Adaptive Stopping Criterion for Fast Time Domain Characterization of Microwave Components

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***Abstract*—This letter proposes a novel adaptive stopping criterion that facilitates a fast time domain characterization of microwave components. By successively computing a rational macromodel based on time-limited transient responses of the microwave component under study, the proposed stopping criterion limits the number of time steps required to capture the frequency behavior up to a predefined accuracy level. Therefore, it is particularly useful for systems where the transient responses decay slowly.**

***Index Terms*—Adaptive methods, Fourier transform, stopping criterion, time domain characterization, vector fitting.**

I. Introduction

In recent years, time domain characterization of complex microwave systems based on e.g. the finite difference time domain (FDTD) technique, the time domain finite element method (TD-FEM), or the time domain method of moments (TD-MoM) has become increasingly important, especially for broadband design and optimization. Compared to their frequency domain counterparts, time domain EM solvers have the advantage that they can capture the overall frequency response in a single simulation run by applying a Fourier transform to the time domain response of the system. Unfortunately, a long record of the time domain samples is often needed to ensure that the transient response on the pulse excitation has decayed sufficiently. Premature termination of the time domain simulation may result in an insufficient frequency resolution, while late termination may lead to an undesired waste of computational resources [1], [2]. To resolve these difficulties, several methods have already been considered in the past, e.g. autoregression [3], [4], generalized-pencil-of-functions [5], neural networks models [6], Prony's method [7] and pole tracking [8]. Many methods often try to extrapolate the transient response, in order to avoid the inaccuracies that arise due to simple zero-padding of the response.

This letter introduces a new adaptive stopping criterion that estimates and minimizes the number of time steps needed to capture the frequency behavior up to a predefined accuracy level by successively building a rational macromodel for the system response in the frequency domain. Within the proposed algorithm, the time domain solver simulates the structure over a relatively short time interval after which the transient response is transformed to the frequency domain using the discrete Fourier transform. Based on these frequency samples a rational macromodel is computed. In successive iterations, the time interval is extended by a fixed amount and the corresponding subsequent rational macromodels are compared. If the deviation between these successive models is smaller than a predefined accuracy threshold, then the frequency content of the extended transient response is assumed to be negligible and the algorithm terminates. This concept is inspired by an adaptive frequency sampling algorithm [9].

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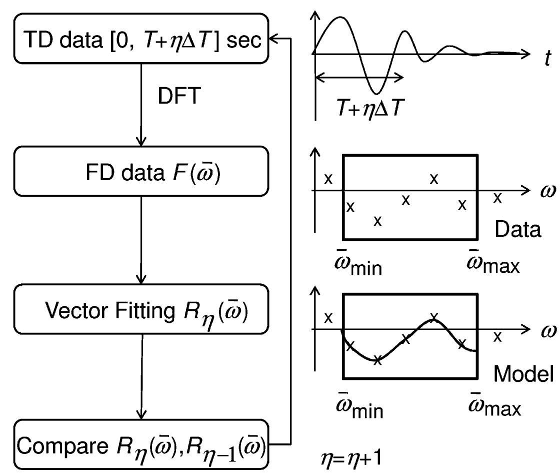

Fig. 1. Flowchart of stopping criterion algorithm.

II. Outline of the Algorithm

The algorithm consists of four steps that are repeated in an iterative way. In the first iteration step $(\eta = 0)$, an initial set of N_η time domain samples are simulated over a short time period $[0, T+\eta\Delta T]$ sec (Section II-A). These time domain samples are transformed into a set of frequency domain samples using the discrete Fourier transform (Section II-B). Only a sparse subset of these frequency samples, which are located within the frequency range of interest, are retained and subjected to a rational macromodeling procedure (Section II-C). In each iteration step of the algorithm $\eta > 0$, the rational model R_η is compared to the model from the previous iteration step $R_{\eta-1}$ (Section II-D). If the deviation is smaller than the desired accuracy, the algorithm terminates and the number of time steps is given by N_η. Otherwise, the iteration step η is increased by 1 and the procedure is repeated until convergence. A flowchart of the algorithm is shown in Fig. 1.

A. Simulation Time-Domain Samples

Although the proposed scheme is applicable to all kinds of time domain simulators such as FDTD, TD-FEM or TD-MoM, the transient responses in this letter are simulated with the commercial FDTD solver that is included in Agilent Technologies' 3D EM platform EMPro [10]. For a complete description of the FDTD algorithm and its main application areas, the reader is referred to [11] and the references therein.

B. Discrete Fourier Transform

A sequence of N_η equispaced time domain data samples $\{t_k, f(t_k)\}_{k=0}^{N_\eta-1}$ is transformed into a sequence of N_η equispaced frequency domain data samples $\{\omega_k, F(\omega_k)\}_{k=0}^{N_\eta-1}$ using the discrete Fourier transform [12], such that $\mathcal{F}(f) = F$

$$F(\omega_k) = \sum_{\upsilon=0}^{N_\eta-1} f(t_\upsilon) e^{-(j2\pi/N_\eta)k\upsilon} \text{ for } k = 0, \dots, N_\eta - 1 \quad (1)$$

The transformed data samples $F(\omega_k)$ from (1) are located at the discrete frequencies $\omega_k = k/(N_\eta \Delta t)$, where Δt denotes the simulation time step. Therefore, they are equally spread over the frequency range $[0, \omega_{\max}]$, where $\omega_{\max}$ corresponds to the maximum frequency $(N_\eta - 1)/(N_\eta \Delta t)$.

