Optimization Design of Electromagnetic Characteristic Parameters of Grid Structure Based on Simulation Design and Response Surface Method

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Abstract: In order to obtain the rapid evaluation of the electromagnetic shielding characteristic parameters optimization of the grid structure, a response surface was introduced in the design process. The optimization model is established with the shielding efficiency of the single hole grid as the optimization objective and the electromagnetic shielding law as the constraint condition of the geometric parameters of the grid. According to the response surface model, the optimal grid geometric parameter combination is obtained. The finite element method and Ansys software are used to simulate the optimization target, and the effectiveness of the optimization results is verified. The results show that the transmission coefficients of the optimized parameters under TE polarization and TM polarization are -139.5dB and -69.17dB, respectively, which are reduced nearly 7 times and 4 times, proving the effectiveness of the optimization.

Keywords: Response surface method; Parameter optimization; Rapid assessment

1. INTRODUCTION

In the research process of electromagnetic shielding characteristics of grating structure, there are many geometric variable parameters and complex conditional forms of incident field(SANG 2013)[1].Traditional electromagnetic stealth calculation uses multi-layer fast multi-pole algorithm to simulate the grid model as a whole. This method has high calculation accuracy, but long calculation time. The above method requires a large number of experiments for repeated iteration to obtain better optimization results (YU 2022,ZHANG 2018)[2-3]. Therefore, many researchers use proxy model method instead of complex simulation calculation, in order to reduce the optimization design cycle and improve optimization efficiency.

Agent models usually delimit parameter ranges and build parameter Spaces first. If the function values corresponding to several adjacent points within a certain radius of a design point are known, the data points around the design point can be interpolated and fitted (LIU 2017)[4]. Response surface Modeling (RSM) is a common proxy model method. In the process of optimization design, RSM models analyze the research objectives according to different objective functions and constraints. In 2015, Li Yan used the response surface method instead of the finite-element method to quickly evaluate the flitter of the aircraft wing surface. The results of sampling inspection showed that this method could meet the needs of engineering

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accuracy (LI 2017)[5]. In 2019, Du Xiaojia et al. combined Kriging proxy model with adaptive genetic algorithm to construct a fast optimization calculation method for radar wave stealth by reducing the RCS of ship masts. The experimental results reduce RCS by 61% compared with the initial scheme (DU 2019)[6].

The purpose of this paper is to improve the electromagnetic shielding characteristics of the multi-scheme grid structure with variable parameters, and to understand the contribution of each parameter variable to the stealth optimization. It is hoped to identify the parameters that have the main impact through RSM, and analyze the coupling effect between each parameter. Thus, the optimal design parameter range of the grating unit is found, and the shielding efficiency of the grating unit is optimized finally. The results show that when the geometric design parameters of the grid are: L=8mm; w=1.5 mm; φ=20°; h=13 mm; When θ=70°, the shielding ratio can be greatly increased, and the complete shielding within the observation bandwidth can be realized.

2. ELECTROMAGNETIC ANALYSIS OF CHARACTERISTICS OF GRID

2.1 Simplified principle and computational boundary conditions of lattice periodic structure

The lattice structure is a typical periodic structure. Floquet theorem can be used to describe the characteristics of electromagnetic wave propagating along the periodic structure. Since the surface of the intake cavity is divided into many small rectangular waveguide cells by multiple sets of horizontal or vertical metal grilles, the electromagnetic shielding of the grilles can be studied using rectangular waveguide mode transmission theory.

FIG. 1 shows the schematic diagram of the S-parameter of the two-port network. T1 and T2 represent the normalized incoming wave voltage and reflected wave voltage on the two reference planes. The positive direction of the incident wave voltage is defined as the incoming network and the positive direction of the reflected wave voltage is defined as the outgoing network. S_{12} indicates the transmission coefficient from port 2 to port 1 when port 1 matches.

