}$$

The permittivity of the materials changes according to filler content and is often presented using the Cole-Cole plot [26]. The Cole-Cole plot represents the complex permittivity on a plane that has the real portion of the complex permittivity (ε') on the x-axis and the imaginary portion (ε'') on the y-axis. The imaginary portion of the complex permittivity can be calculated as a function of the real portion by using the regression equation of the Cole-Cole plot. Hence, the design variables for the optimization are the real portion of the complex permittivity (ε') and the thickness (t_i) of the absorbing layers. The thickness of the layers is a discrete variable that accounts for the laminate composite characteristics. The objective function is specified to make the input impedance ($Z_{in,fi}$) close to the input impedance minimizing RCS ($(Z_{in})_{min\_\sigma,fi}$) as per target frequencies, and the weighting factors (w_i) are used to design the multi-layer RAS. Since there are both continuous and discrete variables in the optimization problem in Eq. (5), the optimization is processed using a GA. The target input impedance minimizing RCS for the target frequencies is determined by Eq. (2) using the complex permittivity and thickness obtained from another optimization, as follows.

$$\begin{aligned} &\text{Minimize } \sum_{i=1}^{n} \sigma_{f_i}(\varepsilon_i',\ \varepsilon_i'',\ t_i) \\ &\text{S.T. } 1)\ \varepsilon'_{\min} \le \varepsilon_i' \le \varepsilon'_{\max} \\ &\qquad 2)\ \varepsilon''_{\min} \le \varepsilon_i'' \le \varepsilon''_{\max} \\ &\qquad 3)\ t_{\min} \le t_i \le t_{\max} \end{aligned} \tag{6}$$

In this optimization, it is important to get the complex permittivity and thickness, ideally minimizing the RCS of the object for wave incident conditions regardless of the specified material. Therefore, the real (ε_i') and imaginary (ε_i'') portions of the complex permittivity and thickness (t_i) of the absorbing layers are independently employed as design variables. The thickness is continuous variable, but it is treated as a fixed value for a single layer RAS. The optimization to obtain the target input impedance minimizing RCS (σ_{fi}) for the target frequencies can be dealt with via the gradient-based optimization since there are no discrete variables. An SQP is used as the gradient-based optimization method [27]. It is important to specify initial design points in the gradient-based optimization. In the proposed method, the initial design points for the optimization in Eq. (6) are selected as the complex permittivity ideally minimizing the reflection coefficient for the target frequencies. One more optimization

DOI: http://dx.doi.org/10.5139/IJASS.2016.17.1.20

process is required in order to evaluate the initial points. The optimization problem is the same as in Eq. (6) if the RCS is replaced by the reflection coefficient. This is conducted with the GA to get the global minimum without the initial points. Consequently, there are three optimization problems in the proposed method.

4. Application and verification

In this study, an efficient method of designing a composite RAS is proposed, and single and double layer dielectric RAS for aircraft wings are designed as numerical examples. The RAS are designed using three different methods – minimizing the reflection coefficient (Min. Γ), minimizing the RCS (Min. σ), and the proposed method. The usability of the proposed method is assessed by comparing the similarity of the results and computation time according to the design methods. The models used for the numerical examples are all of the rectangular type, and they have NACA-0012 and NACA-2412 airfoils, respectively, as shown in Fig. 3. They also have the same cord length (1,000mm) and span (3,000mm). The RCS of the wing models are analyzed using a PO program to evaluate the objective function of the optimizations and wave absorbing performance of the designed RAS [28]. The element size in the analysis models is 1mm to 30mm, and the leading edge of the wing is finely meshed. The radar system is regarded as a mono-static type, and transverse electric (TE) and transverse magnetic (TM) waves are used, respectively. The elevation angle is defined as -90° for the perpendicular direction to the lower surface of the wing, and 90° for the upper surface. Therefore, the incident wave is parallel to the cord and perpendicular to the span at a 0° elevation angle. The RCS for the objective function of the optimizations are calculated for the 0° elevation angle to reduce the RCS for the threat section (20 elevation angle) [9].

