AN ALGORITHM FOR SPACE MAPPING BASED DIRECT OPTIMIZATION OF MICROWAVE CIRCUITS

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abstract

A new technique for direct optimization of microwave circuits is introduced in this work. It is known that the responses generated by electromagnetic (EM) simulators are accurate. However, these simulators require extensive CPU time and that makes them not suitable for direct optimization of microwave circuits. These simulators are usually referred to as fine models. It is assumed that the circuit under consideration can be simulated using a less accurate (coarse) but fast model. This model might be an empirical or circuit theoretic model. This model is then first optimized to get the optimal design of the coarse model. This design is then taken as the starting design of the fine model. Also, the Jacobian of the coarse model responses with respect to the coarse model parameters at the optimal design is taken as initial estimate for the Jacobian of the fine model parameters with respect to the fine model parameters. This follows from the assumption of the presence of certain degree of similarity between the two models. Broyden's update is then used to update the fine model responses Jacobian at each iteration.

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I. INTRODUCTION

In this work, a new technique for direct optimization of microwave circuits is proposed. The technique is gradient-based. It should offer an excellent starting point for the optimization process. The technique exploits Broyden's formula [1] for updating the gradient and thus should reduce the computational time. Also, the initial gradient estimation is obtained from a simpler and less expensive model.

This technique represents an extension to the space mapping technique suggested by Bandler *et al.* [2], [3]. The space mapping technique integrates electromagnetic (EM) simulators into the automated design procedure for microwave circuits. These simulators are known to be accurate but require extensive CPU time. The models represented by these simulators are called fine models. A less accurate model, whose responses can be calculated in a fast way, is first optimized. Such models are called coarse models. A mapping is then established between the coarse model and the fine model. This mapping is then used to find the optimal solution of the fine model.

The proposed technique is similar in idea to one of the techniques used for solving the postproduction tuning problem [4]. It was suggested that the postproduction tuning problem be converted to a linear minimax problem. The sensitivities used in solving this problem were obtained by a computer model.

Several algorithms have been developed for the direct optimization of microwave circuits. The work proposed in [5] is of practical importance. It was suggested in this work that an initial Jacobian estimation be obtained by perturbation. Then, Broyden's formula is used to update the Jacobian of the error vector using function values obtained at each iteration. A special iteration of Powell [6] is then used to prevent collinearity of the optimization steps.

II. FUNDAMENTAL CONCEPTS AND DEFINITIONS

The proposed technique assumes the presence of a coarse model and a fine model for simulating the microwave circuit under consideration. As was indicated before, the fine model responses are accurate but CPU expensive and the coarse model responses are less accurate but can be obtained in a fast way.

Applying direct optimization to the fine model would require a tremendous amount of time. This lead to the introduction of the space mapping technique.

It is assumed that the responses of the coarse model are given by $\boldsymbol{R}_c(\boldsymbol{x}_c)$ which is a vector of dimension m_r where m_r is the number of raw responses. Also, it is assumed that the fine model responses are given by the vector $\boldsymbol{R}_f(\boldsymbol{x}_f)$ which is assumed to have the same dimensionality as $\boldsymbol{R}_c(\boldsymbol{x}_c)$. The corresponding responses of each vector are assumed to have the same physical nature. Let $\boldsymbol{x}_c$ be a vector of coarse model parameters and let $\boldsymbol{x}_f$ be a vector of fine model parameters. Both vectors are assumed to have dimensionality n where $n < m_r$.

Similar to the space mapping technique, the proposed technique starts by applying an optimization technique to the coarse model. An optimal design of the coarse model $\boldsymbol{x}_c^*$ is thus obtained. Also, an approximation of the Jacobian matrix of the coarse model responses at the coarse model optimal solution is obtained. This matrix is denoted by $\boldsymbol{B}_c(\boldsymbol{x}_c^*)$.