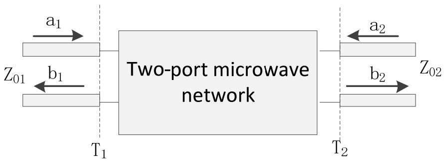


FIG. 1 Schematic diagram of S parameter of dual-port network

For a two-port network, the S-scattering parameter relationship is as follows: Formula 1-3

$$\begin{cases} b_1 = S_{11}a_1 + S_{12}a_2 \\ b_2 = S_{21}a_1 + S_{22}a_2 \end{cases} \tag{1}$$

Examples of two parameters S_{11} ,$S_{21}$are given to illustrate the physical meaning of parameter S in dual-port network. The first is the S11：

$$S_{11} = \frac{b_1}{a_1}\Big|_{a_2=0} \tag{2}$$

S_{11} indicates the reflection coefficient of port 1 when port 2 matches. And for the

$$S_{21} = \frac{b_2}{a_1}\Big|_{a_2=0} \tag{3}$$

S_{21} represents the transmission coefficient from port 1 to port 2 when port 2 is matched

The material of the grid is an ideal conductor, the shape of the unit is selected as diamond, and the medium at both ends of the grid is air. The S parameter can be used to connect the incident wave and the reflected wave, and the shielding problem of the electromagnetic wave of the grid is transformed into the transmission problem of the incident wave.

2.2 Grid element geometry model with custom parameters

Geometric parametric modeling is the basis of comprehensive optimization of stealth performance of intake grille. The commercial software HFSS is used for the parametric geometric modeling of the grille. All models have a 5° pitch Angle. The geometric definition of rhomboid grid element is shown in Figure 2, and the definition of parameter characteristics and symbols are shown in Table 1.

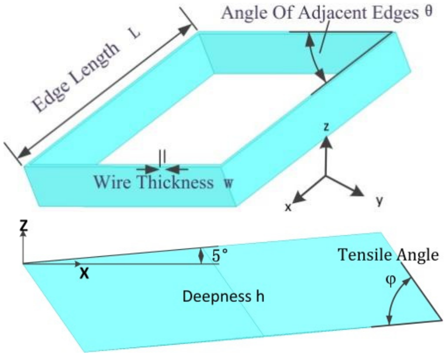


FIG. 2 Front view and side view of the single-hole model

Table 1 Definition and symbols of geometric parameters

Parameter name	Representative symbol	unit
edge length	L	mm
wire thickness	w	mm
deepness	h	mm
tensile angle	φ	°
angle of adjacent edges	θ	°

3. OPTIMIZATION PROCESS OF ELECTROMAGNETIC CHARACTERISTICS OF GRID STRUCTURE BASED ON RESPONSE SURFACE METHOD

3.1 Construction of response surface modelDetermination of design variables

(1) Response surface phase I experiment:

Firstly, the full factor design is used to find the optimal region of the experiment. The fitting linear regression equation is used to judge whether the model is "bending" P value < 0.05. The first-order model approximation formula of the functional relationship between response surface function y and independent variable can be obtained by using the full-factor design, as shown in formula (4)(LIU 2014)[7]:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \cdots + \beta_k x_k + \varepsilon \quad (4)$$

Where ε represents the observed error or noise in response to y; $y = f(x_1, x_2 \ldots, x_k)$; $\nabla f = \left(\frac{\partial f}{\partial x_1}, \frac{\partial f}{\partial x_2}, \ldots, \frac{\partial f}{\partial x_k}\right)$; point p coordinates are $(x_{10}, x_{20}, \ldots, x_{k0}, y_0)$; Suppose $x_{10} = x_{20} = \cdots x_{k0} = 0$ is the base point; The linear equation of the steepest ascending route in the coordinate system can be obtained: $\frac{x_1 - x_{10}}{\frac{\partial f}{\partial x_1}} = \frac{x_2 - x_{20}}{\frac{\partial f}{\partial x_2}} = \cdots = \frac{x_k - x_{k0}}{\frac{\partial f}{\partial x_k}}$

Firstly, the general principal factor design is carried out according to the optimization problem, and the fitting order model is carried out. Then, the "steepest ascending path" is used to seek the optimal region of the experiment. The direction perpendicular to the contour line was selected as the direction of the "steepest ascent path", that is, the experiment was carried out along this direction until the probability of bending in the output result of the full-factor design was significant level.

