A Hybrid Optimization Algorithm for Low RCS Antenna Design

Wei SHAO, Xinyue ZHU

School of Physical Electronics, University of Electronic Science and Technology of China, 610054 Chengdu, China

weishao@uestc.edu.cn, zhuxinyue888@163.com

Abstract. *In this article, a simple and efficient method is presented to design low radar cross section (RCS) patch antennas. This method consists of a hybrid optimization algorithm, which combines a genetic algorithm (GA) with tabu search algorithm (TSA), and electromagnetic field solver. The TSA, embedded into the GA frame, defines the acceptable neighborhood region of parameters and screens out the poor-scoring individuals. Thus, the repeats of search are avoided and the amount of time-consuming electromagnetic simulations is largely reduced. Moreover, the whole design procedure is auto-controlled by programming the VBScript language. A slot patch antenna example is provided to verify the accuracy and efficiency of the proposed method.*

Keywords

Genetic algorithm, RCS, slot antenna, tabu search algorithm.

1. Introduction

An antenna is often a main contributor to the overall radar cross section (RCS) of an aircraft platform. The antenna RCS reduction has been a hot topic for the current stealth technologies in electromagnetic (EM) engineering [1]-[2].

In the past few decades, patch antennas have been widely used due to their conformability and simplicity of design. By creating a resonance with an appropriate load impedance, the RCS of a patch antenna can be substantially reduced at a specific frequency [3]-[4]. For a circular patch antenna, scattering and radiation responses are tuned by controlling the bias voltage across a varactor diode to reduce the antenna RCS at some threat frequencies [5]. The RCS of a rectangular patch antenna in a lossy substrate-superstrate configuration is reduced at the cost of lowering the radiation efficiency [6]. The RCS peaks of a patch antenna printed on a ferrite substrate can be shifted by changing the magnetic bias field [7].

Above methods for RCS reduction of patch antennas are at the cost of worsening the gain and bandwidth of the antennas. Due to the basic radiation requirement of patch antennas, the shaping method becomes one of the most effective methods for the antenna RCS reduction. In [8], circle and rectangular slots on the antenna patch are introduced to cut off surface currents of high-order modes. Techniques of ground-cut slots are applied to the design of a patch antenna which achieves the RCS reduction [9]. [10] introduces some types of fractal slots on an antenna patch to obtain the low backscattering. Frequency selective surface (FSS) structures are also presented to reduce RCS of reflect-array antennas [11].

In general, a low RCS antenna is difficult to design due to the simultaneous consideration on antenna radiation and scattering. This design often relies on an optimization procedure with a number of EM simulations, which are very time consuming. [12] uses a differential evolution algorithm (DEA) to optimize geometric parameters of a low RCS antenna. Based on the separate DEA for the radiation and scattering modules, the individuals of bad radiation performance avoid the unnecessary RCS simulation of the method of moment (MoM). However, the fitness calculations for each generation involve both of the radiation and scattering factors, which maybe lead to an inefficient solution. In [13], combined with the high frequency simulation software (HFSS), a genetic algorithm (GA) is proposed to design two low RCS slot antennas. Some strategies, such as separation of radiation and scattering models, elitist selection and two-point crossover, are used to speed up the convergence of the GA.

Although the GA is robust and widely used in EM optimization, it needs to call the time-consuming EM simulation solver hundreds of times to converge to a global extremum. Therefore, how to reduce the amount of calls of the EM solver is a key issue to improve the optimization efficiency. To possess quicker convergence and obtain global optimum in the most probability, a tabu search algorithm (TSA) is embedded into GA for multilayer optical coating optimization and yard cranes scheduling [14]-[15]. The TSA, as a local search procedure, is a very efficient optimization algorithm whose tabu list avoids the repeats of search. In this article, more exact optimized solutions can be obtained through controlling the searching neighborhood region from the parameter sweeping. For the proposed hybrid algorithm, the GA is applied as the main frame due to its global ability and the improved TSA is embedded into the GA to overcome the disadvantages of slow convergency of GA.

2. Hybrid Optimization Algorithm

Presently, GA has been widely applied to the optimization of various EM problems [16]. It has a particular parallel mechanism that guarantees the diversity of solution to a certain degree. But its converging speed will become slow when the solution approaches the optimum. For our proposed hybrid algorithm, GA is applied as the main frame because the global information can be clearly reflected with the strong ability of general search. A simplified TSA is embedded in GA to overcome the disadvantages of GA. For the low RCS patch antenna design, the flowchart which consists of the optimization module and simulation module is shown in Fig. 1. The optimization module obtains optimized individuals of next generation and controls HFSS with VBScript. With the VBScript, HFSS returns its results to the optimization algorithm for calculating the fitnesses after finishing a simulation of the present generation. The two processes are being run alternately until the program is terminated or an optimal solution is got.

