

An Efficient Topology-based Optimization Method of Broadband Absorbing Material

Li Yiran, Gentaro Konishi, Megumi Saito, and Shigeru Shimamoto

Department of Communications and Computer Engineering, Waseda University, Japan

{yiran2020@moegi, gkonishi@fuji, megumi.saitou@ruri, shima@}waseda.jp

Abstract—Metamaterial has been applied as a new type of radar absorbing material. In the face of increasingly more complex structures, optimization algorithms have become a mainstream method for structure design. Electromagnetic simulations need a lot of time, and in order to improve development efficiency, it is necessary to reduce the use of electromagnetic simulations as much as possible. This paper proposes an efficient topology-based optimization method by combining the surrogate model and Genetic Algorithm (GA), named it as surrogate model/GA. This method uses a less complex surrogate model instead of the electromagnetic model. With sufficient database, using surrogate model greatly reduce optimization time while maintaining high accuracy. Compared with existing optimization studies, the proposed method greatly improves the efficiency. It could achieve wider absorption frequency band after the same optimization time. This method is easy to implement, it could be applied to more complex topology-based structures and the design of other metamaterials.

Keywords— optimization method; topology-based structure; genetic algorithm; surrogate model; kriging interpolation

I. INTRODUCTION

With the continuous development of marine precision guidance technology and detection radar, the anti-radar detection materials have also achieved unprecedented development. In reducing target radar echoes with certain radar characteristics, shape design and the use of absorbing materials are the most common ways. The radar stealth based on shape design is to use system engineering theory to optimize the shape and structure of stealth targets, so that the reflected radar wave energy of the target deviates from the radar emission direction, thereby effectively reducing the average Radar Cross Section (RCS) [1] of the target. However, the shape stealth has obvious limitations. First, the excessive requirements on the shape may affect the hydrodynamic performance of the equipment and reduce the containment space; Second, the decrease of the RCS in a certain angle will inevitably increase the RCS in some other angles. With the development of intensively distant radio communication and over-the-horizon radar systems in the range of high frequencies (HF) [2],[3], it is impossible to reduce the target RCS at the same time in the full three-dimensional range. Therefore, fundamentally endowed the target with excellent stealth performance must rely on materials intrinsic stealth function, i.e. the development of radar absorbing materials.

Metamaterial has been applied as a new type of absorbing material. Due to the structure type diversity and the sensitivity, it is not enough for the design to simply rely on physical models and human experience. Therefore, using mature optimization algorithms have become an important way for metamaterial design. As a novel optimization design method, topology-based optimization [4] overcomes the shortcomings that mentioned above. In [5], the author proposes an optimization-design method for the Frequency Selective Surface (FSS) based on the GA incorporated with a geometry-refinement technique. In [6], it proposed a hybrid algorithm called HIGAPSO, which combine PSO and GA algorithms to improve the convergence speed and the optimum search ability. In [7], the author developed the topology optimization method based on GA, which further improve the convergence speed. The current researches on this field are generally based on improve GA algorithm. However, simply using GA will generate a huge number of electromagnetic simulations and consume a lot of time.

This paper combined GA with the surrogate model to design an efficient topology-based optimization method [8], [9]. First, a series of binary codes are randomly generated by genetic algorithm according to certain rules, then modeling and mathematical evaluations are performed after decoding according to the corresponding mechanism. This method uses Kriging interpolation as the surrogate model instead of the electromagnetic model for the evaluation. By using the kind of mathematical model can greatly reduce the time required for simulation. This paper is organized as follows. In Section II, introduce the model used for optimization in this paper. In Section III, explain the use of surrogate model and present the proposed method. In Sections IV, compare and analyze the optimized results by GA and surrogate model/GA. Finally, draw the conclusion in Section VIII.