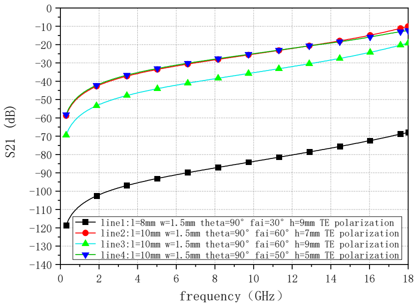
(2) Response surface Phase II experiment:

The response surface test is carried out in the range that has been identified as the optimal region. Different from the above full factor design, the design is expanded into a second order design by using the tightened axial point test scheme and adding star points and central points. The design of star points includes the rotativity of the central composite design, that is, the prediction accuracy of the response variable is the same on the sphere with the design center as the center of the sphere. Then the quadratic/surface regression equation is fitted, as shown in formula (5)(MA 2021)[8]. CCC can be used in the preset area for accurate optimization.

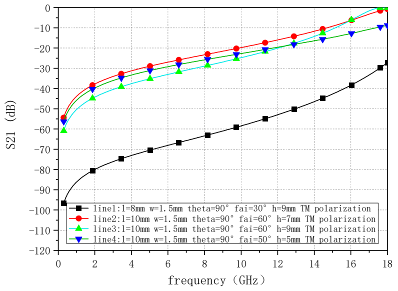
$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j}^{k} \beta_{ij} x_i x_j + \varepsilon \ (5)$$

3.1.1 Determination of design variables

The geometric parameters defined for the shape of the grid (i.e., the edge length of the grid, the wire thickness of the grid, the deepness of the grid, the tensile angle of the grid) represent the 5 design variables in DOE experiment. Each factor in the experiment is set at the 2-factor level, and the horizontal center value is added if necessary. Let the frequency point f_0 with a shielding efficiency of -10dB be the shielding frequency, as shown in FIG. 3. Curves 2 and 4 have the same shielding bandwidth under TE polarization, and curves 3 and 4 have the same shielding bandwidth under TM polarization. Curve 3 and curve 4 are completely shielded under TE polarization, curve 1 and curve 4 are completely shielded under TM polarization, and the shielding bandwidth is the same at 18. Because the same masked bandwidth ratio can represent many different parameter combinations, it cannot be used as the dependent variable. It is found that the integral values of TE and TM polarization transmission parameter curves in the observed frequency band have obvious differentiation degree and consistent correlation with shielding efficiency. Therefore, the integral value of the transmission parameter curve in the observation frequency band is selected as the dependent variable y.



a) TE polarization



b) TM polarization

FIG. 3 Polarization S21 curves of TE and TM with different parameter combinations

3.1.2 Constraints and objective functions

In order to achieve the target of minimum electromagnetic scattering characteristic value, the aperture side length of the grid needs to meet the range where electromagnetic shielding can be realized initially but not completely. Grid linewidth has little effect on electromagnetic scattering and is set as a fixed value. The grid depth should be less than the common value of the project; The range of inclination Angle and Angle between the two sides of the grating is selected as the range with the highest change rate of the single-hole grating S21.

$$\begin{cases} \lambda/4 < L < \lambda/2 \\ \mathrm{w} = 1.5\ \mathrm{mm} \\ h \le 13mm \\ 30° < \mathrm{FAI} < 60° \\ 70° < \mathrm{THETA} < 110° \end{cases} \tag{6}$$

3.1.3 Construct the model test design Affiliations

According to the range of different design variables, the appropriate test sample points were selected and 20 groups of test schemes were obtained. Central composite design CCC adds star points to the model and expands the model. After the expansion, 31 groups of data need to be calculated. As shown in Table 2, the orthogonal horizontal table of response surface method designed by 4 groups of parameters from column 2 to column 5 shows the specific corresponding parameter values intuitively in column 6 to 9, and the last two columns explain the responses of TE polarization and TM polarization under different parameter combinations.

Table 2 Parameter design table of grille response surface method

Number					H	L	THETA	FAI	TE	TM
1	2	0	0	0	17	9	110	40	-2023.97	-924.355
2	1	1	-1	1	13	11	90	60	-1111.19	-1066.78
3	-2	0	0	0	1	9	110	40	-262.328	-143.565
…	…	…	…	…	…	…	…	…	…	…
29	-1	-1	1	1	5	7	30	60	-1140.7	-1077.94
30	1	1	-1	-1	13	11	90	20	-1755.1	-1144.09
31	1	-1	1	-1	13	7	130	20	-3113.29	-1869.3