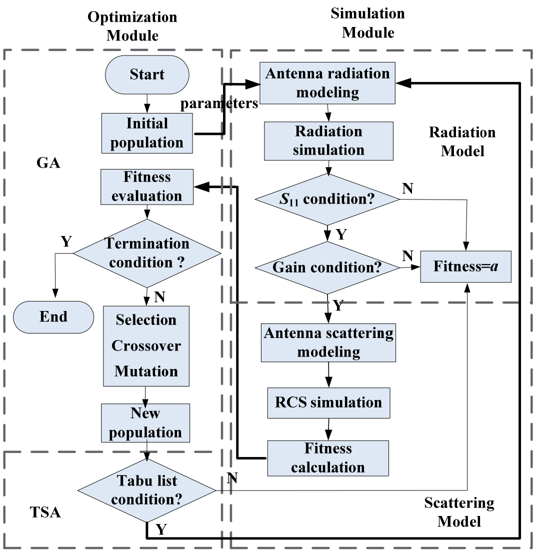


Fig. 1. Flowchart for the low RCS antenna design.

2.1 A Simplified TSA

TSA enhances the search performance by using a tabu list that describes the visited solutions or user-provided sets of rules. If a potential solution has been previously visited within a certain short-term period or if it has violated a rule, the algorithm does not consider its possibility repeatedly. The most important feature of the simplified TSA in this article is to prevent the revisiting of local minima in the parameter space. The tabu list is adopted to depict the features of acceptable individuals and judge the candidates to be simulated or not for the next step. Some parameter information, which has important effect on the radiation performance of antennas, is evaluated by the tabu list. Each individual gets a score determined by a criterion to judge its quality. If the score is low, which means that this individual is not similar to the feature of bad individuals, it will be sent to HFSS simulation. If the score is high, parameters of the individual incorporate more bad features and it will not take time in conducting the simulation in HFSS for it.

In the classical TSA, the search progresses by iteratively moving from the current solution to an improved solution in the neighborhood. Instead, the proposed TSA mainly aims at picking out the individuals with unacceptable radiation performances, which will not be sent to be simulated in HFSS. The tabu list with the effect of parameters is established by pre-determination from parameter sweeping in HFSS. Through the use of the memory structure, the amount of time-consuming simulations will be largely reduced. The score for each individual is given by

$$Score = \sum_{i} a_i \, | \, x_i - T_i \, |, \; i = 1,2,3,... \tag{1}$$

where a_i is the empirical scale factor which stands for the influence of an optimized parameter, x_i is the optimized parameter, and T_i is the corresponding threshold value that determines an acceptable neighborhood of each solution in $| \, x_i - T_i \, |$, where $| * |$ is a norm.

2.2 Optimization for Low RCS Antennas

The initialized population in Fig. 1 is made up of the randomly created chromosomes. Each chromosome coded by a binary number represents an individual prototype of an antenna structure. In the binary coding, the parameters x_i are each represented by a finite length binary string. The combination of all the encoded parameters is a string of ones and zeros.

Firstly, each individual in a new population generated by the GA will be evaluated by the tabu list. If the score is higher than a given value, which means the individual in a poor-scoring area, its fitness value is set to a large number a and it will not be sent to HFSS with simulation. The acceptable individuals with small scores will be sent to be simulated in HFSS through the VBScript. Secondly, according to their geometry parameters, the antenna radiation models are established and calculated in HFSS. Thirdly, if the individuals meet the radiation requirements, such as S_{11} and gain conditions, their corresponding scattering models are established and fitness values are calculated. Otherwise, the fitness value is set to the large number a and the scattering simulation is skipped. Thus, a waste of time to simulate scattering models of the worse individuals is avoided. Last, the fitness of each individual of the current generation is transferred to GA and the parameters of individual are optimized to produce a new population. The fitness function is defined as follows:

$$fitness = \sum_{j=1}^{N} \left(\frac{1}{M} \sum_{i=1}^{M} A_{\mathrm{RCS}(i)} \right) \tag{2}$$

where M is the number of the RCS sample point versus frequencies, A_{RCS} is the RCS value of an individual antenna, and N represents for the different incident angles.