II. STRUCTURE MODEL AND ANALYSIS

The topology-based structure is loaded on the dielectric substrate (epoxy-based glass fiber, hereinafter referred to as FR4), which loaded with the metal backplane. The metamaterial encoding includes two parts: topological encoding and parameter encoding. The topological encoding structure is shown in Figure. 1. Divide the surface of the metamaterial into $M \times M$ Grids, each small unit is filled with 0 or 1, where 0 represents no surface structure, and 1 represents

this unit structure filled with corresponding materials. In the binary optimization, the longer the encoding, the less conducive to the convergence of the optimization algorithm, i.e. the less likely it is to find the optimal solution within a limited range. Therefore, the code length will be shortened as $(M \times M)/4$ according to the axisymmetric binary code.

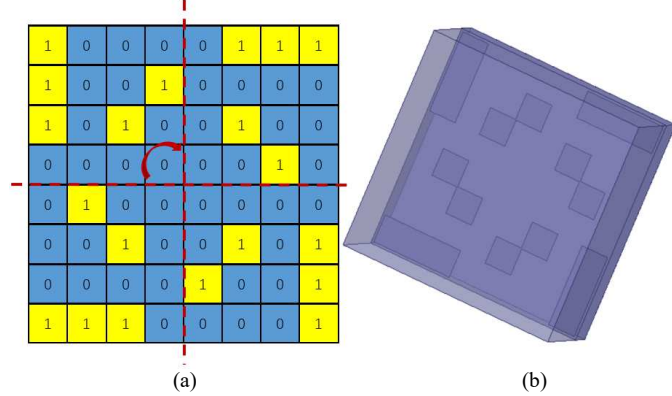


Figure 1. Schematic of the topological encoding method
(a) example of encoding; (b) electromagnetic structure

Parameter encoding is to encode some other structure parameters. The decoding process of parameter encoding is like:

$$Sub_H = Sub_{H_{min}} + 0.2 * (8 * P_1 + 2 * P_2 + 2 * P_3 + P_4) \quad (1)$$

$$R = R_{min} + 16 * P_5 + 8 * P_6 + 4 * P_7 + 2 * P_8 + P_9 \quad (2)$$

$$P = P_{min} + 16 * P_{10} + 8 * P_{11} + 4 * P_{12} + 2 * P_{13} + P_{14} \quad (3)$$

$$tpbits = T(1:16) \quad (4)$$

where Sub_H , R , P represent the binary code of the periodic unit structure, the thickness of the substrate and the square resistance of the resistor value respectively; $Sub_{H_{min}}$, R_{min} , P_{min} are the minimum value of the unit structure parameter, here set $Sub_{H_{min}} = 3$, $R_{min} = 35$ and $P_{min} = 6$.

Set the reflectance of the absorbing composite material as $R(w)$, transmittance as $T(w)$ and absorbance as $A(w)$, according to the equivalent circuit theory:

$$R(w) = |S_{11}|^2, T(w) = |S_{21}|^2 \quad (5)$$

$$A(w) = 1 - R(w) - T(w) = 1 - |S_{11}|^2 - |S_{21}|^2 \quad (6)$$

where S_{11} and S_{21} represent the reflection coefficient and the transmission coefficient. In this structure, because the reflective back plate is loaded at the bottom of the material, $T(w) = 0$,

$A(w)$ can be expressed as:

$$A(w) = 1 - R(w) = 1 - |S_{11}|^2 \quad (7)$$

Therefore, the target of improving the absorbing ability is transformed into making S_{11} sufficiently small.

III. OPTIMIZATION METHOD

For the purpose of further improving the efficiency of topology-based optimization, the most critical issue is how to avoid excessive electromagnetic simulations. In this paper, the core idea is to use surrogate model instead of electromagnetic

simulation when evaluating the performance of different structures.

A. Kriging Interpolation

This paper uses Kriging interpolation [10] to establish the surrogate model. It first considers the distribution of the function value in space and determines the range that has an impact on the value of a point to be interpolated, and then uses the sampling points in this range to estimate the value of this point. This model consists of two parts, i.e. a regression function based on sampled points data, plus an error vector based on Gaussian random process. An unknown point in this model can be expressed as:

$$Y(x) = f(x) + Z(x) \quad (8)$$

where $f(x)$ represents the regression function, $Z(x)$ represents a Gaussian random process. In an optimization problem, the value of an unknown point can be expressed by Kriging as:

$$f_p(x) = \mu + \varepsilon(x) \quad (9)$$

where μ represents the mean value of the response function at the surrounding base points, $\varepsilon(x)$ represents the error value when take 0 as the expected value. Here the error value is given in the form of a correlation function, which is determined by the distance between the desired point and the surrounding base points.

