Optimal Simultaneous Interpolation/Extrapolation Algorithm of Electromagnetic Responses in Time and Frequency Domains

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***Abstract*—In this paper, an optimal simultaneous interpolation and extrapolation algorithm in the time and frequency domains is carried out by adaptively choosing the order of the associate Hermite (AH) expansion. Due to the isomorphism of the AH function and its Fourier transform, the time-domain signal and its corresponding frequency-domain transform can be expanded as two isomorphic AH expansions, that can be used for simultaneous interpolation and extrapolation in the time and frequency domains from the partial sampled data of the two waveforms. By using an optimization algorithm, the origin of the expansion and the optimal scaling factor can be found. Hence, by using an adaptive procedure, the order of the expansion can be chosen that leads to accurate interpolation and extrapolation. Some numerical examples are presented to illustrate the efficiency of this method for the complex signal both with and without random noise. The proposed algorithm is also applied to analyze the time- and frequency-domain responses of the ground bounce and lead frame problems in electronic packaging in which the proposed algorithm remains stable when a large order of Hermite expansion is required.**

***Index Terms*—Frequency-domain analysis, ground bounce, Hermite polynomials, lead frame, time-domain analysis.**

I. Introduction

IN ELECTROMAGNETIC analysis, field quantities are usually assumed to be time harmonic. This suggests that the solution lies in the frequency domain. The method of moments (MoM), which uses an integral-equation formulation, can be used to perform the frequency-domain analysis. However, for broad-band analysis, this approach can become computationally very intensive as the MoM program needs to be executed for each frequency of interest, and for high frequencies, the size of the matrix can be prohibitively large.

The time-domain approach is preferred for broad-band analysis. Other advantages of a time-domain formulation include easier modeling of nonlinear and time-varying media and the use of gating to eliminate unwanted reflections. For a time-domain integral-equation formulation, the method of marching-on-in-time (MOT) is usually employed. A serious drawback of this algorithm is the occurrence of late-time instabilities in the form of high-frequency oscillations [1].

Recently, the simultaneous extrapolation algorithm in time and frequency domains using the Hermite expansions was presented to obtain late-time and broad-band information [2]. However, there are some limitations in this method. The first drawback is that the order of Hermite expansion only varies between 10–20 for different examples. Choosing a large order will introduce oscillations in the extrapolation region and choosing a smaller order will be inaccurate. The second drawback is that the choice of the origin and the scaling factor are both crucial and difficult to determine.

In this paper, an optimal simultaneous interpolation and extrapolation method is presented using an adaptive procedure. This method not only overcomes the aforementioned limitations, but can also perform the simultaneous interpolation in time and frequency domains. By using the optimization algorithm, we can optimally choose the origin and the scaling factor for the Hermite expansion. By using the adaptive algorithm, we can also choose the order of the Hermite expansion. Since the choice of the origin and the scaling factor is optimal, no oscillation will occur when a large order of the Hermite expansion is chosen. In addition, numerical results show that this method is still accurate when random noise is introduced in both the time and frequency domain using known sampled data.

This paper is organized as follows. In Section II, the associate Hermite (AH) expansion is introduced. The adaptive optimal simultaneous interpolation and extrapolation algorithm is then described in Section III. In Section IV, we present some numerical results demonstrating the accuracy and efficiency of the proposed method. In particular, we apply the proposed algorithm to analyze the time- and frequency-domain responses of the ground bounce and lead frame problems in electronic packaging. Finally, conclusions are presented in Section V.

II. AH Expansion

Consider the set of function [3]

$$h_n(t,\lambda) = \frac{1}{\sqrt{2^n n! \sqrt{\pi}\lambda}} H_n\left(\frac{t}{\lambda}\right) \exp\left(-\frac{t^2}{2\lambda^2}\right), \qquad \mathrm{n} \geq 0 \tag{1}$$

where $H_n(t)$ is the Hermite polynomial and n and λ are the order and scaling factors of the Hermite polynomial, respectively.

