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# Mesh-Deformation-Based Space Mapping Modeling Method for Microwave Device

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***Abstract*— Space mapping modeling technology has been widely applied in the field of microwave device modeling. In recent years, the introduction of coarse-fine mesh mapping technology has made space mapping more versatile. For complex electromagnetic structures lacking equivalent circuit models and empirical models, coarse-fine mesh mapping technology achieves efficient modeling by establishing the mapping function between coarse mesh model and fine mesh model. In this paper, we propose a microwave device modeling method based on the coarse-fine mesh mapping technology. And the application of the coarse mesh model with mesh deformation technique to the spatially mapping microwave device modeling method improves the effective range of geometric size modeling while ensuring the modeling time.**

***Index Terms*—Space Mapping; Mesh Deformation; Microwave Devices; Modeling**

## I.INTRODUCTION

Microwave devices play a crucial role in modern communication, radar, and other fields. Efficient and accurate modeling of these devices is a vital step in system design and optimization[1-3]. Space mapping (SM) technology, as an efficient and rapid modeling method, offers good modeling accuracy and computational efficiency[4-7]. However, when modeling more complex microwave device structures, the traditional space mapping method still has some limitations when it is difficult to obtain equivalent circuit models and empirical models[8-10]. Therefore, to address such challenges in the modeling process, researchers have proposed a space-mapping modeling method based on coarse-and fine-mesh models[11]. This method constructs a coarse-mesh model with a sparse distribution of mesh cells and a fine-mesh model with a dense distribution of mesh cells for microwave devices, and calculates the finite-element numerical solutions of the two mesh models respectively. According to the finite-element analysis theory, the denser the distribution of mesh model cells, the higher the accuracy of the finite-element solution, and correspondingly, the longer the required computation time[12]. The space-mapping modeling method based on coarse-and fine-mesh models achieves modeling by establishing a mapping function between the two, taking into account the faster computation speed of the coarse-mesh model and the higher computation accuracy of the fine-mesh model.

To further improve the modeling speed, this paper proposes a space-mapping microwave device modeling method based on mesh deformation. This method incorporates deformation technology into the coarse-mesh model, enabling the original coarse-mesh to be adaptively adjusted when changing the geometric dimensions of the device structure, eliminating the need to regenerate the mesh structure and increasing the effective size range of single-point modeling. In this paper, a third-order cavity filter is taken as an example, and its coarse-mesh meshing is performed. The mesh deformation technology is added to the model, and the effective modeling range is increased under the same modeling conditions. The method proposed in this paper further enhances the effect of space-mapping modeling, providing a basis for subsequent acceleration of device design optimization.

## II.SPACE MAPPING TECHNOLOGY

Space mapping technology is a relatively efficient modeling method. Its implementation process requires the prior establishment of appropriate coarse and fine models. A coarse model is a model with low computational accuracy but high computational speed. The coarse model in the traditional space mapping method relies on empirical knowledge or equivalent circuit models. A fine model is a model with high computational accuracy but low computational speed. The space mapping function establishes a mathematical connection between the coarse model and the fine model, and adjusts the weight parameters of the mapping function through a training process to match the coarse model with the fine model. The mapping function is the core of the space mapping algorithm, enabling the surrogate model composed of the coarse model and the mapping function to combine the fast-calculation advantage of the low-accuracy model and the accuracy of the high-accuracy model[13-15].

The proposed space-mapping modeling method based on coarse-and fine-mesh solves the problem that it is difficult to obtain coarse models such as equivalent circuit models and empirical models in the traditional space-mapping modeling method. In this method, the coarse-mesh model is used as the coarse model, and together with the mapping function, they form a surrogate model to achieve modeling. During the modeling process, the fine-mesh generated by the electromagnetic simulation software is used as the fine model, and training data and test data are generated through the electromagnetic simulation of the fine model. The fine model realizes accuracy control through the convergence process of mesh finite-element calculation. Electromagnetic simulation and mesh refinement are carried out iteratively until the simulation results between consecutive iterations converge[16]. Therefore, fine-mesh simulation is more accurate, but the computational speed is slow. In contrast, the coarse model uses coarse-mesh electromagnetic simulation. In the electromagnetic simulation, only a fixed number of iterations are required, and the convergence of the finite-element calculation results is not necessary. The coarse-mesh model has a high computational speed but low accuracy.