If the algorithm uses this model to completely judge the quality of new solution, it needs a lot of sampling points to get an extremely high accuracy, which will undoubtedly take more time. In order to solve this problem, this paper will screen the newly generated solutions in each generation, select the individuals with the best performance among them, and then use accurate electromagnetic simulation to calculate. There are two advantages of doing this:

- There are constantly new simulation data added to the existing database, and the surrogate model is established based on the database. Therefore, it will become more and more accurate;
- Only one individual is finely simulated in each generation, which requires less time.

B. Surrogate Model/GA

The steps of surrogate model/GA in this article are as follows:

Step 1. Set the basic parameters: including the binary variables to be optimized and some parameters of GA.

Step 2. Initialize the database: extract sampling points and use electromagnetic simulation to calculate.

Step 3. Compare with termination condition: if the termination condition is met, then output the best result in the database; if it is not met, continue to Step 4.

Step 4. Form the population: sort all the solutions in the database, then take N_p best solutions to form a population.

Step 5. Generate the offspring: do the cross mutation operation of GA on the previous generated population.

Step 6. Establish surrogate model: use the sampling solutions in the current database to build a surrogate model.

Step 7. Update database: record the best individual selected by surrogate model, calculate its fitness value using electromagnetic simulation. Add the solution to the database and then return to Step3.

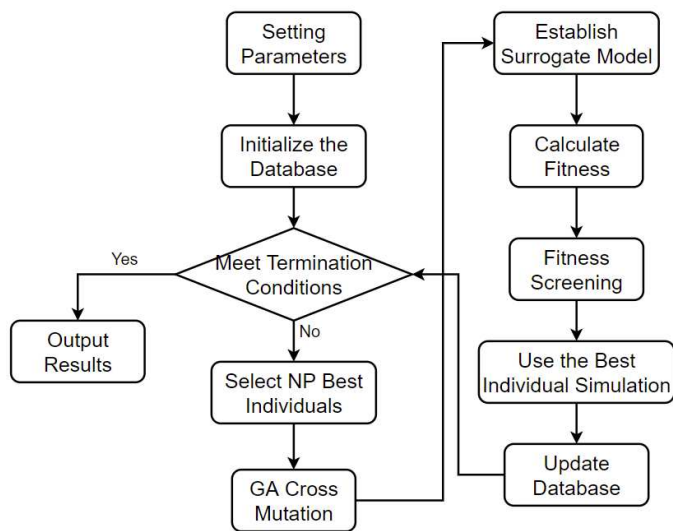


Figure 2. The combined simulation system flow chart of surrogate model/GA

In order to apply GA to the metamaterial design, this paper uses the method of MATLAB and HFSS co-simulation for topology-based optimization design. Uses MATLAB as the main program to run the optimization algorithm, and repeatedly calls HFSS for modeling, condition setting, simulation, and finally returns the evaluation results to the main program to form a loop. The flow chart is shown in Figure. 2. Because individuals with better performance have a similar structure and the Kriging interpolation contributes more to the function value of the unknown point when the sampling points are near to it. It is accurate to use this way to establish the surrogate model.

IV. RESULTS AND DISCUSSION

In order to verify the effectiveness of this method, GA and surrogate model/GA are both used in this section to optimize the topology-based structure introduced above. To verify which method is more efficient, the target is to find which can get better results after passing same time. The relevant parameters are set as follows:

TABLE 1. PARAMETER SETTINGS

Initial sampling point	30
Maximum sampling point of surrogate model	75
Population size	20
Differential scaling factor	0.8
Crossover probability	0.8
The maximum number of evaluations	100

Both simulations are executed on the same computer, which average time of an electromagnetic simulation is about 50-70s. The specific performance parameters of this computer are as follows:

- CPU model: Intel(R) Core (TM) i7-10875H,
- Graphics cards: NVIDIA GeForce RTX 2600.

