Adaptive Frequency Sampling for Broadband Modeling of Microwave Devices Based on the Method of Moments

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***Abstract* — Broadband modeling of microwave devices based on the method of moments is associated with high computational cost, since the interaction matrix must be assembled and the system of linear algebraic equations must be solved at a large number of frequency points. The aim of this work is to develop an adaptive frequency sampling algorithm to reduce the number of frequency points in broadband modelling. The proposed algorithm is based on linear interpolation, recursive interval refinement, and caching of previously computed results. The algorithm constructs a nonuniform frequency grid according to the local behavior of the frequency response and avoids repeated computations at already processed frequencies. Testing performed on two microwave filter models showed that the proposed approach reduces the number of frequency points and the simulation time while preserving the main features of the frequency characteristics. The obtained results demonstrate the feasibility of integrating the proposed algorithm into electromagnetic simulation software for broadband modeling of microwave devices.**

Keywords — adaptive frequency sampling, method of moments, electromagnetic modeling, microwave devices, broadband modeling, frequency response.

I. Introduction

Computer-aided design systems (CAD) play an important role in the development of microwave devices, since they enable numerical analysis of device characteristics, evaluation of the effects of geometric and electrophysical parameters, and a reduction in the amount of full-scale experimental work required at the design stage. This is particularly important for broadband devices, which require repeated simulations under different operating conditions and over wide frequency ranges [1], [2].

Modern electromagnetic simulation systems employ various numerical methods intended for solving problems in both the frequency and time domains. In the frequency-domain analysis of microwave devices, one of the most widely used approaches is the method of moments (MoM), which is based on reducing a system of integral equations (SLAE) to a system of linear algebraic equations [1]. In this case, the surface of the structure under study is usually discretized by means of a triangular surface mesh [3].

When the MoM is employed, the main computational cost is associated with the assembly of the interaction matrix and the subsequent solution of the SLAE [1], [2], [3], [4], [5]. As the number of mesh elements increases, the required computational time and memory resources grow significantly. In broadband modeling problems, these computations must be performed at a large number of frequency points, which leads to a substantial increase in the total simulation time. At the same time, the use of a dense uniform frequency discretization is not always efficient, since the frequency response may vary smoothly in some parts of the range and exhibit sharp variations and oscillations in others.

One of the approaches to reducing the computational cost is adaptive frequency sampling (AFS), in which the frequency grid is formed nonuniformly according to the local behavior of the computed response [6], [7], [8]. Interpolation-based AFS approaches, including methods based on Stoer–Bulirsch rational interpolation, were considered in [9], [10], [11], [12], [13]. These studies showed that the adaptive addition of new frequency points in regions of rapid response variation makes it possible to reduce the number of simulations while preserving acceptable accuracy. In particular, [9] reported a reduction in both the number of frequency points and the computation time by more than an order of magnitude, while [13] proposed an improved interpolation-based algorithm in which the model is constructed stage by stage and new support points are selected statistically. For a microstrip antenna, this approach reduced the error to 4.5% after 40 stages, whereas the standard scheme yielded an error of 12.5% and missed one of the resonances.

Despite the availability of more sophisticated interpolation-based approaches, the present study adopts an approach that can be integrated into the authors' MoM implementation without requiring a complex approximation framework or substantial modification of the existing computational algorithm. Therefore, this paper considers an AFS algorithm based on linear interpolation and intended for use in the authors' MoM implementation for broadband modeling of microwave devices.

The aim of this work is to implement and analyze a computational algorithm for adaptive frequency sampling in broadband modeling of microwave devices based on the method of moments, with its subsequent use in the MoM solver independently developed by the authors.