A glass fiber reinforced composite with a carbon nano-fiber (CNF) filler is used for material. The Cole-Cole plot of the material for 10GHz is shown in Fig. 4 [29]. The regression function of the Cole-Cole plot is generated as (ε_i"=0.024(ε_i')^2+0.073(ε_i')-0.040) for use with the optimizations. The complex permittivity is limited to $4 \le \varepsilon_i' \le 40$, and the increment of the discrete thickness is $\triangle t$=0.1mm considering the property of the material.

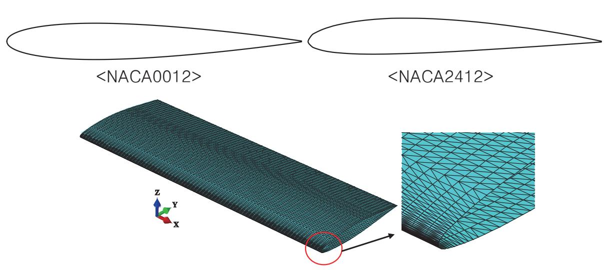


Fig. 3. Numerical example wing models

When designing the RAS, the GA is employed to process the optimizations of the Min. Γ, Min. σ, and portions of the proposed method with the parameters in Table 1 [30].

4.1 Single layer RAS design

The single layer RAS can be designed by minimizing the reflection coefficient (Γ) or RCS (σ) for a target frequency. In this study, the target frequency is 10GHz, and the RAS are designed using the Min. Γ, Min. σ, and the proposed method. The optimization problems of the Min. Γ and Min. σ are as follows.

$$\begin{aligned}&\text{Minimize } \Gamma(\varepsilon', \varepsilon'', t) \;\; or \;\; \sigma_{PO}(\varepsilon', \varepsilon'', t)\\ &\text{S.T. } 1)\; 4 \le \varepsilon' \le 40,\\ &\qquad 2)\; 2 \le t(mm) \le 3,\; \Delta t = 0.1mm\end{aligned} \tag{7}$$

The results from designing the single layer RAS for the NACA-0012 and NACA-2412 wing models are shown in Tables 2 and 3, respectively. The results from the Min. Γ are the same with respect to polarization type because the reflection coefficient is obtained for the normal incident wave. Also, they are not different according to the wing models since the reflection coefficient only adopts the material property regardless of structural shape. The input impedance of the Min. Γ is close to the characteristic impedance of the free space. In contrast to the results from the Min. Γ, the results from the Min. σ are dependent on polarizations and wing models, and there are some differences between the

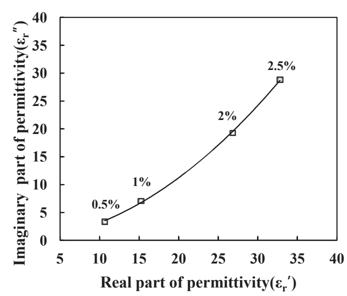


Fig. 4. Cole-Cole plot of the glass fiber reinforced composite with CNF for 10GHz

Table 1. Genetic algorithm parameters

Parameter	Value
Population size	20
Number of generation	10,000
Probability of crossover	0.95
Probability of mutation	0.01

input impedance and characteristic impedance of the free space. Significantly, more time is required to process the optimization of the Min. σ than the Min. Γ.

The input impedance minimizing the RCS of the object should be obtained to operate the proposed method. The optimization in Eq. (6) is conducted with a thickness of 2.0mm, and the input impedance minimizing RCS is calculated as 375.44-34.43j(TE), 356.42+26.09j(TM) for NACA-0012 and 390.46-24.53j(TE), 349.26+9.74j(TM) for NACA-2412. The proposed method is performed with the calculated input impedance minimizing RCS, and the results show less than a 0.1% difference with the Min. σ. In the proposed method, computation time is reduced significantly by processing the RCS minimization by using the gradient-based optimization, although the calculation of the reflection coefficient and impedance increase.