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The Hermite polynomial can be defined recursively as

$$\begin{cases} H_0(t) = 1 \\ H_1(t) = 2t \\ H_n(t) = 2tH_{n-1}(t) - 2(n-1)H_{n-2}(t). \end{cases} \tag{2}$$

Using (1) and (2), the function $h_n(t, \lambda)$, referred to as the AH functions, can be computed recursively, and the recursion relation can be expressed as

$$h_n = \frac{1}{\sqrt{n}}\left(\sqrt{2}th_{n-1} - \sqrt{n-1}h_{n-2}\right). \tag{3}$$

The AH function has a number of interesting properties, one of them is its approximate finite time support, and another one is the isomorphism property between the function and its Fourier transform, which is given by [4], [5]

$$\begin{aligned} \mathrm{F}\left[h_n(t, \lambda)\right] &= (-j)^n \frac{\sqrt{2\sqrt{\pi}\lambda}}{\sqrt{2^n n!}} H_n(2\pi\lambda f) \exp\left[-\frac{(2\pi\lambda f)^2}{2}\right] \\ &= (-j)^n h_n(f, \mu) \end{aligned} \tag{4}$$

where $\mu = 1/(2\pi\lambda)$. This means that the Fourier transform of an AH function with a scaling factor λ and order n is an AH function with the scaling factor $\mu = 1/(2\pi\lambda)$ and order n.

The set of AH functions $\{h_n(t, \lambda)\}$ constitutes an orthogonal basis with respect to the following inner product:

$$\langle h_m(t, \lambda), h_n(t, \lambda)\rangle = \int_{-\infty}^{+\infty} h_m(t, \lambda)h_n(t, \lambda)\, dt.$$

Assume that a signal $x(t)$ can be expanded by the AH functions of order zero to N as follows:

$$x(t) = \sum_{n=0}^{N} a_n h_n(t, \lambda). \tag{5}$$

Its Fourier transform $X(f)$ can then be expressed as

$$X(f) = \sum_{n=0}^{N} (-j)^n a_n h_n(f, \mu) \tag{6}$$

or

$$X_R(f) = \sum_{k=0}^{2k\le N} (-1)^k a_{2k} h_{2k}(f, \mu) \tag{6a}$$

$$X_I(f) = -\sum_{k=0}^{2k+1\le N} (-1)^k a_{2k+1} h_{2k+1}(f, \mu). \tag{6b}$$

where $X_R(f)$ and $X_I(f)$ denote the real and imaginary parts of the transform $X(f)$. The expansion coefficients a_n can be computed by

$$a_n = \langle x(t), h_n(t, \lambda)\rangle = \int_{-\infty}^{+\infty} x(t)h_n(t, \lambda)\, dt \tag{7}$$

and the Paresval's relation yields

$$\sum_{n=0}^{+\infty} a_n^2 = \int_{-\infty}^{+\infty} x^2(t)\, dt.$$

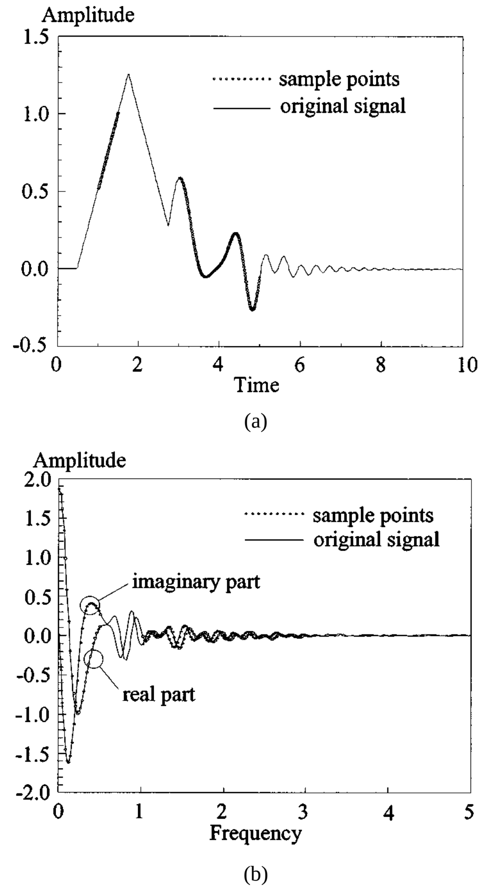


Fig. 1. Time- and frequency-domain signal to be determined with slope discontinuities in the time-domain data and sample points for simultaneous interpolation and extrapolation. (a) Time-domain signal. (b) Frequency-domain signal.

