Fast RCS Computation over a Frequency Band Using Method of Moments in Conjunction with Asymptotic Waveform Evaluation Technique

C. J. Reddy, M. D. Deshpande, C. R. Cockrell, and F. B. Beck

***Abstract*—The method of moments (MoM) in conjunction with the asymptotic waveform evaluation (AWE) technique is applied to obtain the radar cross section (RCS) of an arbitrarily shaped three-dimensional (3-D) perfect electric conductor (PEC) body over a frequency band. The electric field integral equation (EFIE) is solved using MoM to obtain the equivalent surface current on the PEC body. In the AWE technique, the equivalent surface current is expanded in a Taylor's series around a frequency in the desired frequency band. The Taylor series coefficients are then matched via the Padé approximation to a rational function. Using the rational function, the surface current is obtained at any frequency within the frequency range, which is in turn used to calculate the RCS of the 3-D PEC body. A rational function approximation is also obtained using the model-based parameter estimation (MBPE) method and compared with the Padé approximation. Numerical results for a square plate, a cube, and a sphere are presented over a frequency bandwidth. Good agreement between the AWE and the exact solution over the bandwidth is observed.**

***Index Terms*—Moment methods, radar cross sections.**

I. INTRODUCTION

THE solution of the electric field integral equation (EFIE) via the method of moments (MoM) has been a very useful tool for accurately predicting the radar cross section (RCS) of arbitrarily shaped three-dimensional (3-D) perfect electric conductor (PEC) objects in the frequency domain [1]. In MoM, EFIE is set up by subjecting the total tangential electric field over the surface of the PEC body to zero. Dividing the PEC body surface into subdomains such as triangles, rectangles, or quadrilaterals and employing Galerkin's technique, the integral equation is reduced to a matrix equation. The matrix equation is then solved using either by a direct method or by an iterative method for the equivalent surface currents. The RCS is computed from the knowledge of the surface currents. The generation of the matrix equation and its solution are the two major computationally intensive operations in MoM.

To obtain the RCS over a band of frequencies using MoM, one has to repeat the calculations at each frequency over the band of interest. If the RCS is highly frequency dependent one needs to do the calculations at finer increments of frequency to get an accurate representation of the frequency response. This can be computationally intensive and for electrically large objects it can be computationally prohibitive despite the increased power of the present generation of computers. There were some attempts to obtain the wide-band data from the method of moments by interpolating the impedance matrix [2]. This method trades reduced central processing unit (CPU) time for increased memory. In [3], the model-based parameter estimation (MBPE) is used to obtain the wide-band data from frequency and frequency-derivative data. A similar technique called the asymptotic waveform evaluation (AWE) technique has been proposed for the timing analysis of very large scale integration (VLSI) circuits [4], [5]. The AWE technique is finding increasing interest in the electromagnetic analysis of microwave circuits [6], [7]. Recently, a detailed description of AWE applied to frequency-domain electromagnetic analysis was presented in [8], [9]. AWE was also successfully applied for efficient dispersion analysis of dielectric waveguides [10].

In this paper, the application of AWE for predicting the RCS over a band of frequencies using MoM is described. In the AWE technique, the electric current is expanded in the Taylor series around a frequency. The coefficients of the Taylor series (called "moments") are evaluated using the frequency derivatives of the EFIE. In most cases, Taylor series gives fairly good results. However, the accuracy of the Taylor series is limited by the radius of convergence and it will not converge beyond the radius of convergence. In such cases, the rational function approach is used to improve the accuracy of the numerical solution. The coefficients of the Taylor series are then matched via the Padé approximation to a rational function. Using the rational function, the electric current distribution can be obtained at any frequency within the bandwidth. Using this current distribution, the RCS is obtained. Alternatively, by matching the frequency derivatives of the function to the rational function, the MBPE method can be used to obtain a rational function approximation in a rather straight forward fashion, instead of going through the Taylor series [11]. In this paper, both the Padé approximation and MBPE are pursued to show that they are identical to each other.

The rest of the paper is organized as described below. In Section II, the AWE implementation for the EFIE is described along with the Padé approximation and MBPE. Numerical results for a square plate, cube, and a sphere are presented in Section III. The numerical data is compared with the exact solution over the bandwidth. CPU time and storage require-

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ments for the AWE formulation are given for each example and are compared with those required for the exact solution at each frequency. Numerical results are also compared with the MBPE method. Concluding remarks on the advantages and disadvantages of the current method are presented in Section IV.