The RCS of the designed RAS is calculated along the elevation angle to evaluate the wave absorbing performance of the single layer RAS. The design results in Tables 2 and 3 are applied to the skin of each wing model. The RCS plots of each wing model with the designed RAS are shown in Figs. 5 and 6, respectively. The PEC in the legends indicate that the wing models are regarded as the perfect electric conductor, like metals that do not absorb waves. According to the results, the RCS reduction of the RAS Min. Γ is larger on the upper and lower faces of the wings than it is around the leading edge because the reflection coefficient is obtained for a flat surface. On the other hand, the RAS Min. σ produces a greater RCS reduction for the specified polarization and incident angle than the RAS Min. Γ. The RCS reduction of ± 20 in terms of elevation angle is important for air vehicles to avoid radar detection [9]. Therefore, the RCS is a more appropriate parameter when designing RAS for aircraft wings. The RCS plots of the RAS Min. σ and the proposed method are shown superimposed since the design results of each method are almost the same. This indicates that the proposed method can reach the same results as the optimization minimizing RCS, with a reduced RCS analysis.

4.2 Double layer RAS design

The double layer RAS can be designed by minimizing the reflection coefficient or the RCS for more than a target frequency. Target frequencies need to be defined with consideration given to the broadband absorbing performance. In this study, the target frequencies are 9GHz and 10GHz, and the double layer RAS are designed with preference given to the acquisition of a 10GHz wave

Table 2. Design results of single layer RAS for NACA-0012 wing model

Design method	Polarization	Complex permittivity	Thickness (mm)	Input impedance(Ω)	Number of calculations	Computation time(sec)
Min. Γ (GA)	-	12.05-4.29j	2.20	378.60-2.03j	20,000(Γ)	3
Min. σ (GA)	TE	11.51-3.91j	2.30	382.06-48.19j	20,000(σ)	127,263
	TM	12.83-4.86j	2.10	353.17+28.27j	20,000(σ)	127,263
Proposed Method (SQP+GA)	TE	11.50-3.91j	2.30	382.62-47.92j	40,000(Γ) 21(σ) 20,000(Z_{in})	143
	TM	12.83-4.87j	2.10	352.95+27.99j	40,000(Γ) 24(σ) 20,000(Z_{in})	161

Table 3. Design results of single layer RAS for NACA-2412 wing model

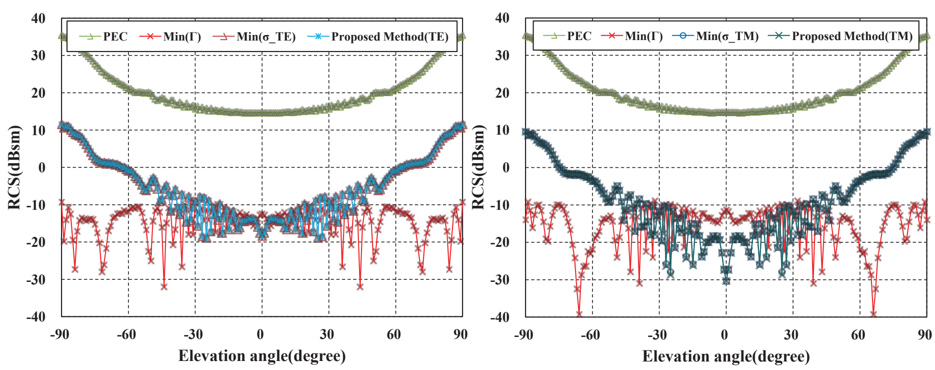
Design method	Polarization	Complex permittivity	Thickness (mm)	Input impedance(Ω)	Number of calculations	Computation time(sec)
Min. Γ (GA)	-	12.05-4.29j	2.20	378.60-2.03j	20,000(Γ)	3
Min. σ (GA)	TE	11.35-3.80j	2.30	398.50-38.05j	20,000(σ)	127,263
	TM	13.02-5.01j	2.10	341.99+15.55j	20,000(σ)	127,263
Proposed Method (SQP+GA)	TE	11.35-3.80j	2.30	398.50-38.05j	40,000(Γ) 21(σ) 20,000(Z_{in})	143
	TM	13.02-5.01j	2.10	341.99+15.56j	40,000(Γ) 21(σ) 20,000(Z_{in})	143

absorbing performance. The optimization problems with respect to designing a double layer RAS by minimizing the reflection coefficient or RCS are as follows.