According to the results of fitness evaluation, individuals are selected by the proportionate selection strategy. The selected individuals act as parents for a two-point crossover to rearrange the genes for producing better combinations of genes. Therefore, a new generation will have more fit individuals than the former one. In order to speed up the convergence of GA, a certain amount of best individuals are saved and inserted into the new generation directly in the elitist strategy. Moreover, the TSA reduces the consuming time of EM simulations, too. In order to avoid sticking at local optima, the mutation occurs with a low probability, of a value of 0.01 in this article. After the GA produces a new generation, the individuals in the new population are evaluated by the tabu list and sent to HFSS for simulation again. The simulation and optimization are run alternatively until the termination condition is satisfied.

3. A Low RCS Slot Antenna Example

As an example, a slot patch antenna, shown in Fig. 2, is studied. The substrate is 2 mm thick RT5880 with a relative permittivity of 2.2. The coaxial feed probe is 3.3 mm beneath the center of the patch. The width of each rectangular slot on the patch and ground is 2 mm. The parameters to be optimized are the slot location P_i (i=1, 2, 3) on patch and G_j (j=1, 2, 3, 4) on ground, and slot length l_{Pi} (i=1, 2, 3) and l_{Gj} (j=1, 2, 3, 4). A rectangular patch antenna without slots is used as a reference antenna, with a patch of 41.6×32 mm^2 on a ground of 80×70 mm^2.

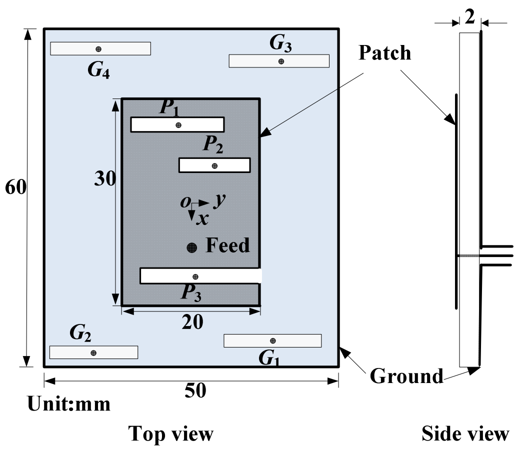


Fig. 2. Geometric structure of the optimized slot antenna.

Sweeping each optimized parameter in HFSS before the whole optimization process is needed to determine a_i and T_i in (1). As mentioned above, the tabu list is obtained with the radiation requirement, and the operating frequency of 2.2 GHz is considered here. Taking the length l_{Pi} of the three patch slots for example, Fig. 3 plots the results of parameter sweeping. So, a_i is appropriately determined by the slope of each curve, and T_i is appropriately the value corresponding to 2.2 GHz for each curve, respectively. For example, the value of 12 mm can be extract from the intersection of the dot line and circle line, which stands for the threshold value of l_{P1}. Because the slope of l_{P3} curve is larger than those of l_{P1} and l_{P2}, the empirical scale factor a corresponding to l_{P3} is chosen larger than the two others. Similarly, a_i and T_i corresponding to the locations P_i of the patch slot can be obtained through the parameter sweeping. Thus, a tabu list can be established from Fig. 3, as shown in Tab. 1. Here, only the positions and lengths of patch slots are involved because the effect of ground slots on radiation performance is relatively weak. Through the use of tabu list, about one fifth of the individuals in a population avoid the unnecessary radiation simulation in HFSS in this design.

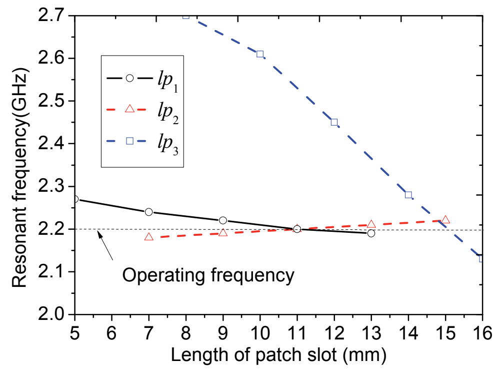


Fig. 3. Parameter sweeping for the lengths of patch slots.

	P_1	P_2	P_3	l_{P1}	l_{P2}	l_{P3}
a	1	2.5	2	3	3	5
T(mm)	(-10,-3)	(-5,3)	(7,2.5)	12	11	15

Tab. 1. Information of the tabu list.

A population incorporates 40 individuals and the maximal iteration of generation is 10. The acceptable radiation performance is set as S_{11} < -15 dB and gain > 7dB, respectively. Besides, the best 10% individuals of population have been considered as the elitists. The optimization results are listed in Tab. 2.