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II. Computational Algorithm

The proposed AFS algorithm is based on linear interpolation. This approach is characterized by the fact that it is easy to implement, does not require a sophisticated mathematical apparatus, and at the same time allows reducing the number of frequency points in broadband MoM modeling. The input data include the initial and final frequencies of the range, the accuracy coefficient «AFS_errorcoef», and the number of desired intervals «AFS_intervals». At the first stage, electromagnetic simulation is carried out at the boundary frequencies of the range, after which the admissible error errorRate and the maximum interval width maxInterval are determined. The admissible error is calculated as the product of «AFS_errorcoef» and the difference between the values of the characteristic under study at the boundaries of the current frequency interval, while the maximum interval width is determined from the total width of the range and the prescribed number of intervals.

The main part of the algorithm is implemented in a recursive interval refinement procedure. For the current interval, its midpoint frequency is determined as follows:

$$f_{\mathrm{mid}} = \frac{f_1 + f_2}{2}, \quad (1)$$

where f_1 and f_2 are the initial and final frequencies of the interval under consideration, and f_{mid} is the midpoint frequency. Then, using the values at the ends of the interval, the predicted value of the characteristic under study is calculated by linear interpolation as follows:

$$S_{\mathrm{pred}} = S_1 + \frac{S_2 - S_1}{f_2 - f_1}(f_{\mathrm{mid}} - f_1), \quad (2)$$

where S_1 and S_2 are the known values of the characteristic at frequencies f_1 and f_2, and S_{pred} is the predicted value at frequency f_{mid}. If the interval exceeds the prescribed maximum width or if the deviation between the predicted and reference values at the midpoint exceeds the admissible error, the interval is divided into two subintervals, in which the procedure is repeated. Otherwise, the interval is accepted without further refinement. In this way, the algorithm automatically refines the frequency grid in regions of rapid response variation while retaining a larger step size in regions where the characteristic varies smoothly.

To avoid repeated computations, the algorithm includes a result caching mechanism. The exact values of the characteristic under study at new frequency points are obtained through a separate procedure that first checks whether the given frequency has already been evaluated and initiates a new solver run only if it has not. After new points are added, the results are sorted by frequency. This makes it possible to avoid repeated assembly and SLAE solution for frequencies that have already been processed. As a result, an adaptive frequency grid is formed that covers the entire range while taking into account the local features of the frequency response. The flowchart of the algorithm is shown in Fig. 1.

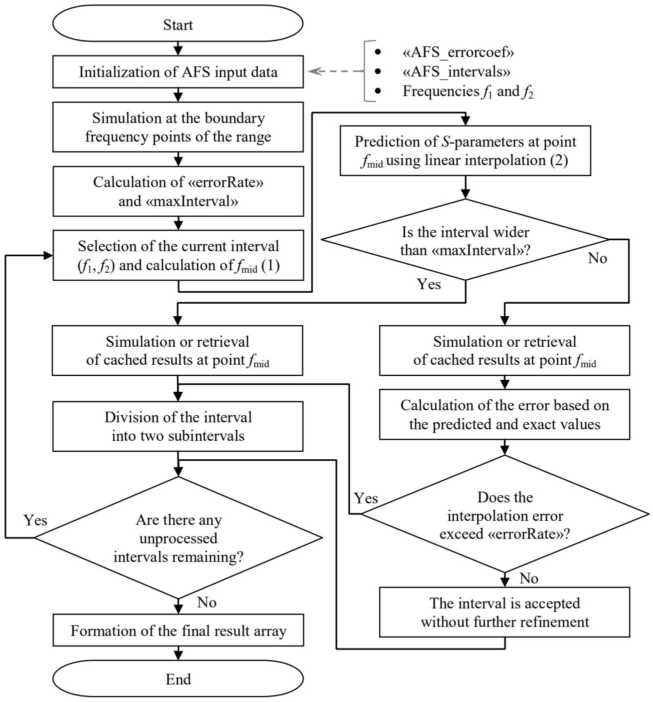

Fig. 1. Flowchart of the adaptive frequency sampling algorithm based on linear interpolation.