$$\text{Minimize} \sum_{i=1}^{n} w_i \Gamma_{f_i}(\varepsilon_i', \varepsilon_i'', t_i) \;\; or \;\; \sum_{i=1}^{n} w_i \sigma_{PO\_f_i}(\varepsilon_i', \varepsilon_i'', t_i)$$
$$\text{S.T. } 1)\ 4 \le \varepsilon_2' \le 40, \qquad (8)$$
$$2)\ t_1 + t_2 \le 5, \Delta t = 0.1mm$$

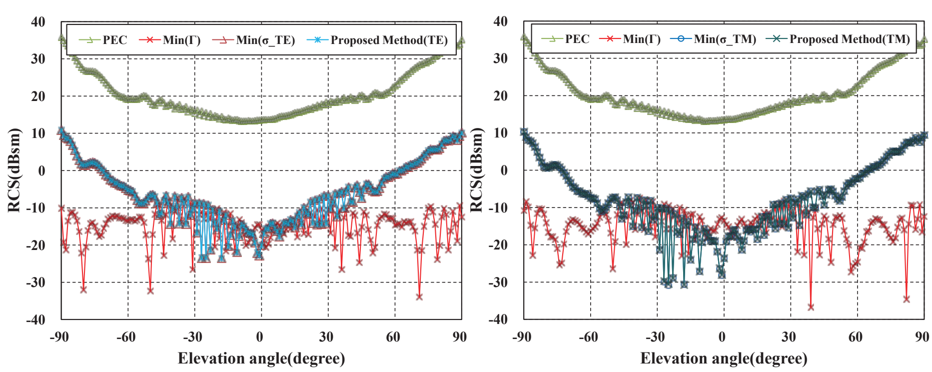
The first layer (outer layer) of the double layer RAS usually has very low permittivity to match the characteristic impedance to the free space. Therefore, the complex permittivity of the first layer is assumed as the permittivity of the composites without CNF filler as ε_1=4.75-0.14*j*. The design variables for the optimizations are the thickness of each layer and permittivity of the second layer. The objective function is defined to minimize the summation of the reflection coefficient or RCS for the target frequencies. The weighting factors are set as $w_2=2w_1$ to acquire the preferred absorbing performance of 10GHz. The results from designing the double layer RAS for the NACA-0012 and NACA-2412 wing models are shown in Tables 4 and 5, respectively. The results from minimizing the reflection coefficient (Min. Γ) are the same with respect to polarization type and wing models for the same reason as in the single layer RAS. The input impedance of the RAS Min. Γ for the target frequencies are all close to the characteristic impedance of the free space. On the other hand, the results of minimizing the RCS (Min. σ) are different depending on the polarization and wing models. The input impedance of the target frequencies does not match the characteristic impedance of the free space. The input impedance minimizing RCS of the target frequencies are calculated as 361.89-25.09j (9GHz, TE), 368.79-25.74j (10GHz, TE), 366.07+18.91j (9GHz, TM), 359.32+17.65j (10GHz, TM) for the NACA-0012 and 375.15-19.24j (9GHz, TE), 381.34-19.95j (10GHz, TE), 358.58+5.47j (9GHz, TM), 354.23+3.31j (10GHz, TM) for the NACA-2412 wing models by the optimization in Eq. (7). The double layer RAS designed by the proposed method using the calculated input impedance is also in the Tables. According to the results, the proposed method obtains similar results with the Min. σ to the first decimal place while being less time consuming.

The RCS of the designed RAS is analyzed according to frequency range to evaluate the wave absorbing frequency performance of the double layer RAS. The design results in Tables 4 and 5 are applied to each wing model, and the RCS is calculated for the 0° elevation angle, just as it was in the



(a) RCS for TE polarization (b) RCS for TM polarization

Fig. 5. RCS plot of single layer RAS for NACA0012 wing model



(a) RCS for TE polarization (b) RCS for TM polarization

Fig. 6. RCS plot of single layer RAS for NACA2412 wing model

objective function calculation.