II. Theory

Consider an arbitrarily shaped PEC body. For RCS calculations, a plane wave is assumed to be incident at an angle (θ_i, ϕ_i). At the surface of the PEC body, the total tangential electric field is zero. The total tangential field in terms of the scattered and incident fields on the PEC body is, therefore, written as

$$\mathbf{E}_{\text{scat}} + \mathbf{E}_{\text{inc}} = 0. \quad (1)$$

In a subdomain MoM approach, the PEC surface is divided into triangles, rectangles, or quadrilaterals. In this paper, we follow the triangular subdomain approach reported in [12]. Writing $\mathbf{E}_{\text{scat}}$ in terms of the equivalent electric current distribution $\mathbf{J}$ on the surface of the PEC object and applying Galerkin's method, a set of simultaneous equations are generated and are written in a matrix equation form as

$$Z(k)I(k) = V(k) \quad (2)$$

where

$$Z(k) = \frac{jk\eta_o}{4\pi}\iint \mathbf{T}\cdot\iint \mathbf{J}\frac{\exp(-jkR)}{R}\,ds'\,ds - \frac{j\eta_o}{4\pi k}\iint(\nabla\cdot T)\iint(\nabla'\cdot\mathbf{J})\frac{\exp(-jkR)}{R}\,ds'\,ds \quad (3)$$

and

$$V(k) = \iint \mathbf{T}\cdot\mathbf{E}_{\text{inc}}\,ds \quad (4)$$

where$\mathbf{T}$ is the vector testing function, k is the wavenumber at frequency f, and η_o is the intrinsic wave impedance. R is the distance between the source point and the observation point. ∇' operates over the source coordinates and similarly ds' indicates the surface integration over the source coordinates. In (2), $Z(k)$ is a complex and dense matrix. $V(k)$ is the excitation column vector. Equation (4) is calculated using a harmonic plane wave

$$\mathbf{E}_{\text{inc}} = \mathbf{E}_i \exp[j(k_x x + k_y y + k_z z)] \quad (5)$$

where

$$\mathbf{E}_i = \mathbf{x}E_{xi} + \mathbf{y}E_{yi} + \mathbf{z}E_{zi} \quad (6)$$

and

$$E_{xi} = \cos\theta_i\cos\phi_i\cos\alpha - \sin\phi_i\sin\alpha \quad (7)$$

$$E_{yi} = \cos\theta_i\sin\phi_i\cos\alpha + \cos\phi_i\sin\alpha \quad (8)$$

$$E_{zi} = -\sin\theta_i\cos\alpha \quad (9)$$

$$k_x = k\sin\theta_i\cos\phi_i \quad (10)$$

$$k_y = k\sin\theta_i\sin\phi_i \quad (11)$$

$$k_z = k\cos\theta_i \quad (12)$$

The matrix (2) is solved at any specific frequency f_o (with wavenumber k_o) either by a direct method or an iterative method. The solution of (2) gives the unknown current distribution, which is used to obtain the scattered electric field. The radar cross section is given by

$$\sigma = \lim_{r\to\infty} 4\pi r^2 \frac{|\mathbf{E}_{f\text{scat}}(\mathbf{r})|^2}{|\mathbf{E}_{\text{inc}}(\mathbf{r})|^2}. \quad (13)$$

A. AWE/MBPE Implementation

The RCS given in (13) is calculated at one frequency. If one needs the RCS over a frequency range, this calculation must be repeated for the different frequencies of interest. Instead, AWE or MBPE can be applied for rapid calculation of RCS over a frequency range. The AWE technique involves expanding the unknown coefficient vector in a Taylor series and then obtaining a rational function representation via the Padé approximation. Alternatively, MBPE involves determination of the rational function by matching the frequency derivatives of the function at one or more frequency points. Mathematical steps involved in this process are given below.