Once the optimal solution of the coarse model is obtained, it is used as an initial guess for the fine model optimal solution, i.e., $\boldsymbol{x}_f^{(1)} = \boldsymbol{x}_c^*$. Also, the matrix $\boldsymbol{B}_c(\boldsymbol{x}_c^*)$ is used as an initial guess for the Jacobian matrix of the fine model, i.e., $\boldsymbol{B}_f^{(1)} = \boldsymbol{B}_c(\boldsymbol{x}_c^*)$. The second phase of the technique is to use direct optimization to match the responses of the fine model to the corresponding optimal responses of the coarse model. To achieve this target, the error vector

$$\boldsymbol{f}^{(j)} = \boldsymbol{R}_c(\boldsymbol{x}_c^*) - \boldsymbol{R}_f(\boldsymbol{x}_f^{(j)}) \tag{1}$$

is defined, where the index j represents the iteration count. The next iterate $\boldsymbol{x}_f^{(j+1)}$ is found by using the quasi-Newton iteration

$$\boldsymbol{x}_f^{(j+1)} = \boldsymbol{x}_f^{(j)} + \boldsymbol{h}^{(j)} \tag{2}$$

where $\boldsymbol{h}^{(j)}$ is the iteration step obtained by solving

$$\boldsymbol{B}_f^{(j)} \boldsymbol{h}^{(j)} = \boldsymbol{f}^{(j)} \tag{3}$$

where $\boldsymbol{B}_f^{(j)}$ is an approximation of the Jacobian matrix of the fine model at the j th iteration and $\boldsymbol{f}^{(j)}$ is the value of the error function at the j th iteration. The system of equations defined by (3) is an overdetermined system of linear equations. A solution for this overdetermined system can be obtained using one of two methods. A least squares solution can be obtained by solving the system of equations

$$\boldsymbol{B}_f^{(j)T} \boldsymbol{B}_f^{(j)} \boldsymbol{h}^{(j)} = \boldsymbol{B}_f^{(j)T} \boldsymbol{f}^{(j)} \tag{4}$$

It is assumed that the matrix $\boldsymbol{B}_f^{(j)}$ is a full rank matrix. The second suggested method is that only a subset of the fine model responses be used to determine the iteration step. Consider the index set I_s of cardinality n such that

$$I_s = \{i_1, i_2, . ., i_n \} \tag{5}$$

where i_k, k =1, 2, . ., n are the indices of the fine model responses that significantly deviates from their corresponding optimal coarse model responses in (1). A square matrix $\boldsymbol{B}_s^{(j)}$ of dimension n is then defined whose rows are the subset of the rows of $\boldsymbol{B}_f^{(j)}$ with indices in I_s. This implies that the rows of $\boldsymbol{B}_s^{(j)}$ are approximations to the gradients of the selected fine model responses. Once the matrix $\boldsymbol{B}_s^{(j)}$ is constructed, the iteration step is then found by solving the system of linear equations

$$\boldsymbol{B}_s^{(j)} \boldsymbol{h}^{(j)} = \boldsymbol{f}_s^{(j)} \tag{6}$$

where $\boldsymbol{f}_s^{(j)}$ is an n-dimensional vector whose components are the subset of the components of $\boldsymbol{f}^{(j)}$ with indices in I_s. A similar approach was adopted in [4] for determining the subset of responses to be used as tuning responses. It was suggested that all the responses close to violating the objective function of the linearized minimax problem be included as tuning responses.

After obtaining the iteration step $\boldsymbol{h}^{(j)}$, the new solution for the fine model $\boldsymbol{x}_f^{(j+1)}$ is obtained using (2). The new approximation of the Jacobian matrix of the fine model responses is obtained by updating the old one using Broyden's formula which is given by

$$\boldsymbol{B}_f^{(j+1)} = \boldsymbol{B}_f^{(j)} + \frac{\boldsymbol{B}_f^{(j+1)} - \boldsymbol{B}_f^{(j)} - \boldsymbol{B}_f^{(j)} \boldsymbol{h}^{(j)}}{\boldsymbol{h}^{(j)T} \boldsymbol{h}^{(j)}} \boldsymbol{h}^{(j)T} \tag{7}$$

The iterations proceed until a good match between the fine model responses and the coarse model optimal responses is obtained. The technique implementation is given in the following section.