The RCS plots of each wing model with the designed RAS are shown in Figs. 7 and 8. Depending on the results, the RCS reduction of the RAS Min. Γ is not maximized at the target frequencies since the reflection coefficient could not account for the structural shape. On the contrary, the RAS Min. σ reduces the RCS further for the target frequency, and it expands the frequency range, which shows an RCS lower than -20dBsm. Therefore, the broadband performance of the RAS can be acquired using the Min. σ. The RCS plots of the proposed method follow the results of the Min. σ, though there are small differences in each design result. This indicates that the proposed method is able to effectively obtain the double layer RAS minimizing RCS.

5. Conclusion

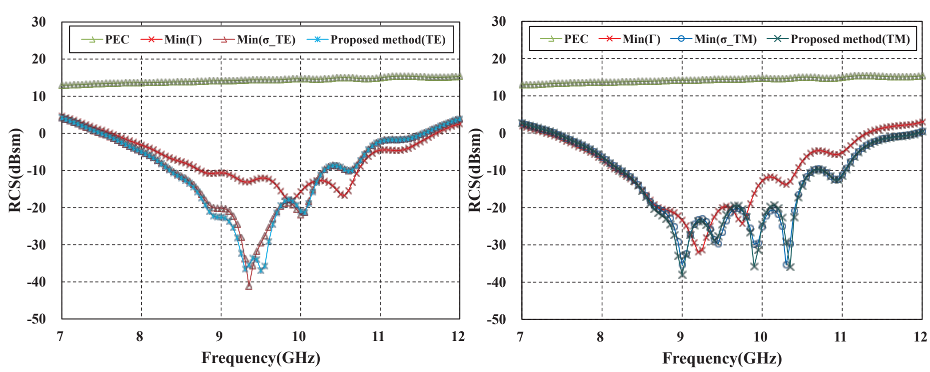
An efficient optimization method of designing composite RAS is proposed that gives consideration to the structural

Table 4. Design results of double layer RAS for NACA-0012 wing model

Design method	Polarization	Complex permittivity	Thickness (mm)	Input impedance(Ω)	Number of calculation	Computation time(sec)
Min. Γ (GA)	-	4.75-0.14j 38.08-39.73j	3.20 1.20	9GHz:373.23+12.72j 10GHz:377.38-6.14j	80,000(Γ)	11
Min. σ (GA)	TE	4.75-0.14j 38.95-39.47j	3.30 1.20	9GHz:370.93-15.39j 10GHz:369.85-35.97j	40,000(σ)	254,126
	TM	4.75-0.14j 38.15-37.97j	3.10 1.20	9GHz:366.46+2.12j 10GHz:363.79+12.16j	40,000(σ)	254,126
Proposed Method (SQP+GA)	TE	4.75-0.14j 38.76-39.13j	3.30 1.20	9GHz:369.19-18.32j 10GHz:366.70-37.04j	60,000(Γ) 166(σ) 40,000(Z_{in})	1,083
	TM	4.75-0.14j 38.03-37.74j	3.10 1.20	9GHz:366.02+18.97j 10GHz:362.09+10.66j	60,000(Γ) 410(σ) 40,000(Z_{in})	2,678

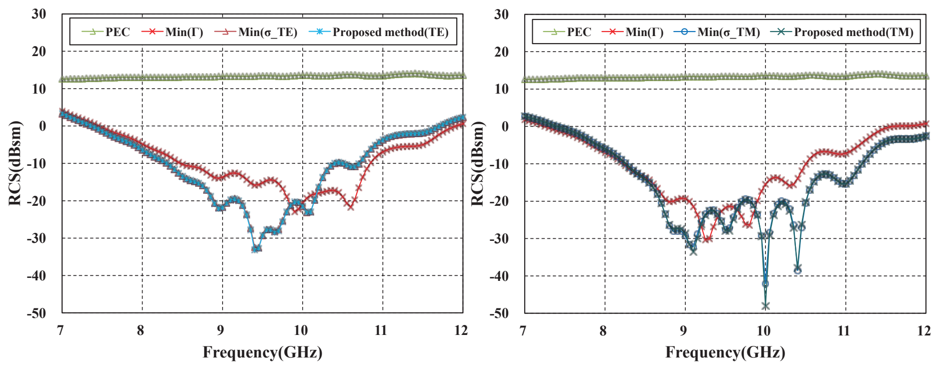
Table 5. Design results of double layer RAS for NACA-2412 wing model