Taylor Series Expansion: The solution of (2) at a particular frequency f_o gives the unknown current coefficient column vector $I(k_o)$ at a particular frequency f_o, where k_o is the wavenumber at f_o. Instead, $I(k)$ can be expanded in a Taylor series around k_o and is written as

$$I(k) = \sum_{n=0}^{\infty} m_n (k-k_o)^n \quad (14)$$

with the moment column vector m_n given by [8]

$$m_n = Z^{-1}(k_o)\left[\frac{V^{(n)}(k_o)}{n!} - \sum_{q=0}^{n}\frac{(1-\delta_{qo})Z^{(q)}(k_o)m_{n-q}}{q!}\right] \quad (15)$$

where $Z^{(q)}(k_o)$ is the qth derivative with respect to k of $Z(k)$ given in (3) and evaluated at k_o. Similarly, $V^{(n)}(k_o)$ is the nth derivative with respect to k of $V(k)$ given in (4) and evaluated at $k_o \cdot \delta_{qo}$ is the Kronecker delta.

The evaluation of $Z^{(q)}(k)$ in (15) is a lengthy process due to the presence of $1/k$ in the second term of (3). A complete derivation of $Z^{(q)}(k)$ and $V^{(n)}(k)$ is given in [8]. Using the moments in the Taylor series, the electric current distribution can be obtained, which is used to compute the RCS over the frequency range.

Padé Approximation: In many cases, the Taylor series expansion gives fairly good results. However, the accuracy of the Taylor series is limited by the radius of convergence. It will not converge to the right answer beyond the radius of convergence and it sometimes requires a large number of terms to converge over a frequency range. In such cases, one may want to replace the Taylor series expansion with a rational function via the Padé approximation [13] to improve the accuracy of the numerical solution.

To obtain the Padé approximation, the Taylor series expansion in (14) is matched with a rational function [13]

$$\sum_{n=0}^{L+M+1} m_n (k-k_o)^n = \frac{P_L(k-k_o)}{Q_M(k-k_o)} \quad (16)$$

where

$$P_L(k-k_o) = a_o + a_1(k-k_o) + a_2(k-k_o)^2 + \cdots + a_L(k-k_o)^L$$
$$Q_M(k-k_o) = b_o + b_1(k-k_o) + b_2(k-k_o)^2 + \cdots + b_M(k-k_o)^M$$

where b_o is set to 1 as the rational function can be divided by an arbitrary constant. Since there are $(L+M+1)$ unknowns, $(L+M)$ moments of the Taylor series should be matched. Equating the coefficients for powers $(k-k_o)^{L+1} \cdots (k-k_o)^{L+M}$, the coefficients of $Q_M(k-k_o)$ can be obtained by solving the resulting matrix equation. The numerator coefficients can be found by equating the powers $(k-k_o)^0 \cdots (k-k_o)^L$. Once the coefficients of the rational function are obtained, (14) can be rewritten as

$$I(k) = \frac{a_o + a_1(k-k_o) + a_2(k-k_o)^2 + \cdots + a_L(k-k_o)^L}{b_o + b_1(k-k_o) + b_2(k-k_o)^2 + \cdots + b_M(k-k_o)^M}. \tag{17}$$

For a given amount of computational effort, one can easily construct a rational function that has a smaller error than a polynomial approximation. Also for a fixed value of $L+M$, the error is smallest when $L=M$ or $L=M+1$ [10]. Using (17), the electric current coefficients at frequencies around the expansion frequency are obtained. The electric current distribution hence obtained is used to compute the scattered electric field and, finally, the radar cross section using (13).

MBPE Method: Alternatively, the coefficients of the rational function given in (17) can be obtained by matching the derivatives of $I(k)$ at the expansion frequency f_o. Since there are $(L+M+1)$ unknowns $(L+M)$ derivatives of $I(k)$ should be matched. This results in a matrix equation to be solved for the coefficients of the rational function. A detailed description of the MBPE method is given in [11].

It can be easily shown that the Padé approximation and MBPE are identical. The Padé approximation is derived through a Taylor series, whereas MBPE is derived through matching the derivatives of the function. Once the rational function is obtained, the numerical results for the Padé approximation and MBPE are also identical.

III. Numerical Results

To validate the analysis presented in the previous section, a few numerical examples are considered. RCS calculations over a frequency band are done for a square plate, a cube, and a sphere. The numerical data obtained using AWE with the Padé approximation is compared with the results calculated at each frequency using the triangular patch method of moments. We will refer to the latter method as the "exact solution." The numerical results are also compared with the data obtained using the MBPE method [3]. In the examples presented below, the same data are used for AWE and MBPE and the computational cost in terms of CPU time and storage requirements is exactly the same for both of methods. In the numerical examples presented below, the expansion frequency is chosen to be the center frequency of the band of interest. This choice of expansion frequency gives the maximum bandwidth as AWE is equally valid on both sides of the expansion frequency. All the computations reported below were done on a SGI-*Indigo* 2 (with 250 MHz IP22 processor) computer.

