Microwave Structure Characterization by a Combination of FDTD and System Identification Methods

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Abstract—**Microwave structure characterization is achieved by application of the system identification (SI) technique to the finite-difference time-domain algorithm (FDTD). The parameters of a deterministic auto-regressive moving-average model (ARMA) are computed recursively such that the model output matches the FDTD simulation. The ARMA model parameter convergence is rapid, and provides savings in the computation time.**

I. Introduction

THE finite-difference time-domain algorithm is an effective computational method for full vector analysis of microwave structures [1]. The theoretical formulation directly follows the Maxwell's equations, and algorithm implementation is simple and flexible for general structures of interest. The computation requirements, however, are excessive due to the spatial-temporal discretization. Recently, digital signal processing methods have been used to reduce the computational requirements of the time-domain methods [2]–[6]. For example, the Prony's method is used to estimate the time signal in terms of the previously computed values [2], [3], also a covariance based system identification (SI) algorithm has been used to reduce the computation cost of the Transmission Line and FDTD Methods by employing a stochastic ARMA model [4], [5]. In this letter, a least-squares based system identification projection algorithm for a deterministic auto-regressive moving average model is applied to the FDTD algorithm [7]. The application of this algorithm to the partially filled rectangular cavity has demonstrated excellent numerical results. Savings in the computation requirements are achieved by replacing the computationally intensive FDTD algorithm by the ARMA model for output signal computation, after the system parameters converge to their final values. In addition, the frequency response is evaluated directly from the computed system parameters, thus eliminating the need for Fourier transformation.

II. Theory

The computed time signal at an appropriate location in the computational volume and the corresponding input signal can be interpreted as the input and output signals of a discrete linear system. This linear system description is

$$y(n) = -\sum_{k=1}^{K} a_k y(n-k) + \sum_{m=0}^{M} b_m x(n-m), \qquad (1)$$

where $y(n)$ is the output signal and $x(n)$ is the input signal. The output signal is completely known when the model parameters (a_k, b_m) are computed. The parameter space is taken to be large enough to allow the convergence of the model output to the FDTD simulated field values. Equation (1) can be written in a compact form

$$y(n) = \Phi^T(n-1)\Theta_0, \qquad (2)$$

where T stands for transpose, and Φ is a vector containing the present and past values of the input and output which can be considered as data. The vector Θ_0 contains the system parameters and uniquely defines the properties of the linear system such as the resonance frequencies. Equation (2) represents the output of a linear system as the inner product of the Φ and the parameter vector. Using the available data vector Φ, the output signal can be estimated in terms of the estimated system parameters

$$y(n) = \Phi^T(n-1)\hat{\Theta}(n-1). \qquad (3)$$

The difference in (2) and (3) is minimized with respect to the system parameters to arrive at a parameter update law

$$\hat{\Theta}(n) = \hat{\Theta}(n-1) + \frac{P(n-1)\Phi(n-1)}{\Phi(n-1)^T P(n-1)\Phi(n-1)}[e(n)] \qquad (4)$$

$$P(n) = P(n-1) - \frac{P(n-1)\Phi(n-1)\Phi(n-1)^T P(n-1)}{\Phi(n-1)^T P(n-1)\Phi(n-1)}$$

$$P(0) = I, \qquad (5)$$

where $P(n)$ provides an orthogonal projection search in the parameter space which results in rapid parameter convergence [6], $\Theta(n)$ is the computed parameter vector, and $e(n)$ is the discrepancy between the estimated output and the FDTD computed field value. Computation of (4) and (5) requires only vector addition and multiplication, and results in minimal additional cost to the FDTD computation. We note that the system parameters converge to their final values when the output error is sufficiently small.

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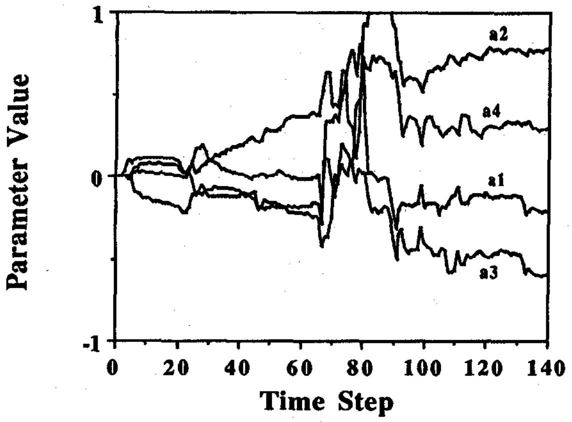

Fig. 1. Parameter convergence of the ARMA model with 80 coefficients. Evolution of the first four output coefficients, see (1), is demonstrated.