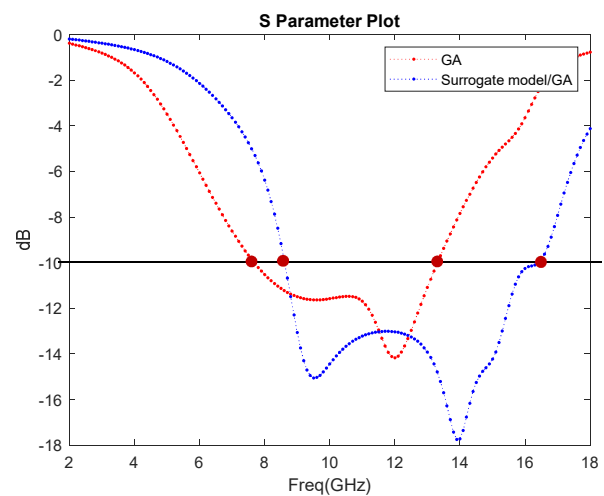
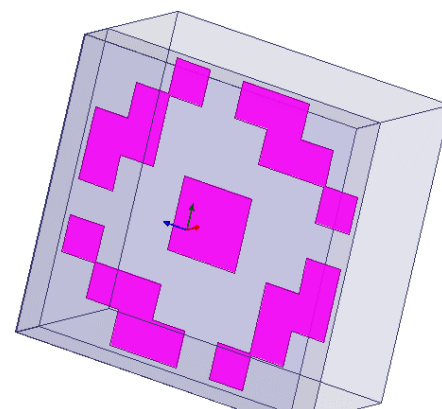
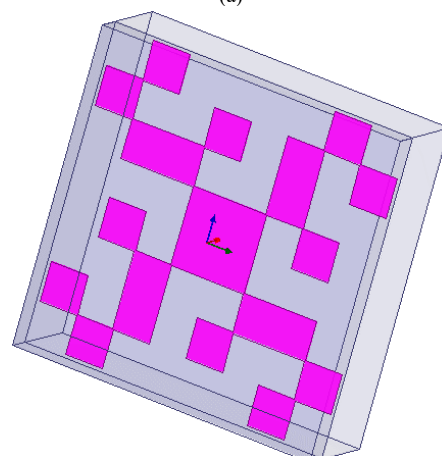


Figure 3. The corresponding S11 curve of the optimized absorbing material by GA (blue) and surrogate model/GA (red)



(a)



(b)

Figure 4. (a) The optimized structure by GA; (b) The optimized structure by surrogate model/GA

The optimized structures are shown in the Figure. 4. In Figure. 3, the red line shows that the S11 values of the structure optimized by GA are less than -10dB in 7.6 ~ 12.5GHz. The blue line shows that the S11 values of the structure optimized by surrogate model/GA are less than -10dB in 8.6 ~ 16.4GHz.

TABLE 2. COMPARISON OF TWO METHODS

	Time Consuming	Absorbing Frequency Band
GA	63 min	7.6~12.5GHz(4.9GHz)
Surrogate model/GA	59 min	8.6~16.4GHz(7.8GHz)

When using GA, the simulation must be done in each evaluation, which means electromagnetic simulation is used 20 times in each generation. Therefore, 100 times simulation means the optimization has only been carried out for 5 generations. While in surrogate model/GA electromagnetic simulation is used only during model establishment and verification of each generation. The optimization can carry out for 100 generations. The fitness value in Figure. 5 represents the proportion of frequency bands that cannot be absorbed, it can be seen that this method has found the best design parameters in the 76th generation.