3.2 Test and analysis of the constructed

The parameter R^2 (determination coefficient) can be used to test the goodness of fit of the model. The closer R^2 value is to 1, the more consistent the model is with the real situation. In the statistical category, the regression analysis R^2 should be at least greater than 0.3. This regulation also serves as a criterion for the reliability of subsequent models. When the variable is increased, the value of R^2 will also increase, which cannot accurately reflect the real impact of the variable on the model, so it is necessary to use the correction determination coefficient for error analysis. The formula for R^2 and R_{adj}^2 is as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \widehat{y_i})^2}{\sum_{i=1}^{n}(y_i - \overline{y_i})^2} \tag{7}$$

$$R_{adj}^2 = 1 - \frac{n - \sum_{i=1}^{n}(y_i - \widehat{y_i})^2}{n - k - \sum_{i=1}^{n}(y_i - \overline{y_i})^2} \tag{8}$$

Where n is the sample size; k is the total number of variables of each order in the model, which can also be expressed as degrees of freedom. y_i is the test value; y_i as the average value of test; $\widehat{y_i}$response values in order to optimize the model. The closer the R_{adj}^2 (adjustment) andR_{adj}^2 (prediction) values are, and the closer they are to 1, the more reasonable the fitting of the optimization model is. Table 3 shows the determination coefficient of the model in this paper.

Table 3 Determination coefficient analysis of response surface method model

Polarization mode	R^2	R_{adj}^2（adjustment）	R_{adj}^2（prediction）
TE	64.62%	57.54%	36.22%
TM	70.35%	58.42%	38.06%

It can be found that the values of both R^2 and R^2_{adj}decreased significantly but did not fall below 0.3, indicating that the same factor level is not enough to form a low error fitting model.

FIG. 4-7 shows the response surface under partial design variable TE polarization mode. In this paper, the parameters that can bend the response surface and their ranges are presented to illustrate the interaction of the two variables on the shielding efficiency. As can be seen from FIG. 6, in TE polarization mode, the shielding efficiency is enhanced with the increase of H, while H remains unchanged, L presents a response surface and a nonlinear increase or decrease relationship, indicating that a coupling effect occurs between parameter H and L. As can be seen from FIG. 8, in the measured area, L and FAI present a nonlinear increase or decrease trend and a coupling relationship.

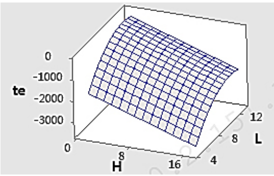


FIG. 4 Coupling relation of H*L

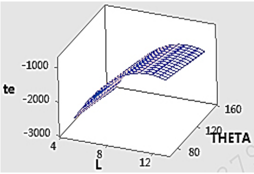


FIG. 5 Coupling relation of L*THETA

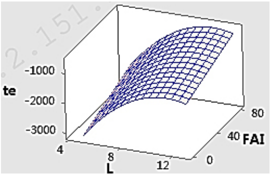


FIG. 6 Coupling relation of L*FAI

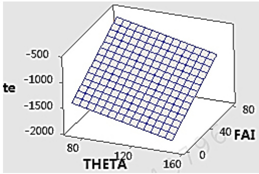


FIG. 7 Coupling relation of THETA*FAI

4. ANALYSIS OF ELECTROMAGNETIC CHARACTERISTIC OPTIMIZATION RESULTS OF GRID STRUCTURE

4.1 Optimization result

FIG. 8shows the parameter contour curve under TM polarization (TE polarization contour curve is similar to TM, so it is not shown here). According to the equivalent curve of the response surface, it can be found that this model is a rising ridge system model, and one or more model feature roots are close to (or equal to) zero in the detection region of you and the model in the second order of the stability point principle.

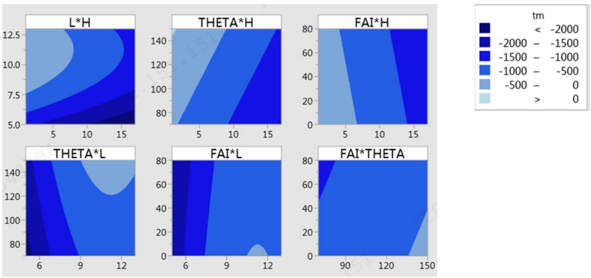


FIG. 8 Parameter contour curve under TM polarization

Therefore, in the process of optimization, the optimal parameter obtained is not a certain set of characteristic values but the optimal value region along the direction of the optimal value rise.