## III.SPACE-MAPPING MODELING METHOD BASED ON MESH DEFORMATION

To improve the modeling speed, this paper proposes the introduction of mesh-deformation technology during the

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modeling process. When geometric parameters change, the mesh-deformation technology is utilized to deform the mesh nodes, eliminating the need to regenerate the mesh model, thus accelerating the modeling speed. Since the number of coarse-mesh elements is relatively small and the computational complexity is low, the deformation operation on the coarse-mesh model can be completed rapidly, greatly improving the modeling efficiency.

### *A. Mesh-Deformation Technology*

The coarse-mesh model is a three-dimensional structure, and its node coordinates, quantity, and connection methods are crucial for the finite-element calculation process. Mesh deformation refers to adjusting the geometric coordinates of the corresponding points in the coarse-mesh model according to the new geometric parameters when the geometric parameters change[17-19]. During the implementation of this method, the number of mesh nodes and the connection method remain unchanged. Therefore, the calculation results of the mesh model using the mesh-deformation technology are continuous. Mesh-deformation technology can be divided into mesh-deformation technology based on physical analogy and mesh-deformation technology based on interpolation. In this paper, the Radial Basis Function (RBF) interpolation mesh-deformation method is adopted. By applying it to mesh deformation, the displacement of the nodes that need to be deformed is calculated to achieve the deformation of mesh elements caused by fine-tuning geometric parameters[20-22].

Radial basis function (RBF) interpolation can be used to achieve smooth deformation of the vertices of mesh cells. In the boundary region of the deformation, RBF interpolation can generate high-quality mesh that maintain good orthogonality. This method does not require mesh connectivity information. The solved system of equations is linear, and the scale of the linear system of equations is proportional to the number of boundary nodes. Calculating RBF interpolation requires a set of center point $c_j$ and corresponding weights $m_j$ , and the radial basis function defined by them is:

$$h(x)=\sum_{j}^{m}\lambda_j\eta(\|c_j-x\|)+q(x) \qquad (1)$$

In the formula, $\eta(\|c_i-x\|)$ is the radial basis function defined at the center $c_j$ , and $q(x)$ is a low-order polynomial function to ensure accuracy. Let $\boldsymbol{\varphi}$ represent the vector of geometric design variables of the fine model, and let $\boldsymbol{\varphi}_c=y(\boldsymbol{\varphi},\boldsymbol{\omega})$ be the input space-mapping function, where $y$ is the input mapping function based on displacement, $\boldsymbol{\varphi}_c$ is the vector of geometric variables of the coarse model, and $\boldsymbol{\omega}$ is the vector of weight parameters in the mapping function $y$ . Let $\boldsymbol{D}^k$ be a $3\times n$ matrix representing the three-dimensional coordinates of all mesh nodes, where $\boldsymbol{D}^k=[d_1^k\ d_2^k\cdots d_n^k]$ . Based on the principle of mesh deformation, $\boldsymbol{D}^k$ can be expressed as a set of continuous functions of $\boldsymbol{\varphi}_c$ . Let $\boldsymbol{K}$ represent the system matrix for solving the electromagnetic response of the coarse mesh using the finite-element method, and calculate $\boldsymbol{K}$ based on the three-dimensional coordinates $\boldsymbol{D}^k$ of all mesh nodes. Let $R_c^k$ represent the electromagnetic response of the coarse mesh, which includes the mesh deformation corresponding to $\boldsymbol{\varphi}_c$ during the $k$ -th set of geometric parameter modeling. The formula is as follows:

$$R_c^k(\boldsymbol{\varphi}_c)=\boldsymbol{c}^T[\boldsymbol{K}(\boldsymbol{D}(\boldsymbol{\varphi}_c))]^{-1}\boldsymbol{e} \qquad (2)$$

Among them, $\boldsymbol{c}$ and $\boldsymbol{e}$ are the constant vectors required for the finite-element calculation of the electromagnetic response in electromagnetic simulation. By introducing mesh deformation, the mesh node numbers remain unchanged, while the three-dimensional coordinates $\boldsymbol{D}^k$ f the mesh nodes change continuously with the change of the geometric variable $\boldsymbol{\varphi}_c$ .

Therefore, $\boldsymbol{K}$ changes continuously with the change of $\boldsymbol{\varphi}_c$ . Thus, the coarse-mesh model established in this paper can generate a continuous electromagnetic response with the continuous change of the geometric design variable values.