Design method	Polarization	Complex permittivity	Thickness (mm)	Input impedance(Ω)	Number of calculation	Computation time(sec)
Min. Γ (GA)	-	4.75-0.14j 38.08-39.73j	3.20 1.20	9GHz:373.23+12.72j 10GHz:377.38-6.14j	80,000(Γ)	11
Min. σ (GA)	TE	4.75-0.14j 39.52-40.56j	3.30 1.20	9GHz:376.30-6.27j 10GHz:379.74-32.68j	40,000(σ)	254,126
	TM	4.75-0.14j 37.40-36.59j	3.10 1.20	9GHz:363.72+7.30j 10GHz:353.51+3.00j	40,000(σ)	254,126
Proposed Method (SQP+GA)	TE	4.75-0.14j 39.50-40.53,	3.30 1.20	9GHz:376.13-6.57j 10GHz:379.41-32.79j	60,000(Γ) 354(σ) 40,000(Z_{in})	2,314
	TM	4.75-0.14j 37.44-36.66j	3.10 1.20	9GHz:363.85+7.98j 10GHz:354.00+3.44j	60,000(Γ) 458(σ) 40,000(Z_{in})	2,991



(a) RCS for TE polarization (b) RCS for TM polarization

Fig. 7. RCS plot of double layer RAS for NACA0012 wing model



(a) RCS for TE polarization (b) RCS for TM polarization

Fig. 8. RCS plot of double layer RAS for NACA2412 wing model

shape with a reduced RCS analysis to improve aircraft stealth performance. In the proposed method, the RAS is designed to match the input impedance with the input impedance minimizing RCS of the object for the specified wave incident conditions through several optimization processes. According to the results, it is difficult to account for the structural shape by using the reflection coefficient since it is evaluated from a flat surface. The RCS is a more appropriate parameter when designing non-flat RAS, but it also requires a tremendous time increase. In contrast, the proposed method obtains the same results as minimizing the RCS by matching the impedance, and the computation time is reduced significantly, although there is an increase in the calculations of the reflection coefficient and impedance. In addition, the optimization to minimize the RCS can be performed by the gradient-based optimization method with suitable initial design points. The composite RAS is designed in a short time by using continuous and discrete optimizations with the SQP and GA, respectively. Consequently, the proposed method attains the same results as the stochastic optimization, which takes a long time, by adopting the RCS as the objective function. The efficiency of designing the composite RAS can be enhanced by reducing the number of RCS analyses.

References

[1] Grant, R., *The Radar Game: Understanding Stealth and Aircraft Survivability*, Mitchell Institute Press, 1998.

[2] Ball, R. E., *The fundamentals of aircraft combat survivability analysis and design*, AIAA, 2003.

[3] Lee, D. S., Gonzalez, L. F., Srinivas, K. and Periaux, J., "Robust evolutionary algorithms for UVA/UCAV aerodynamic and RCS design optimisation", *Computer and Fluids*, Vol. 37, 2008, pp. 547-564.

[4] Bondeson, A., Yang, Y. and Weinerfelt, P., "Optimization of radar cross section by a gradient method", *IEEE Trans. Magn.*, Vol. 40, 2004, pp. 1260-1263.

[5] Saville, P., "A review of radar absorbing material", *TM 2005-003, Defence R&D Canada -Atlantic*, 2005.

[6] Hong, C. S., "Stealth aircraft and composites", *J. of KSAS*, Vol. 24, 1996, pp. 156-160.

[7] Jung, W. K., Kim, B. K., Won, M. S. and Ahn, S. H., "Fabrication of radar absorbing structure(RAS) using GFR-nano composite and spring-back compensation of hybrid composite RAS shells", *Composite Structures*, Vol. 75, 2006, pp. 571-576.