Therefore, the convergence condition is $\int_{-\infty}^{+\infty} x^2(t)\, dt < +\infty$ and the expansion error for order N can be expressed as

$$e_N = \int_{-\infty}^{+\infty}\left[x(t) - \sum_{n=0}^{N} a_n h_n(t, \lambda)\right]^2 dt = \sum_{n=N+1}^{+\infty} a_n^2.$$

Generally, for a causal signal, (i.e., $x(t) = 0$ for $t \le 0$), the origin t_o needs to be chosen appropriately. Therefore, the signal $x(t)$ and its Fourier transform $X(f)$ can be expanded as

$$x(t) = \sum_{n=0}^{N} a_n h_n(t - t_0, \lambda) \tag{8}$$

$$X(f) = e^{-j2\pi f t_0} \sum_{n=0}^{N} (-j)^n a_n h_n(f, \mu). \tag{9}$$

III. Adaptive Optimal Simultaneous Interpolation/Extrapolation Algorithm

In this section, the adaptive optimal simultaneous interpolation and extrapolation algorithm is described for the above-mentioned AH expansion.

A. Calculation of Expansion Coefficient a_n

When only part of the sampled data of the signal $x(t)$ and its Fourier transform $X(f)$ are given, (7) cannot be used to calculate the expansion coefficient a_n. Let M_1 and M_2 be the number of time- and frequency-domain known sampled data, and N be even. Equations (5) and (6) can be expressed by an matrix representation

$$H\,a = X \tag{10}$$

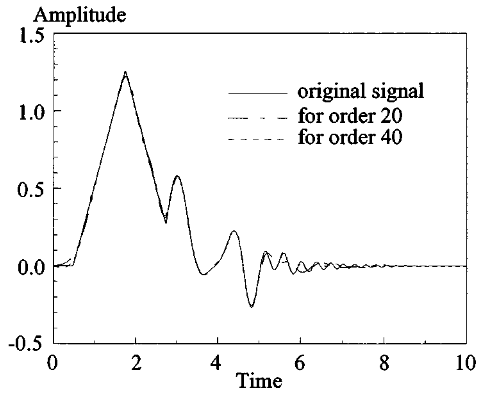
where H is an $(M_1+2M_2)\times(N+1)$ matrix, and a and X are $N+1$ and M_1+2M_2 dimensional column vectors, respectively. They can be represented as shown by the equation at the bottom of this page.

Equation (10) is a set of linear equations. Generally, the number $M_1 + 2M_2$ of equations is greater than the number $N + 1$ of the expansion coefficients a_n, thus, a least-squares method [6] can be employed to calculate the coefficients.

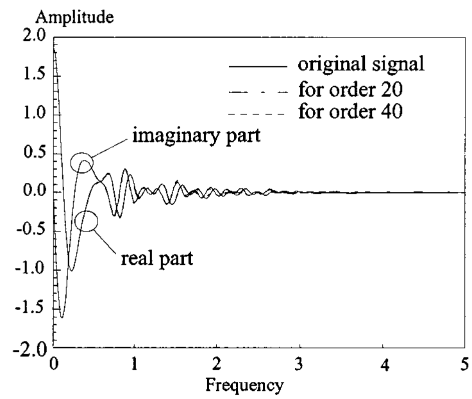
B. Optimal Choice of the Origin t_0 and Scaling Factor λ