In the proposed modeling method, the electromagnetic simulation of the coarse mesh combined with mesh deformation is used as the coarse model, and the electromagnetic simulation of the fine mesh is used as the fine model. We define a surrogate model that combines the coarse model with the mapping function, and the formula is:

$$R_s^k(\boldsymbol{\varphi},\boldsymbol{\omega})=\boldsymbol{c}^T[\boldsymbol{K}(\boldsymbol{D}(y(\boldsymbol{\varphi},\boldsymbol{\omega})))]^{-1}\boldsymbol{e} \qquad (3)$$

Among them, $R_s^k$ represents the response of the surrogate model corresponding to $\boldsymbol{\varphi}$ 和 $\boldsymbol{\omega}$ during the $k$ - th set of geometric parameter modeling. By introducing mesh deformation, the response $R_s^k$ of the electromagnetic-based coarse-mesh surrogate model changes continuously with the change of the geometric design variable $\boldsymbol{\varphi}$ value, which helps to accelerate the electromagnetic modeling of the coarse mesh.

### *B. Space-mapping modeling process based on mesh deformation*

In order to achieve efficient modeling of three-dimensional electromagnetic structures through the mesh space-mapping method, first, appropriate geometric parameters need to be selected as the initial modeling geometric parameters, and an electromagnetic simulation software is used at this point to generate a coarse-mesh model. Write a coarse-model program for space-mapping modeling using Matlab software. The coarse-model program mainly includes the following steps:

The first step: Read the node information of the coarse-mesh model. The required node information includes node coordinates, quantity, connectivity information, etc.

The second step: Incorporate the mesh-deformation technology into the program. According to the new geometric parameters, adjust the coordinates of the nodes that need to be changed, and regenerate the changed coarse-mesh model.

The third step: Perform finite-element calculations on the coarse-mesh model to obtain the response of the new coarse-mesh model.

After the coarse model is established, a surrogate model needs to be built to achieve modeling. Use an electromagnetic simulation software to generate a fine-mesh model of the initial modeling geometric parameters and calculate the electromagnetic simulation results. Use this set of simulation results as training data for single-point modeling of the microwave device. Learn the non-linear relationship between the input and output of the fine model through the training data, and adjust the weight variables of the input mapping so that the output value of the surrogate model is consistent with the output result of the fine model. Use the NeuroModeler software to implement the modeling and testing processes. The complete space-mapping modeling process based on mesh deformation is as follows:

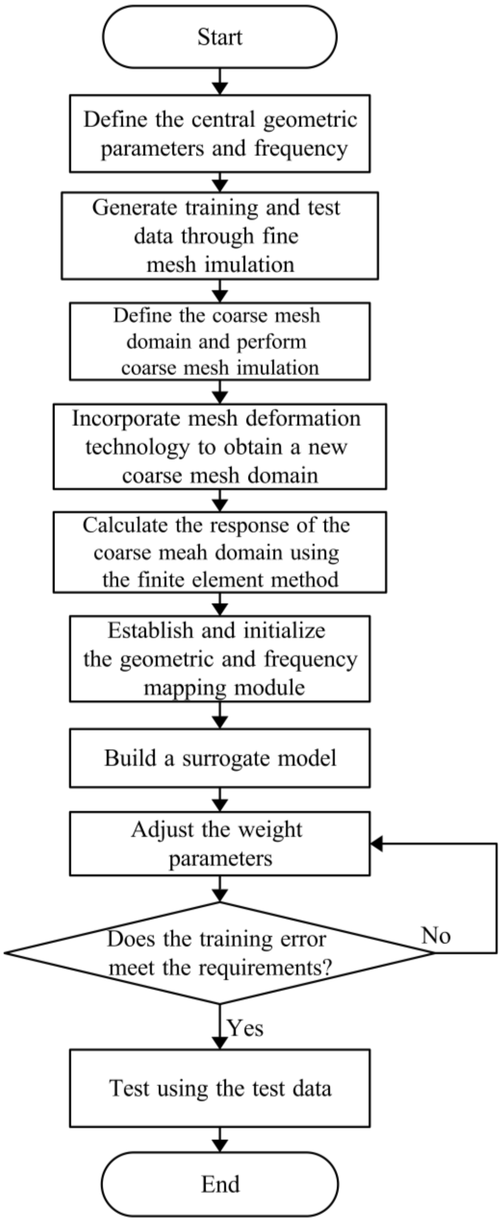

Fig.1 Flowchart of Space-Mapping Modeling Based on mesh Deformation

Step 1: Select and define the central geometric parameter $g_0$ and the frequency parameter $f$, perform simulation to generate the fine-mesh response $p_f$ corresponding to the fine-mesh model of the electromagnetic structure as the training data. Use the DOC sampling method to select data near the geometric parameter as the geometric parameter $g_f$ of the fine-mesh model of the electromagnetic structure, and perform simulation to generate the fine-mesh response of the electromagnetic structure fine-mesh model.