III. Experimental Results

The proposed algorithm was tested in the authors' in-house MoM software implementation using two microwave structure models. To evaluate its efficiency, simulation results obtained with a fixed frequency step were compared with those obtained using the AFS algorithm. In both cases, the magnitudes of the reflection coefficient S_{11} and the transmission coefficient S_{21}, as well as the number of frequency points and the total computation time, were analyzed. The simulations were performed on a workstation equipped with an AMD Ryzen 9 5900X processor and 64 GB of RAM. To ensure a reliable time assessment, the simulation time was measured several times and the results were averaged.

The first model was a low-pass filter on a dielectric substrate ($\varepsilon_r = 12.9$) with the following parameters: conductor thickness of 0.01 mm, substrate thickness of 0.2 mm, substrate width and length of 4 mm, feed line width of 0.14 mm, stub width of 2 mm, and conductor width of 0.03 mm (Fig. 2). For this model, a computational mesh was generated using the Gmsh software library [14], resulting in 3974 triangular elements. The simulation was carried out over the frequency range from 1 to 18 GHz with a fixed frequency step of 0.17 GHz, corresponding to 101 frequency points, and also using the AFS algorithm. The obtained results showed that, while preserving the overall behavior of the $|S_{11}|$ (Fig. 3) and $|S_{21}|$ (Fig. 4) responses, the AFS algorithm required only 53 frequency points instead of 101, thereby reducing the number of frequency points and, consequently, the simulation time by nearly a factor of two. To quantitatively assess the accuracy of the adaptive frequency discretization, a piecewise-linear approximation of the frequency response was constructed from the values obtained at the AFS points, after which the mean absolute error, the root-mean-square error, and the maximum absolute deviation with respect to the reference results were evaluated. It was found that the mean absolute error was 0.15

dB, the root-mean-square error was 0.31 dB, and the maximum absolute deviation did not exceed 1.93 dB.

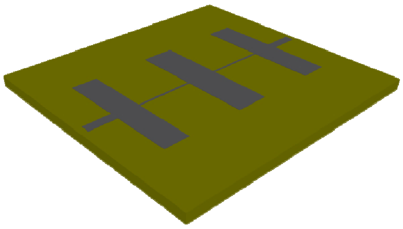

Fig. 2. Low-pass filter model.

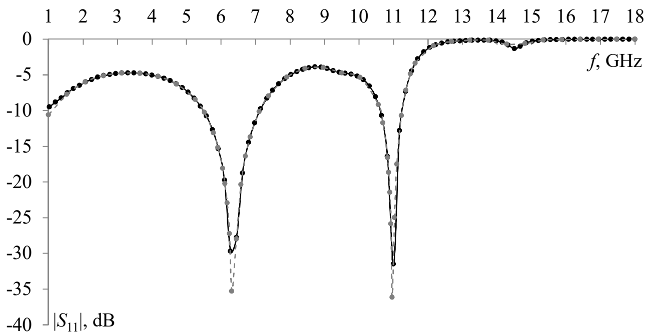

Fig. 3. $|S_{11}|$ of the low-pass filter obtained with a fixed frequency step (—) and with the AFS algorithm (- - -).

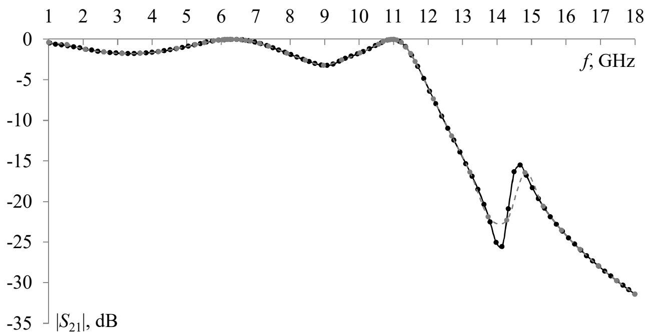

Fig. 4. $|S_{21}|$ of the low-pass filter obtained with a fixed frequency step (—) and with the AFS algorithm (- - -).