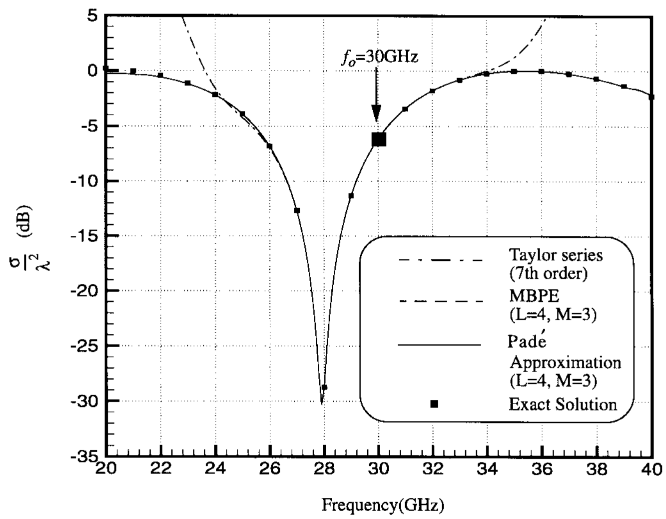

Fig. 1. RCS frequency response of the square plate (1 cm × 1 cm) from 20 to 40 GHz.

Square Plate: The first example is for a square plate (1 cm × 1 cm) with an E-polarized $(\alpha = 90^\circ)$ incident electric field at $\theta_i = 90^\circ$ and $\phi_i = 0^\circ$. The square plate is discretized with triangular subdomains resulting in 603 unknown current coefficients. The AWE frequency response with 0.1-GHz increments is calculated using the Padé approximation with $L=4$ and $M=3$ at $f_o = 30$ GHz. The RCS frequency response is plotted from 20 GHz to 40 GHz in Fig. 1 along with the calculations using MBPE with $L=4$ and $M=3$. For comparison, the frequency response obtained with the Taylor series expansion is also plotted. AWE took 3296 s CPU time to fill the matrices (including the derivative matrices) whereas the exact solution took 429 s for matrix fill at each frequency (i.e., 9009 s for 21 frequencies). The LU factorization took 18 s CPU time for AWE, whereas it took 18 s CPU time for the exact solution at each frequency calculation (378 s for 21 frequencies). It can be observed that Taylor series solution is accurate between 26 GHz and 33 GHz, whereas the Padé approximation and MBPE give accurate solutions over the entire frequency range from 20 to 40 GHz. It can also be noted that the Padé approximation and MBPE gave identical numerical results, hence the curves representing the Padé approximation and MBPE are almost indistinguishable.

Cube: The RCS response of a PEC cube (1 cm × 1 cm × 1 cm) is calculated over a frequency band using AWE with a plane wave incident at $\theta = 0^\circ$ and $\phi = 0^\circ$. The cube is discretized with 348 triangular subdomains resulting in 522 current unknown coefficients. AWE frequency response with 0.1 GHz increments is calculated using Padé approximation with $L=4$ and $M=3$ at $f_o = 12$ GHz. The RCS frequency response is plotted from 2 to 22 GHz in Fig. 2 along with the calculations using MBPE with $L=4$ and $M=3$. The AWE took 2867 s CPU time for filling up the matrices including the derivative matrices and 8 s CPU time for LU factorization.

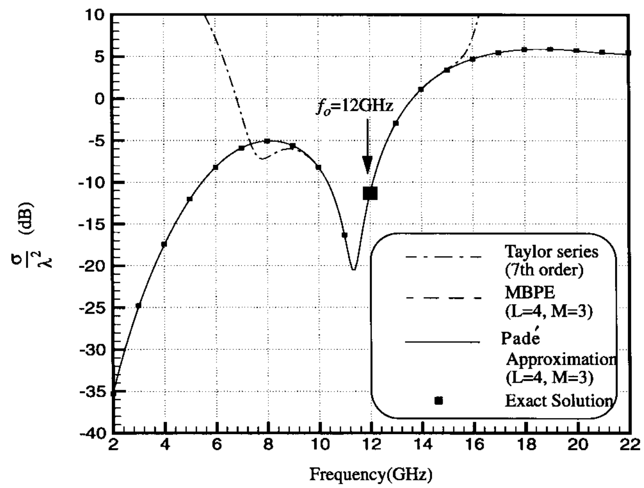

Fig. 2. RCS frequency response of the cube (1 cm × 1 cm × 1 cm) from 2 to 22 GHz.