Step 2: According to the central geometric parameter $g_0$ and the frequency parameter $f$ obtained in Step 1, define the three-dimensional coarse-mesh domain $M_{d1}$ of the corresponding coarse-mesh model of the electromagnetic structure, and perform simulation to generate the coarse-mesh response $p_c$ of the coarse-mesh model of the electromagnetic structure.

Step 3: Add mesh-deformation technology to the mesh domain $M_{d1}$ obtained in Step 2 to get a new mesh domain $M_{d2}$, and write a Matlab program to perform finite-element calculations on the mesh domain $M_{d2}$. Use this program as the coarse model, and record the obtained calculation response as $p_m$.

Step 4: Construct geometric mapping modules and frequency mapping modules using linear mapping. Use the obtained training data to adjust the internal weight variables $w_1$ to $w_1^0$ of the geometric mapping modules and the internal weight variables $w_2$ to $w_2^0$ of the frequency mapping modules to obtain unit geometric mapping modules and unit frequency mapping modules, and realize $p_c = p_m$, ensuring that the accuracy of the overall model is not reduced after adding the mapping network.

Step 5: Add the unit geometric mapping modules and unit frequency mapping modules established in Step 4 to the input end of the coarse model constructed in Step 3, build a surrogate model, and train the surrogate model with the training data obtained in Step 1. Adjust the weight variables $w_1^0$ to $w_1^\#$ of the geometric mapping modules and the weight variables $w_2^0$ to $w_2^\#$ of the frequency mapping modules to make the training error of the surrogate model meet the requirements. If the training error does not meet the accuracy requirements, then return to Step 4, re-construct geometric mapping modules and frequency mapping modules, and continue training until the training error meets the requirements, so that the established surrogate model can accurately represent the characteristics of the electromagnetic structure of the central geometric parameter.

Step 6: Test the surrogate model with the test data obtained in Step 1, and record the response error in the range of each group of geometric parameters, and finally realize the establishment of the model.

Through the above steps, rapid modeling of microwave devices can be achieved. There is no need to generate coarse-mesh multiple times. mesh deformation is realized through programs to calculate the responses of different geometric parameters. The flowchart of the space-mapping modeling based on mesh deformation is shown in Figure 1.

## IV.APPLICATION EXAMPLE

For the mesh-deformation-based space-mapping modeling method for microwave devices proposed in this paper, an H-plane three-cavity filter is selected as an example for verification. The length and width of the cavity are selected as geometric parameters, denoted as $x = [l_1\ l_2\ w_1\ w_2]^T$. The input waveguide, output waveguide, and resonator of the filter are set according to the standard WR-75, where $a = 19.05\text{mm}$, $b = 9.525\text{mm}$. The filter is symmetric, and its structure is shown in Figure 2. The central geometric parameter $x = [13.98\ 15.2\ 9\ 6]^T$ is defined, and the initial modeling frequency is set to 11.5 GHz. The electromagnetic simulation software HFSS is used to generate a coarse-mesh model, and the stop-iteration number is set to 5. The generated coarse-mesh has 5058 mesh elements. The electromagnetic simulation software HFSS is used to generate a fine-mesh model of the initial modeling geometric parameters, and the stop-iteration error is set to 0.02. During the modeling process, the coarse-mesh model is used as the coarse-mesh space-mapping network, and its input and output are connected to form a super-generation model. Through training, adjusting the weight variables of the mapping, and reducing the training error of the model, single-point modeling of the H-plane three-cavity filter at the central geometric parameter is realized. After training, the training error of the model is 1.0%.