Patch slots		
	Location (x, y)	lP
P1	(-10.4,-0.65)	14.3
P2	(-2.9,2.85)	10.5
P3	(8.6, 1.6)	16.8
Ground slots		
	Location (x, y)	lG
G1	(17.6, 16.7)	14.8
G2	(24.2, -16.15)	16.9
G3	(-27.6, 14.35)	14.3
G4	(-27.8, -17)	13.4

Tab. 2. Geometry of the optimized slot antenna (unit: mm)

Fig. 4 shows the convergence for RCS reduction of the hybrid GA, non-elitist GA and elitist GA programs, which consist of the minimum values of average RCS of different incident angles for each generation. From Fig. 4, the convergency speed of the hybrid GA, which involves the parameter sweeping in HFSS before optimization process, is higher than that of the Non-elitist GA and elitist GA.

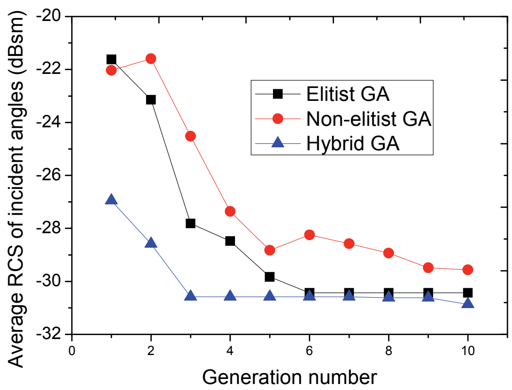
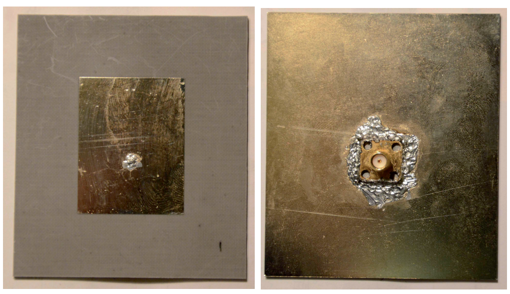


Fig. 4. Convergence for RCS reduction of three GAs.

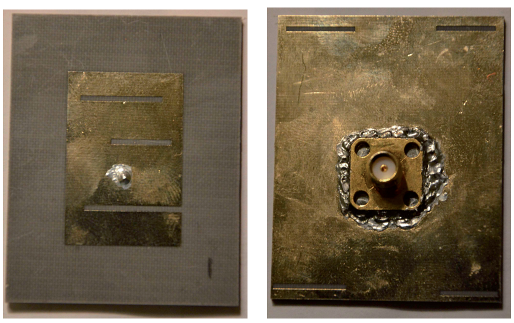
Tab. 3 shows the calculation time of the three GAs. Because the simulation time in HFSS is much more than the GA operation time in Matlab, only the CPU time of HFSS simulation is given in Tab. 3. All calculations are performed on an AMD X6 2.8-GHz and 4G RAM machine. Although more CPU time is required for parameter sweeping in the hybrid GA, more than 20% of individuals in a population are not sent to HFSS for radiation simulation with the tabu list, which leads to an efficient solution.

	Elitist GA	Non-elitist GA	Hybrid GA
Parameter sweeping	---	---	4617
Radiation simulation	27640	28462	21376
Scattering simulation	16552	17068	11945
Total time	44192	45530	37938

Tab. 3. Calculation time for three GAs (unit: sec).



(a) Reference antenna



(b) Slot antenna

Fig. 5. Photographs of the antennas with top and back views.

The photographs of the reference and slot antennas are shown in Fig. 5. Fig. 6 depicts the simulated and measured return losses of the two antennas. Both their resonant frequencies are about 2.17 GHz. The simulated *xoz*-plane and *yoz*-plane radiation patterns of the antennas at 2.17 GHz are shown in Fig. 7. The slot antenna has normal radiation performance compared with that of the reference antenna.