[8] Park, K. Y., Lee, S. E., Kim, C. G. and Han, J. H., "Fabrication and electromagnetic characteristics of electromagnetic wave absorbing sandwich structures", *Composite Science and Technology*, Vol. 66, 2006, pp. 576-584.

[9] Knott, E. F., Shaeffer, J. F. and Tuley, M. T., *Radar Cross Section*, Artech House, 1993.

[10] Saville, P., "A review of optimization techniques for layered radar absorbing materials", *TM 2004-260, Defence R&D Canada -Atlantic*, 2004.

[11] Oh, J. H., Oh, K. S., Kim, C.G. and Hong, C. S., "Design of radar absorbing structures using glass/epoxy composite containing carbon black in X-band frequency ranges", *Composite Part B*, Vol. 35, 2004, pp. 49-56.

[12] Musal, H. M. and Hahn, H. T., "Thin-layer electromagnetic absorber design", *IEEE Trans. Magn.*, Vol. 25, 1989, pp. 3851-3853.

[13] Perini, J. and Cohen, L. S., "Design of broad-band radar absorbing materials for large angle of incidence", *IEEE Trans. Electromagn. Compat*, Vol. 35, 1993, pp. 223-230.

[14] Michielssen, E.. Sajer, S. M., Ranjithan, S. and Mittra, R., "Design of lightweight, broad-band microwave absorbers

using genetic algorithms", *IEEE Trans. Microwave Theory Tech*, Vol. 41, 1993, pp. 1024-1031.

[15] Haupt, R. L., "Comparison between genetic algorithm and gradient based optimization algorithms for solving electromagnetic problems", *IEEE Trans. Magn.*, Vol. 31, 1995, pp. 1932-1935.

[16] Park, H. S., Choi, I. S., Bang, J. K., Suk, S. H., Lee, S. S. and Kim, H. T., "Optimization design of radar absorbing materials for complex target", *J. of Electromagnetic Waves and Applications*, Vol. 18, 2004, pp. 1105-1117.

[17] Lee, S. E., Kang, J. H. and Kim, C. G., "Fabrication and design of multi-layered radar absorbing structures of MWNT-filled glass/epoxy plain-weave composites", *Composite Structures*, Vol. 76, 2006, pp. 379-405

[18] Chin, W. S. and Lee, D. G., "Development of the composite RAS(radar absorbing structure) for X-band frequency range", *Composite Structures*, Vol. 77, 2007, pp. 457-465.

[19] Kim, J. B., Lee, S. K. and Kim, C. G., "Comparison study on the effect of carbon nano materials for single-layer microwave absorber in X-Band", *Composite Science and Technology*, Vol. 68, 2008, pp. 2909-2916.

[20] Jenn, D. C., *Radar and Laser Cross Section Engineering*, AIAA Education Series, 2005.

[21] Cheng, D. K., *Fundamentals of engineering electromagnetics*, Prentice Hall, 1992.

[22] Collin, R. E., *Foundations for microwave engineering*, McGraw-Hill, 1992.

[23] Mahafza, B. R., *Radar systems analysis and design using MATLAB*, Chapman & Hall/CRC, 2000.

[24] Garrido, E. E. Jr. and Jenn, D. C., "A MATLAB physical optics RCS prediction code", *ACES Newsletter*, Vol. 5, 2000.

[25] Myong, R. S. and Cho, T. H., "Development of a computational electromagnetics code for radar cross section calculations of flying vehicles", *J. of KSAS*, Vol. 33, 2005, pp. 1-6.

[26] Cole, K. S. and Cole, R. H., "Dispersion and absorption in dielectrics I, alternating current characteristics", *J. of Chemical Physics*, Vol. 9, 1941, pp. 341-352.

[27] Rao, S. S., *Engineering Optimization Theory and Practice*, A Wiley-interscience publication, 1996.

[28] http://faculty.nps.edu/jenn/

[29] Kim, J. B., "Design of microwave absorbing composite laminates by using semi-empirical permittivity models", Ph.D. Thesis, *KAIST*, 2007.

[30] Goldberg, D. E., *Genetic algorithm in search, optimization, and machine learning*, Addison-Wesley, 1987.