C. Selective Rational Macromodeling

The adaptive algorithm only selects a subset of the data samples $F(\omega_k)$, denoted by $\bar{F}(\bar{\omega}_k)$, which are located within a user-defined frequency range of interest $[\bar{\omega}_{\min}, \bar{\omega}_{\max}]$, where $0 \leq \bar{\omega}_{\min} \leq \bar{\omega}_k \leq \bar{\omega}_{\max} \leq \omega_{\max}$. This sparse set of data samples $\bar{F}(\bar{\omega}_k)$ is subjected to a rational fitting procedure, called Vector Fitting [13]. This yields a pole-residue model

$$\bar{F}(\bar{\omega}_k) \approx R_\eta(\bar{\omega}_k) = \sum_{p=1}^{P} \frac{c_p^{mn}}{j\bar{\omega}_k - a_p^{mn}} + d^{mn} \quad (2)$$

with poles a_p^{mn}, residues c_p^{mn} and optional constant term d^{mn} that approximates the frequency samples $\bar{F}(\bar{\omega}_k)$ in a least-squares sense (see [13] for details). The number of poles P is chosen in such a way that the accuracy in the selected data samples corresponds to the desired accuracy level.

D. Quality Assessment

To assess the frequency content of the additional time steps, the rational model $R_\eta(\bar{\omega}_k)$ is compared to the rational model from the previous iteration step $R_{\eta-1}(\bar{\omega}_k)$. If the maximum deviation between the successive models is smaller than δ,

$$\max_{m,n,k} \left[20 \log_{10} \left(|R_\eta(\bar{\omega}_k) - R_{\eta-1}(\bar{\omega}_k)|\right)\right] < \delta \quad (3)$$

then the algorithm terminates and the number of time steps is given by N_η. Otherwise, the iteration step η is increased by 1 and the procedure is repeated until (3) is satisfied.

III. Example: Microwave Filter

The effectiveness of the adaptive stopping criterion is illustrated by applying it to a two-port symmetric microwave filter that consists of 2 coupled tuning stubs (as shown in Fig. 2). The 2

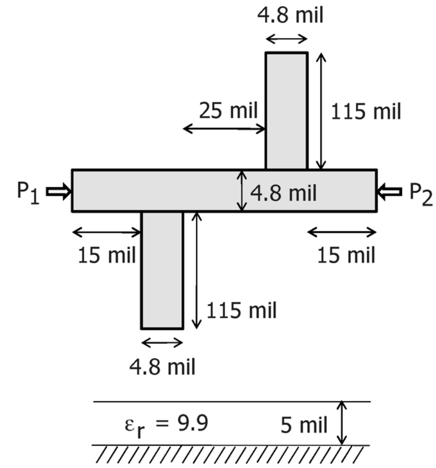

Fig. 2. Structure of the microwave filter.

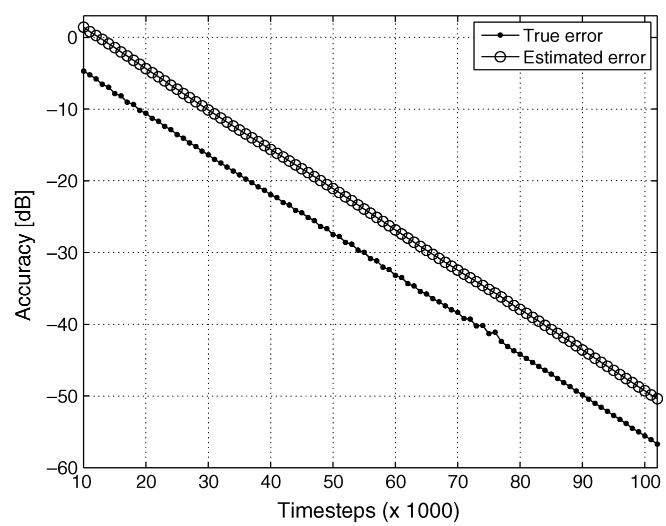

Fig. 3. Maximum absolute error versus number of time steps.

stubs couple via their mutual inductance, causing the single resonance to split into 2 resonances, and therefore reducing the Q of the filter circuit. An accurate EM analysis of the device under test is required to model the complex filter behavior between dc and 30 GHz. The transient responses, due to a Gaussian input pulse with a rise time of about 3.5 ps, are simulated with the 3D EM platform EMPro.