4.2 Optimization result analysis

The optimal parameter is: L=8mm; w=1.5 mm; φ=20°; h=13 mm; θ=70°.FIG.10 represents the polarization curve of parameter L=10mm; h=5mm; φ=20°; θ=60°before optimization.The optimal parameters were used for modeling and shielding efficiency was calculated. The results are shown in FIG. 9: It can be seen that the model electromagnetic shielding efficiency of the grid at the same incidence Angle can achieve complete shielding in the observation band, and the transmission coefficient S_{21} is -34.8dB at 18GHz, and the shielding efficiency is greater than 99%. When the incident wave frequency is 9.375GHz, the transmission coefficients S_{21} under polarization of TE and TM are -139.5dB and -69.17dB, respectively.

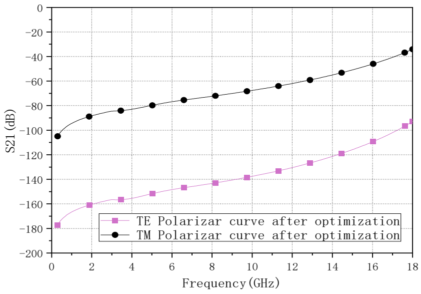


FIG. 9 Grid structure TE, TM polarization S21 curve

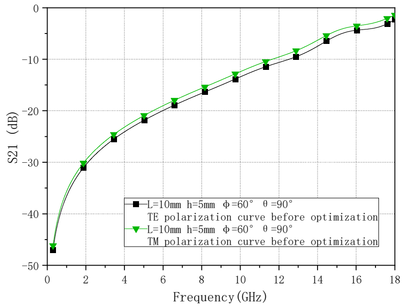


FIG. 10 Optimized front grid structure TE, TM polarization S21 curves

5. CONCLUSIONS

In this paper, full factor model selection is used to verify whether the selection parameter range approximates the optimal parameter range. The response surface method was used to obtain the optimal parameter strip and select the optimal parameter, and the shielding efficiency before and after optimization was compared. The full factor model and response surface model were constructed successively to optimize the grid structure, and the following conclusions were obtained:

1) Coupling effect exists between model parameters. 2) The response surface model R^2 has a low value due to insufficient calculation times of simulation experiments and parameter coupling. If you want to increase the value of R^2, you can continue to expand the number of experiments. 3) This model has several model feature roots close to (or equal to) zero, which is a ridge system. Therefore, the optimal parameter obtained is not a certain set of characteristic values, but the optimal value region along the direction of the maximum value rise. 4) After calculating the electromagnetic shielding efficiency of periodic structure by HFSS finite element method, the transmission coefficients S_{21} under TE polarization and TM polarization are -139.5dB and -69.17dB, which decrease nearly 7 times and 4 times respectively.

REFERENCES

[1] SANG Jianhua. Low-Observable Technologies of Aircraft[M]. Beijing:Aviation Industry Press, 2013:1-5

[2] Zhang le,Zhouzhou.Research on Integrated Design of Aerodynamic and Stealthy Performance with Intake and Exhaust for Flying-Wing Layout[J],2018,(7)

[3] YU longzhou.Electromagnetic shielding principles and technologies of cavity grille[J].Acta Aeronautica et AstronauticaSinica,2022,43(1):324803(inCinese) .doi:10.7527/S1000-6893.2020.24803

[4] Liu Zhenping. Comprehensive Optimization of Airfoil Aerodynamic Stealth Based on Machine Learning [D]. Nanjing: Nanjing University of Aeronautics and Astronautics, 2017

[5] Liu Zhenping. Comprehensive Optimization of Airfoil Aerodynamic Stealth Based on Machine Learning [D]. Nanjing: Nanjing University of Aeronautics and Astronautics, 2017

[6] Du Xiaojia Zhu Xianming Ding Fan Liao Zhangqi. Stealth optimization of ship mast radar based on Kriging agent model [J],2019,v.14; No.83(06)

[7] Liu Zhenxue, Wang li.Experimental design and data processing[M] Beijing. Chemical Industry Press, 2014

[8] Ma qingyong.Structural design of SPS chimney and optimization of Box-Behnken response surface method[J] ship science and technology, 2021, Vol. 43, No. 9