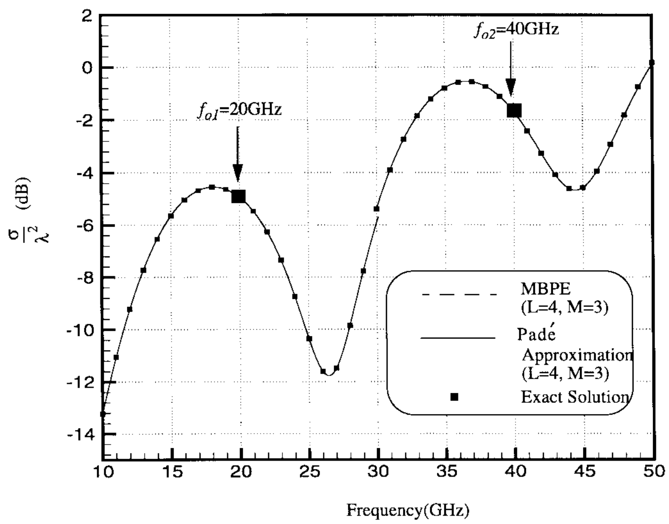

Fig. 3. RCS frequency response of a sphere (radius = 0.318 cm) from 10 to 50 GHz using two frequency points at 20 and 40 GHz.

The exact solution took about 346 s CPU time to fill the matrix (7266 s for 21 frequencies) and 8 s CPU time for LU factorization (168 s for 21 frequencies). The frequency response calculated with the Taylor series expansion is also plotted in Fig. 2 for comparison purposes.

Sphere: As a third example, a PEC sphere of radius 0.318 cm is considered. To demonstrate the usefulness of AWE over a wide bandwidth, two frequency points are considered at 20 and 40 GHz to obtain the frequency response over the frequency range from 10 to 50 GHz. The sphere is discretized into 248 triangular elements at 20 GHz and 504 triangular elements at 40 GHz. The frequency response is plotted in Fig. 3 along with the exact solution calculated using a 1-GHz frequency increment over the 40-GHz bandwidth. The numerical data is calculated using both AWE with the Padé approximation and MBPE with $L = 4$ and $M = 3$ with frequency increments of 0.1 GHz. It can be seen that both the AWE and MBPE calculations agree well with the exact solution. The discontinuity seen at 30 GHz is due to the error between values obtained from the AWE approximation at 20 and 40 GHz, respectively. The CPU timings for matrix fill and LU factorizations are given in Table I. It can be seen from Table I that the exact solution with a frequency increment of 1 GHz took around 4 h and 27 min of CPU time to calculate the frequency response over the frequency bandwidth (10 to 50 GHz), the AWE calculation requires only 1 h and 34 min of CPU time.

TABLE I
CPU TIMINGS FOR RCS CALCULATIONS OF THE PEC SPHERE

Method	Frequency Band (GHz)				**Total Time** (secs)
	10GHz-30GHz (372 unknowns)		31GHz-50GHz (756 unknowns)		
	Matrix Fill (secs)	LU Factor (secs)	Matrix Fill (secs)	LU Factor (secs)	
AWE_MoM with Padé approximation or MBPE	977	3	4,633	35	5,648
MoM (20 Frequency Points)	5,160	72	10,080	720	16,032

Comment on storage: In all the above examples, when solving a matrix equation, one needs to store a complex dense matrix $Z(k_o)$ of size $N \times N$ for the exact solution at each frequency. For nth order AWE, one needs to store n number of complex dense matrixes $(Z^{(q)}(k_o), q = 1, 2, 3, \cdots n)$ of size $N \times N$ along with the matrix $Z(k_o)$ of size $N \times N$. For electrically large problems, this could impose a burden on computer resources. This problem can be overcome by storing the derivative matrices $Z^{(q)}(k_o)$ out-of-core, as the derivative matrices are required only for matrix–vector multiplication.