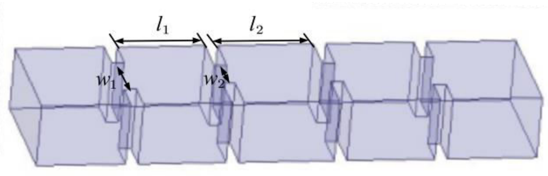

Fig.2 Schematic Diagram of a Three-order Cavity Filter Model in the 3D H-plane

To verify the effectiveness of the proposed method, this paper uses the multi-layer perceptron as the coarse-model space-mapping modeling method to model the H-plane three-cavity filter and compares the modeling results with the method in this paper. The DOE sampling method is used to select 169 sets of geometric parameter data as the training data of the coarse-model. The electromagnetic simulation software HFSS is used to generate the coarse-mesh model, and the stop-iteration number is set to 5. Its mesh is used for electromagnetic simulation, and the response obtained from the simulation is used to train the multi-layer perceptron. After the training is completed, the multi-layer perceptron is used as the coarse-model. Geometric mapping modules and frequency mapping modules are added to the input end of the coarse-model for single-point space-mapping modeling of the central geometric parameters. After training, the training error of the model is 1.2%.

Table 1:Comparison of Test Errors of Different Modeling Methods

| Geometric Parameter Fluctuation Range | ±1% | ±2% | ±5% | ±10% |
|---|---|---|---|---|
| SM Modeling Method Based on MLP | 426.4% | 731.4% | 826.7% | 430.0% |
| SM Modeling Method Based on mesh Deformation | 2.2% | 3.1% | 4.0% | 5.3% |

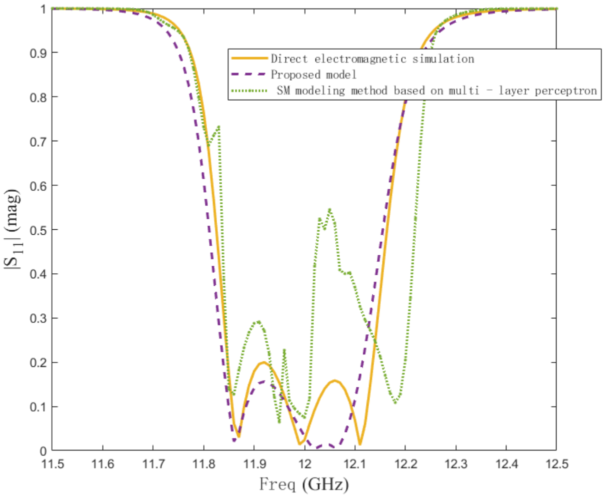

Fig.3. Comparison of the response curves obtained from the modeling method proposed in this paper, the SM modeling method based on multi-layer perceptron, and direct electromagnetic simulation.

This paper uses the same test data to test the modeling results. The test results show that the mesh-deformation-based space-mapping modeling method has a better modeling effect than the space-mapping modeling method using the multi-layer perceptron as the coarse-model. The fluctuation ranges of the test data selected in the experiment relative to the central geometric parameters are within ±1%, ±2%, ±5% and ±10% respectively. The DOE sampling method is used to randomly select 25 sets of test data for testing, and the test results are shown in Table 1.The test errors of the mesh-deformation-based space-mapping modeling method in the above four ranges are far smaller than those of the space-mapping modeling method using the multi-layer perceptron as the coarse-model. In the fluctuation range within ±1% , a set of geometric parameters $\boldsymbol{x} = [13.98\ 15.2\ 9\ 5.94]^{\mathrm{T}}$ is selected. The modeling methods proposed in this paper and the SM modeling method based on the multi-layer perceptron are compared, as shown in Figure 3. The curve obtained by the method proposed in this paper is closer to the curve obtained by electromagnetic simulation. The modeling error of the method proposed in this paper is far smaller than that of the SM modeling method using the multi-layer perceptron as the coarse-model. The surrogate model obtained by using the mesh-deformation-based space-mapping modeling method shows better adaptability during testing. The surrogate model proposed in this paper can provide a more reliable output in the subsequent optimization process.

## V.CONCLUSION

This paper proposes a space-mapping modeling method based on mesh deformation, which can be applied to the modeling of three-dimensional electromagnetic structures. Through the modeling method presented in this paper, the surrogate model established using single-point data can have good adaptability. In particular, it can maintain a low test error within a range where the data fluctuation is small. The mesh-deformation-based space-mapping modeling method for microwave devices proposed in this paper expands the effective range of single-point modeling of cavity filters, laying a foundation for subsequent optimization.

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