Obviously, by choosing a different origin t_o and scaling factor λ, different expansion coefficients a_n will be obtained for a fixed expansion order N by solving (10). We will then obtain a different AH expansion and will have a corresponding expansion error e_N and matching error at these sample points. The matching error can be represented as

$$e(t_0,\,\lambda) = \sum_{m=1}^{M_1}\left|x(t_m) - \sum_{n=0}^{N} a_n h_n(t_m - t_0,\,\lambda)\right|^2 + \sum_{m=1}^{M_2}\left|X(f_m) - e^{-j2\pi f_m t_0} \cdot \sum_{n=0}^{N}(-j)^n a_n h_n(f_m,\,\mu)\right|^2. \tag{11}$$



(a)



(b)

Fig. 2. Comparisons of the results for order of expansion 10, 20, 30, and 40 and the original signals shown in Fig. 1. (a) Time domain. (b) Frequency domain.

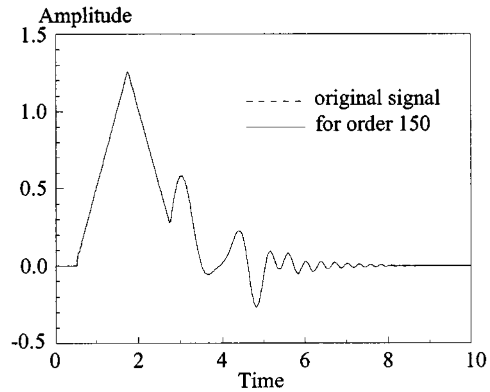
An optimal choice of the origin and scaling factor is obtained when the matching error in the approximation of the given data is minimized. This gives rise to the following nonlinear programming problem with respect to the origin t_o and the scaling factor λ:

$$\min\left\{e(t_0,\,\lambda)\right\}. \tag{12}$$

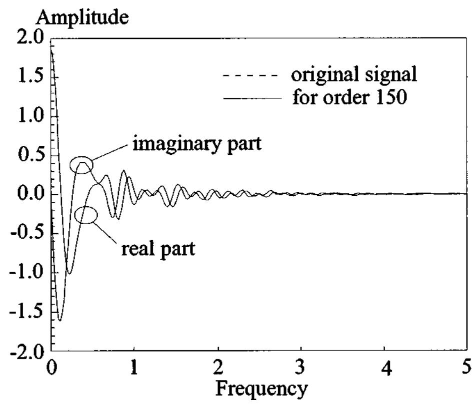
$$H = \begin{bmatrix} h_0(t_1,\lambda) & h_1(t_1,\lambda) & \cdots & h_{N-1}(t_1,\lambda) & h_N(t_1,\lambda) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ h_0(t_{M_1},\lambda) & h_1(t_{M_1},\lambda) & \cdots & h_{N-1}(t_{M_1},\lambda) & h_N(t_{M_1},\lambda) \\ h_0(f_1,\mu) & 0 & \cdots & 0 & (-1)^{N/2}h_N(f_1,\mu) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ h_0(f_{m_2},\mu) & 0 & \cdots & 0 & (-1)^{N/2}h_N(f_{m_2},\mu) \\ 0 & -h_1(f_1,\mu) & \cdots & (-1)^{N/2-1}h_N(f_1,\mu) & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & -h_1(f_{m_2},\mu) & \cdots & (-1)^{N/2-1}h_N(f_{m_2},\mu) & 0 \end{bmatrix}$$

$$a = [a_0 \quad a_1 \quad \cdots \quad a_N]^T$$

$$X = [x(t_1) \quad \cdots \quad x(t_{M_1}) \quad X_R(f_1) \quad \cdots \quad X_R(f_{M_2}) \quad X_I(f_1) \quad \cdots \quad X_I(f_{M_2})]^T$$

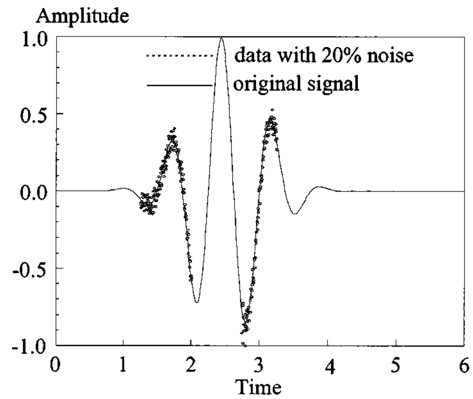


(a)



(b)

Fig. 3. Comparison of the results for expansion order 150 and the original signals shown in Fig. 1. (a) Time domain. (b) Frequency domain.