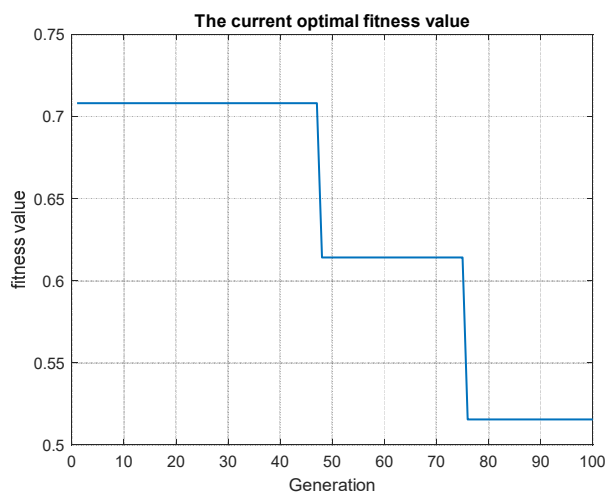


Figure 5. The evolution curve of surrogate model/GA

In future research, there are still many issues that could be further explored. For example, the surrogate model used in this article is the Kriging interpolation. In fact, there are many other excellent surrogate models to choose, such as Artificial Neural Networks (ANN), Support Vector Machines (SVM), Radial Basis Functions (RBF), and so on. For different problems, choosing different surrogate models may further improve optimization efficiency and accuracy.

V. CONCLUSIONS

This paper proposed an efficient topology-based optimization method for broadband absorbing material called surrogate model/GA. This method combined GA and surrogate

model. Using surrogate model to evaluate the performance of different structures can avoid excessive electromagnetic simulations. In section IV, use this method to optimize a topology-based metamaterial structure and designed an absorbing material that could work between 8.6 ~ 16.4GHz. Compared with only use GA with the same optimization time, the use of the surrogate model/GA has a certain improvement in the quality, the range of absorbing wave band has been expanded by 1.6 times larger. It could be clearly seen that the use of this method greatly improves the optimization efficiency of topology-based absorbing material.

The model in the article is just an example, this method can be applied to more complex topology-based structures. It is also practical in the design of other metamaterials such as Frequency Selective Surfaces (FSS) and electromagnetic band gap structures. The future work will include applying this method in other models and choosing different surrogate models for different problems.

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networks.

Li Yiran was born in Henan province, China, on October 5, 1998. She received the B.E. degree in electrical and electronic engineering from China University of Mining and Technology, Jiangsu province, China in 2020. Currently she is pursuing the M.E. degree with the Department of Computer Science and Communications Engineering, School of Fundamental Science and Engineering, Waseda University. Her research interest includes optimization methods and communication



Gentaro Konishi was born in Kanagawa Prefecture, Japan, on October 15, 1997. He received the B.E. (Hons) degree in electrical and electronic engineering from The University of Auckland, Auckland, New Zealand in 2020. Currently he is an Assistant Researcher and is working toward the M.E. in computer science and communications engineering at Waseda University, Tokyo, Japan. His early research was concerning the design and optimization, as well as the additive

manufacturing of passive microwave devices. More recently, he has been involved with the electromagnetic analysis and challenges related to radio frequency identification systems in achieving multiple access.



Megumi Saito (S'15-M'20) received the M.S. degree from the Graduate School of Global Information and Telecommunication Studies, Waseda University, Japan, in 2014, where she is currently pursuing the Ph.D. degree with the Department of Computer Science and Communications Engineering, School of Fundamental Science and Engineering. She is also an assistant professor at Waseda University. Her research interest includes D2D and cooperative access schemes in cellular

networks.



Shigeru Shimamoto (Member, IEEE) received the B.E. and M.E. degrees in communications engineering from The University of Electro-Communications, Tokyo, Japan, in 1985 and 1987, respectively, and the Ph.D. degree from Tohoku University, Japan, in 1992. From 1987 to 1991, he joined NEC Corporation. From 1991 to 1992, he was an Assistant Professor with The University of Electro-Communications. From 1992 to 1993, he was an Assistant Professor with the Department of Computer Science, Gunma University,

where he was also an Associate Professor, from 1994 to 2000. Since 2002, he has been a Professor with the Graduate School of Global Information and Telecommunication Studies, Waseda University. In 2008, he served as a Visiting Professor with Stanford University, USA. In 2014, he became a Professor with the Department of Communications and Computer Engineering, Waseda University. His research interests include satellite and mobile communications, access scheme, and unmanned aerial vehicle for disaster networks. (Based on document published on 13 May 2020).