IV. CONCLUDING REMARKS

An implementation of AWE for frequency-domain MoM is presented. The RCS for different PEC objects such as a square plate, cube, and sphere are computed and compared with the exact solution over a band of frequencies. AWE results are also compared with those obtained with MBPE method. It is also found to be useful to use multifrequency expansion points to get a wide-frequency bandwidth. From the numerical examples presented in this paper, AWE is found to be superior in terms of the CPU time to obtain a frequency response. It may also be noted that though calculations are done at one incidence angle for all the examples presented, with a nominal cost, the frequency response at multiple incidence angles can also be calculated. AWE is accurate at and around the frequency of expansion. Its accuracy deteriorates beyond a certain bandwidth. The accuracy of AWE over a desired frequency band and its relation to the order of AWE to be used are topics of interest for future research. With these topics addressed, AWE will be of good use in computing the frequency response using a frequency-domain technique such as MoM.

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REFERENCES

[1] E. K. Miller, L. Medgysi-Mitschang, and E. H. Newman, Eds., *Computational Electromagnetics: Frequency Domain Method Of Moments*. New York: IEEE Press, 1992.

[2] E. H. Newman, "Generation of wide-band data from the method of moments by interpolating the impedance matrix," *IEEE Trans. Antennas Propagat.*, vol. 36, pp. 1820–1824, Dec. 1988.

[3] G. J. Burke, E. K. Miller, S. Chakrabarthi, and K. Demarest, "Using model-based parameter estimation to increase the efficiency of computing electromagnetic transfer functions," *IEEE Trans. Magn.*, vol. 25, pp. 2807–2809, July 1989.

[4] L. T. Pillage and R. A. Rohrer, "Asymptotic waveform evaluation for timing analysis," *IEEE Trans. Comput.-Aided Design*, pp. 352–366, Apr. 1990.

[5] T. K. Tang, M. S. Nakhla, and R. Griffith, "Analysis of lossy multiconductor transmission lines using the asymptotic waveform evaluation technique," *IEEE Trans. Microwave Theory and Techniques*, vol. 39, pp. 2107–2116, Dec. 1991.

[6] D. Sun, J. Manges, X. Yuan, and Z. Cendes, "Spurious modes in finite element method," *IEEE Antennas Propagat. Mag.*, vol. 37, pp. 12–24, Oct. 1995.

[7] J. Gong and J. L. Volakis, "AWE implementation for electromagnetic FEM analysis," *Electron. Lett.*, vol. 32, pp. 2216–2217, Nov. 1996.

[8] C. R. Cockrell and F. B. Beck, "Asymptotic waveform evaluation (AWE) technique for frequency domain electromagnetic analysis," NASA Tech. Memo 110292, Nov. 1996.

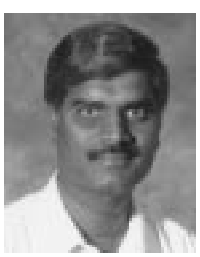
[9] C. J. Reddy and M. D. Deshpande, "Application of AWE for RCS frequency response calculations using method of moments," NASA Contractor Rep. 4758, Oct. 1996.

[10] S. V. Polstyanko, R. Dyczij-Edlinger, and J. F. Lee, "Fast frequency sweep technique for the efficient analysis of dielectric waveguides," *IEEE Trans. Microwave Theory Tech.*, vol. 45, pp. 1118–1126, July 1997.

[11] E. K. Miller and G. J. Burke, "Using model based parameter estimation to increase the physical interpretability and numerical efficiency of computational electromagnetics," *Comput. Phys. Commun.*, vol. 68, pp. 43–75, 1991.

[12] S. M. Rao, D. R. Wilton, and A. W. Glisson, "Electromagnetic scattering by surfaces of arbitrary shape," *IEEE Trans. Antennas Propagat.*, vol. AP-30, pp. 409–418, May 1982.

[13] E. Chiprout and M. S. Nakhla, *Asymptotic Waveform Evaluation*. Norwell, MA: Kluwer, 1994.



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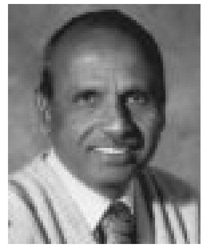

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