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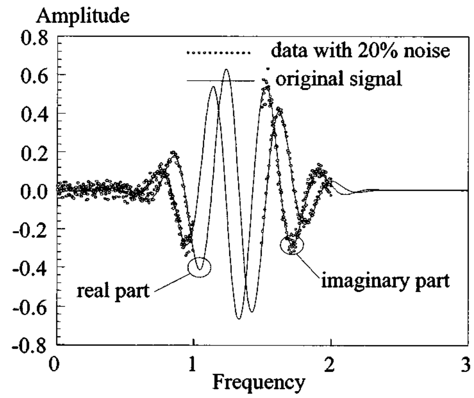


(b)

Fig. 4. Time- and frequency-domain original signals to be determined along with the sample points contaminated with 20% noise for simultaneous interpolation and extrapolation. (a) Time-domain signal. (b) Frequency-domain signal.

We can employ an optimization algorithm to solve this nonlinear programming problem and, in this paper, we choose the Powell method [7].

C. Adaptive Choice of Expansion Order N

The choice of Hermite expansion order N is very crucial. Choosing a small order will lead to a bad interpolation and extrapolation result, and choosing a large order will introduce oscillations in the interpolation or extrapolation regions. Here, an adaptive algorithm is presented to choose an appropriate order. The procedure of this adaptive algorithm is given in the following steps.

- Step 1) Start with a small expansion order N. Generally, we let the expansion order be $N \leq 5$.
- Step 2) Set an initial origin t_o and Hermite scaling factor λ. Generally, we choose the initial origin $t_0 = (t_1 + t_{M_1})/2$ (assuming $t_1 < t_2 < \cdots < t_{M_1}$) and the initial Hermite scaling factor $\lambda = 3.0$.
- Step 3) Optimize the nonlinear programming problem $\min\{e(t_0, \lambda)\}$ to find the optimal origin t_o and the optimal Hermite scaling factor λ for the order of approximation N. The optimal AH expansion for the order N is then obtained.
- Step 4) Evaluate the expansion error e_N and the matching error $e(t_o, \lambda)$ of the optimal AH expansion of order N so as to verify whether the associate Hermite expansion meets the accuracy requirement. The accuracy of the method depends on the expansion and matching errors. We can evaluate the expansion error by using the last several expansion coefficients and calculate the matching error by using (11). If the expansion error e_N and the matching error $e(t_o, \lambda)$ are less than the given precision, this adaptive procedure will stop. Otherwise, replace the order N by the order $N+1$ and choose the optimal origin t_o and the optimal Hermite scaling factor λ obtained in Step 3) as the initial t_o and λ for the new order N; then go to Step 3).

Obviously, an adaptive order N will be obtained when the adaptive procedure terminates.

IV. Numerical Results

In order to validate our adaptive optimal simultaneous interpolation and extrapolation algorithm, some examples are presented in this section.

Example 1: In the first example, we consider the unknown time-domain signal, and the corresponding frequency-domain signal is displayed in Fig. 1 (solid line). The time derivative of the time-domain signal includes some discontinuous points, and the frequency-domain signal has values in a wide frequency range. Here, the known sample points of the two signals are shown in Fig. 1 (dotted line). By using our adaptive optimal si-