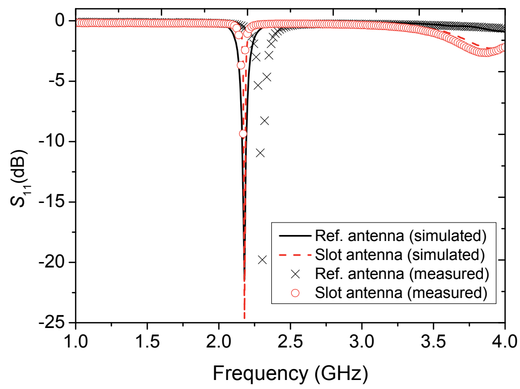
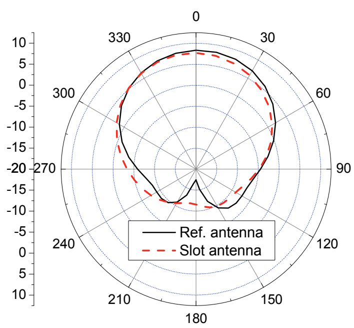
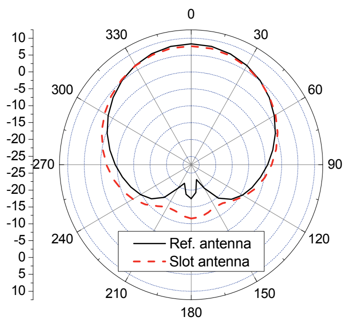


Fig. 6. S_{11} of the reference and slot antennas.



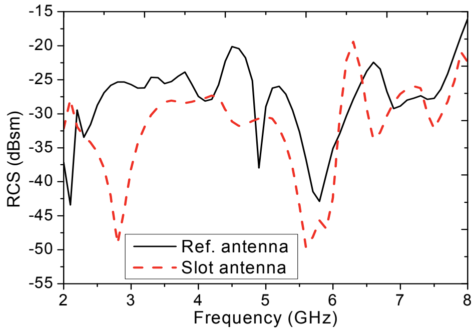
(a) *xoz*-plane



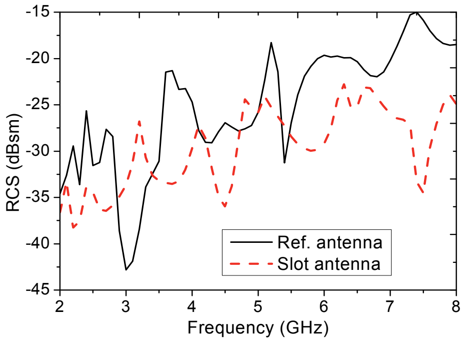
(b) *yoz*-plane

Fig. 7. Simulated radiation patterns of the reference and slot antennas at 2.17 GHz.

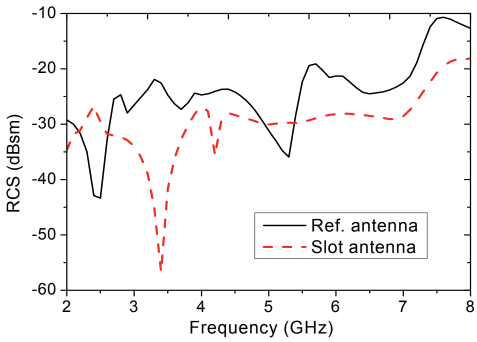
The comparisons of simulated RCS versus frequency between the slot and reference antennas for different incident angles are shown in Fig. 8. The incident plane wave is with the θ polarization. As shown in Fig. 8, the monostatic RCS of the optimized slot antenna is reduced in the frequency range of 2-8 GHz compared to that of the reference antenna.



(a) Incident angle $(\theta = 60^o, \varphi = 0^o)$



(b) Incident angle $(\theta = 60^o, \varphi = 45^o)$



(c) Incident angle $(\theta = 60^o, \varphi = 90^o)$

Fig. 8. Simulated RCS of the reference and optimized slot antennas.

4. Conclusions

This article proposes a simple and efficient approach that combines the GA/TSA optimizer with HFSS to design low RCS patch antennas. About one fifth of the individuals in a population are not sent to HFSS for simulation through the use of tabu list. And this largely reduces the consuming time. In addition, the proportionate selection together with the elitist model for the selection strategy and the two-point crossover accelerate the convergence of the GA. The data exchange between the optimization module and simulation module is realized automatically by the VBScript language. The results show that the optimized slot antenna achieves the obvious RCS reduction in a broad frequency range from 2 to 8 GHz at different incident angles, while it maintains good radiation performances.

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About Authors ...

Wei SHAO was born in Chengdu, China in 1975. He received the M. Sc. and Ph. D. degrees in Radio Physics from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2004 and 2006, respectively. He joined the UESTC and is now an associate professor. He has been a visiting scholar in the Electromagnetic Communication Laboratory, Pennsylvania State University in 2010. His research interests include the computational electromagnetics and antenna technique.

Xinyue ZHU was born in Henan, China in 1985. He received the B. E. degree in Henan Polytechnic University, Jiaozuo, China, in 2009. From 2009 to now, he is pursuing the M. Sc. degree in the Institute of Applied Physics at UESTC, Chengdu, China. His current research interests include the antenna design and optimization method.