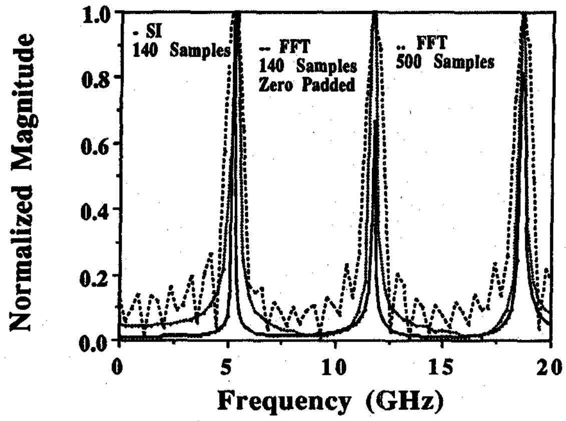

Fig. 2. FDTD generated output spectrum. 140 time samples (at a rate of 1 sample per 5 FDTD output values) are used to obtainthe spectrum by the SI method. Similar spectrum is obtained by Fourier transformation of 500 samples. The Fourier transform of the 140 samples with zero padding is distorted.

III. Results

The numerical behavior of this method is demonstrated by applying it to the cavity problem. An ARMA model with system parameters $K = 40$, $M = 40$, (see (1)), is used to obtain the resonance frequencies of a rectangular cavity. The cavity is excited at the center plane by imposing a TE_{10} mode distribution with impulsive temporal dependence. Fig. 1 shows the parameter convergence for a number of system coefficients. The initial condition for the parameters is set to the origin of the parameter space, and the parameter values are updated at each sampled interval.

The resonance frequencies of the cavity can be derived directly from the poles of the ARMA model. They can also be recovered from the spectrum of the output signal. This spectrum is computed by the Fourier transform of the output signal, or directly by evaluation of the Z-transform of (1) on the unit circle which is defined in terms of the system parameters. Fig. 2 shows the spectrum of the output signal using the system parameters and the Fourier transformation of the output signal. The recovered resonance frequencies of the first three odd modes are illustrated. The location of the observation point coincides with the null position of the even modes. As a result these modes can not be recovered from this time signal. In this example, the ARMA based spectrum is computed using 140 output time samples. Similar spectrum is obtained by applying the Fourier transformation to 500 output time samples. Fig. 2 also shows the Fourier transform of the 140 output samples which are augmented with zero padding to provide sufficient spectral resolution for locating the spectrum peaks. This spectrum, while qualitatively locates the resonance frequencies, is distorted and might not provide sufficient resolution where the resonance frequency separation is small. We note that the first two resonance frequencies are predicted accurately for this example, while higher order modes are underestimated due to frequency dispersion of the FDTD spatial grid. This method is used to obtain the resonant frequencies of a partially filled rectangular cavity. Fig. 3 shows the shift in the resonant frequency as the permittivity is gradually changed from $\varepsilon = 1$ to $\varepsilon = 2$.

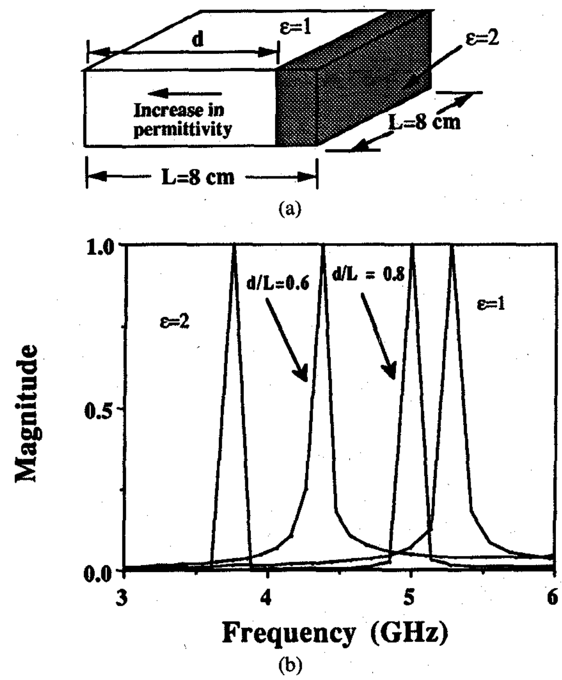

Fig. 3. Resonance frequency computation of a partially filled rectangular cavity using the ARMA model. (a) Cavity geometry. (b) The first resonance frequency shifts as the permittivity ischanged gradually from $\varepsilon = 1$ to $\varepsilon = 2$.

IV. Conclusion

In this letter, a projection SI algorithm is applied to FDTD simulation of cavity problems. The SI algorithm requires minimal additional computational cost, provides rapid convergence of the system parameters, and computes the parameters of a deterministic ARMA model recursively using the input and output signals of the FDTD simulation. Savings in the computation requirements are achieved by replacing the computational intensive FDTD algorithm with the ARMA model once the system parameters converge to their final values. In addition, the ARMA model directly provides the frequency spectrum thus eliminating the use of Fourier transformation.

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