The second model was a band-pass filter on a dielectric substrate ($\varepsilon_r = 3.38$) with the following parameters: substrate thickness of 0.79 mm, substrate width of 20.45 mm, conductor length of 24.36 mm, and conductor thickness of 0.13 mm (Fig. 5). For this model, a computational mesh was generated in Gmsh, resulting in 5286 triangular elements. The simulation was performed over the frequency range from 1 to 10 GHz with a fixed step of 0.09 GHz, which also corresponded to 101 frequency points, and with the proposed algorithm. The obtained results showed that, while preserving the overall behavior of the $|S_{11}|$ (Fig. 6) and $|S_{21}|$ (Fig. 7) responses, the AFS algorithm required 55 frequency points instead of 101, thereby providing an almost twofold reduction in both the number of frequency points and the simulation time. For these results, the mean absolute error, the root-mean-square error, and the maximum absolute deviation with respect to the reference results were evaluated in the same manner. It was found that the mean absolute error was 0.17 dB, the root-mean-square error was 0.64 dB, and the maximum absolute deviation did not exceed 3.56 dB.

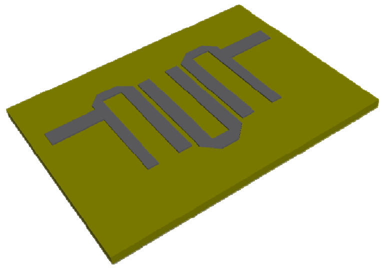

Fig. 5. Band-pass filter model.

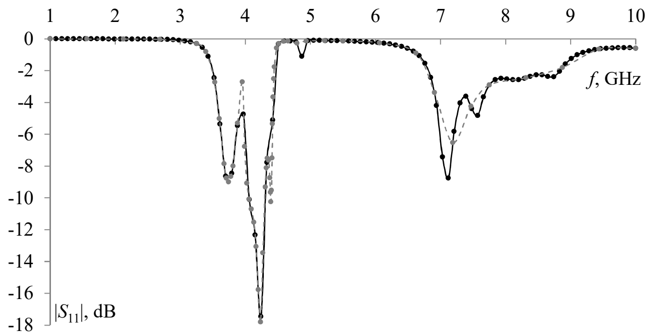

Fig. 6. $|S_{11}|$ of the band-pass filter obtained with a fixed frequency step (—) and with the AFS algorithm (- - -).

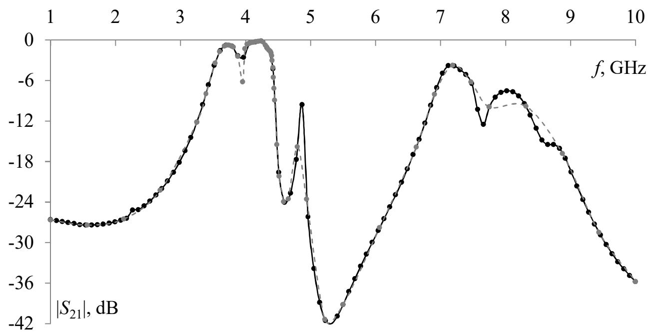

Fig. 7. $|S_{21}|$ of the band-pass filter obtained with a fixed frequency step (—) and with the AFS algorithm (- - -).

Thus, the test results showed that the proposed computational algorithm for adaptive frequency point selection makes it possible to reduce the number of frequency points and nearly halve the simulation time while preserving the main features of the frequency characteristics of the structures under study.

IV. Conclusion

In this paper, we have investigated an approach to reducing the number of frequency points in broadband MoM-based modeling of microwave devices through the use of AFS. Based on the literature analysis, we selected an interpolation-based AFS approach and complemented it with a developed computational algorithm that employed linear interpolation, recursive interval refinement, and caching of previously obtained results. The test results showed that the proposed algorithm allowed us to reduce the number of electromagnetic solution iterations and decrease the simulation time while preserving the main features of the frequency characteristics of the structures under study. This confirms the relevance of applying the developed algorithm as part of software tools for broadband modeling of microwave devices. This confirms the relevance of applying the developed algorithm as part of software tools for broadband modeling of microwave devices. In future work, we will investigate its applicability to more complex electromagnetic problems, including antenna problems.

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