III. THE ALGORITHM

Step 0. Obtain the optimal solution of the coarse model $\boldsymbol{x}_c^*$ and the corresponding approximation to the Jacobian matrix $\boldsymbol{B}_c(\boldsymbol{x}_c^*)$.

Step 1. Initialize $\boldsymbol{x}_f^{(1)} = \boldsymbol{x}_c^*$, $\boldsymbol{B}_f^{(1)} = \boldsymbol{B_c}(\boldsymbol{x}_c^*)$ .and j = 1. Evaluate $\boldsymbol{R}_f(\boldsymbol{x}_f^{(1)})$. If $\left\| \boldsymbol{f}^{(1)} \right\| < e$, stop.

Step 2. Determine the iteration step. If least squares is used, the iteration step is obtained by solving the system of equations

$$\boldsymbol{B}_f^{(j)T} \boldsymbol{B}_f^{(j)} \boldsymbol{h}^{(j)} = \boldsymbol{B}_f^{(j)T} \; \boldsymbol{f}^{(j)}$$

Otherwise, the iteration step is found by solving the equations

$$\boldsymbol{B}_s^{(j)} \boldsymbol{h}^{(j)} = \boldsymbol{f}_s^{(j)}$$

Step 3. Set $\boldsymbol{x}_f^{(j+1)} = \boldsymbol{x}_f^{(j)} + \boldsymbol{h}^{(j)}$

Step 4. Evaluate $\boldsymbol{R}_f(\boldsymbol{x}_f^{(j+1)})$. If $\left\| \boldsymbol{f}^{(j+1)} \right\| < \varepsilon$, stop.

Step 5. Update $\boldsymbol{B}_f^{(j)}$ to $\boldsymbol{B}_f^{(j+1)}$ using the Broyden formula.

Step 6. Set $j = j + 1$. Go to Step 2.

IV. CONCLUSIONS

A new technique for the direct optimization of microwave circuits is suggested here. First, the technique optimizes the design of a coarse model of the circuit under consideration. This model is a fast model but is less accurate than the EM simulators. The optimal solution of the coarse model and the Jacobian of the coarse model responses are taken as initial guess for the fine model solution and the fine model Jacobian matrix, respectively. At each iteration, the Jacobian matrix of the fine model is update using Broyden's formula. Convergence is achieved when the fine model responses are matched to the optimal coarse model responses.

REFERENCES

[1] C.G. Broyden, "A class of methods for solving nonlinear simultaneous equations," *Mathematics of Computation*, vol. 19, 1965, pp. 577-593.

[2] J.W. Bandler, R.M. Biernacki, S.H. Chen, P.A. Grobelny and R.H. Hemmers, "Space mapping technique for electromagnetic optimization," *IEEE Trans. Microwave Theory Tech.*, vol. 42, 1994, pp. 2536-2544.

[3] J.W. Bandler, R.M. Biernacki, S.H. Chen, R.H. Hemmers and K. Madsen, "Electromagnetic optimization exploiting aggressive space mapping," *IEEE Trans. Microwave Theory Tech.*, vol. 43, 1995, pp. 2874-2882.

[4] J.W. Bandler and A.E. Salama, "Functional approach to microwave postproduction tuning," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, 1985, pp. 302-310.

[5] J.W. Bandler, S.H. Chen, S. Daijavad and K. Madsen, "Efficient optimization with integrated gradient approximations," *IEEE Trans. Microwave Theory Tech.*, vol. 36, 1988, pp. 444-455.

[6] M.J. Powell, "A Fortran subroutine for unconstrained minimization, requiring first derivatives of the objective functions," Atomic Energy Research Establishment, Harwell, Berkshire, England, Rep. AERE-R. 6469, pp. 20-27, 1970.