Initially, the FDTD simulator calculates the currents $i(t)$ and voltages $v(t)$ for 10.000 time steps at the two ports of the structure (Section II-A). Their frequency domain counterparts $I(\omega_k)$ and $V(\omega_k)$ are obtained by the discrete Fourier transform and constitute the S-parameter response $\{S(\omega_k)\}$ of the system (Section II-B). A subset of the S-parameter data samples $\{\bar{S}(\bar{\omega}_k)\}$ is subjected to the selective rational macromodeling procedure (Section II-C), and the time interval is extended by 1000 time steps in successive iterations until the frequency domain macromodels converge to a common solution (Section II-D). The evolution of the maximum absolute error between consecutive macromodels $R_\eta(\bar{\omega}_k)$ in the frequency domain (i.e. estimated error) is shown in Fig. 3. It is found that

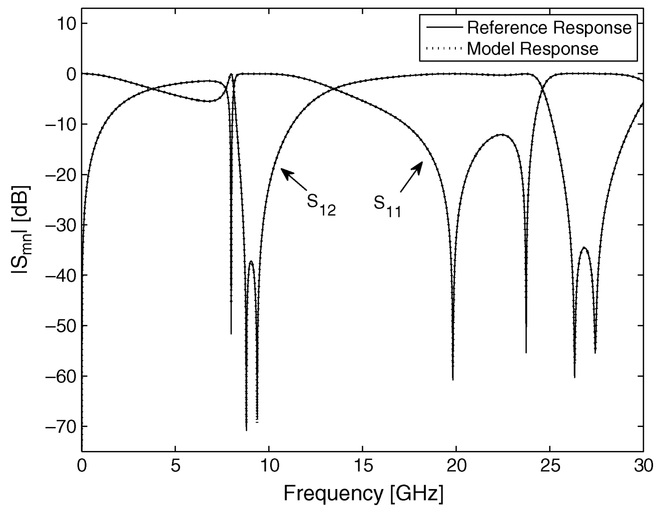

Fig. 4. Frequency response of model based on 102.000 timesteps.

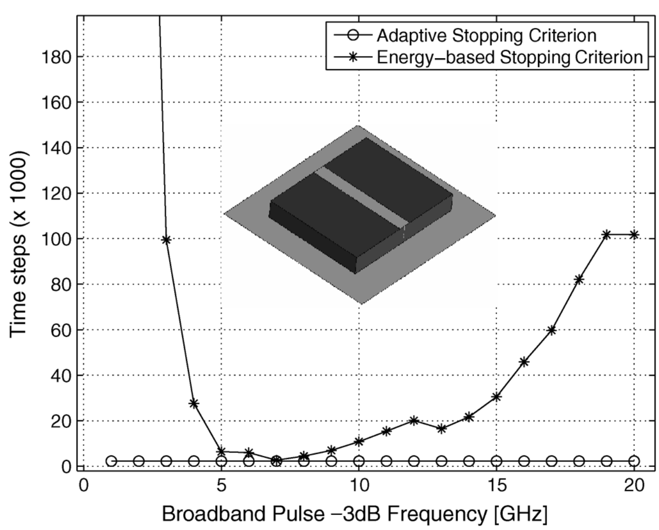

Fig. 5. Number of time steps needed vs. frequency content of input pulse.

at least 102.000 time steps are needed to obtain the desired accuracy of $\delta = -50$ dB. This leads to a significant reduction when compared to classical energy-based stopping criteria [10] that require at least 482.700 time steps. The (unknown) reference frequency response is computed for validation purposes and the true error is shown in Fig. 3. Clearly, both error curves are closely correlated and follow a similar trend. Fig. 4 shows a comparison of the frequency response of the converged macromodel and the reference frequency response, and an excellent agreement is observed.

IV. Example: Microstrip Line

As a second example, the adaptive stopping criterion is applied to characterize a simple 50 Ω microstrip line that is excited and terminated by a 50 Ω voltage source/load. Fig. 5 shows the number of time steps that are needed to obtain the desired accuracy of $\delta = -40$ dB from dc up to 2 GHz versus the frequency content of the Gaussian input pulse. It is found that the adaptive stopping criterion is much less dependent on the actual input pulse, when compared to the classical energy-based stopping criterion [10]. The adaptive stopping criterion always converges to the correct S-parameters with the minimal number of time steps that would also be sufficient for the energy-based stopping criterion if one excites the microstrip with the (a posteriori known) optimal input pulse.

V. Discussion

The time step Δt of the transient response determines the maximum frequency of the frequency response, as calculated by the discrete Fourier transform. Only a sparse subset of the frequency samples, corresponding to the discrete frequencies that are located within the frequency range of interest $[\bar{\omega}_{\min}, \bar{\omega}_{\max}]$, are selected by the algorithm. As the length of the simulated time domain signal $f(t)$ increases in successive iterations, the frequency step of the Fourier transformed signal $F(\omega)$ becomes smaller, and an increasing number of frequency samples are involved in the macromodeling process. Due to the macromodeling of sparse bandlimited frequency domain data, the truncation ringing that may occur after zero-padding of the transient response is avoided.

VI. Conclusion

A new reliable stopping criterion is introduced to minimize the number of time steps that are needed to capture the broadband behavior of microwave components. An example indicates that the method is reliable and significantly reduces the computational cost of time domain characterization, especially if the pulse excitation of the system is slowly decaying.

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