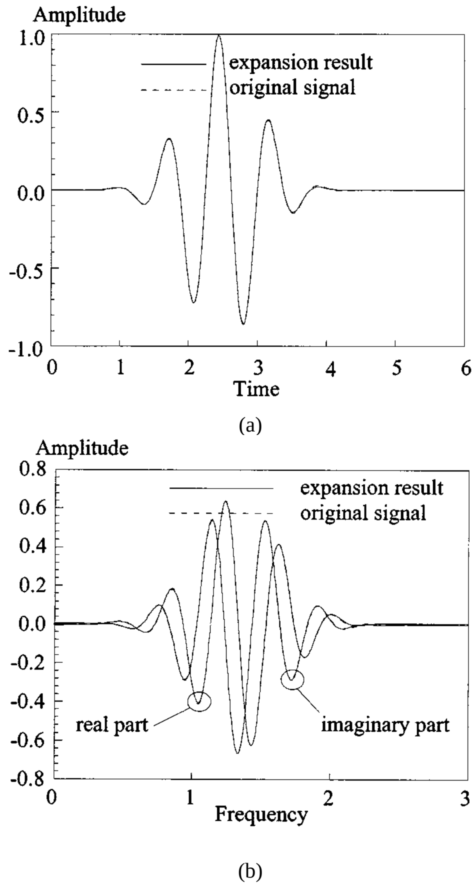


Fig. 5. Comparison of the results along with the sample data contaminated with 20% noise and the original signals shown in Fig. 4. (a) Time domain. (b) Frequency domain.

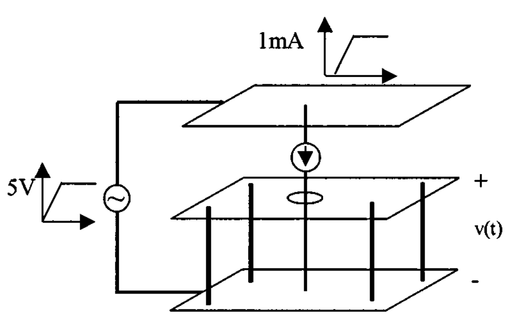


Fig. 6 Geometry of the ground bounce problem.

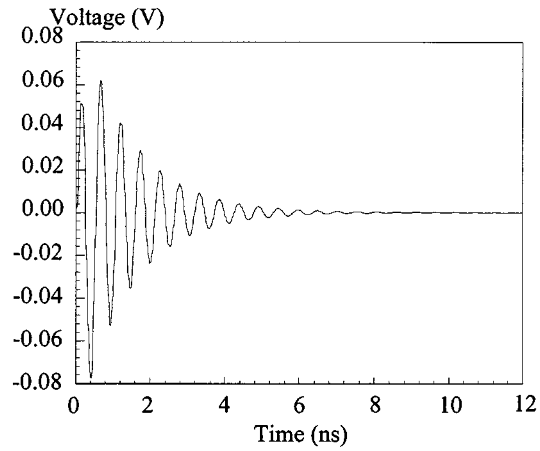


Fig. 7. Time variation of the voltage disturbance $v(t)$.

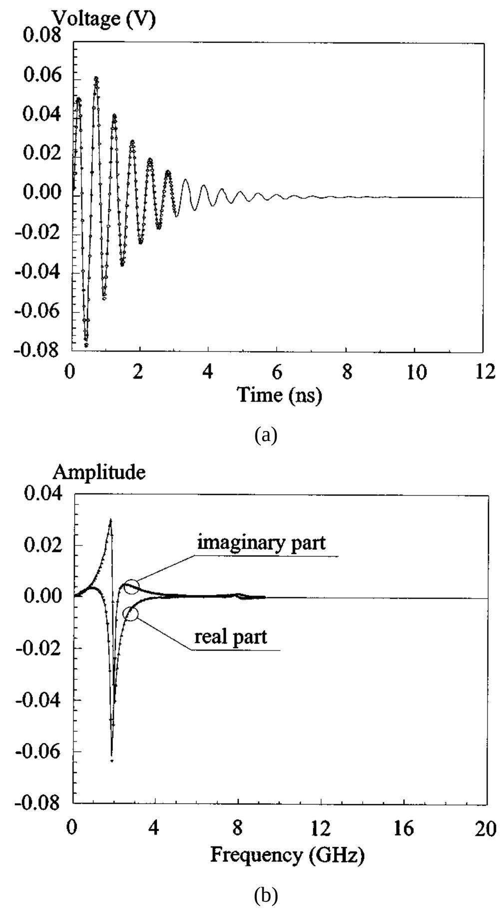


Fig. 8. Sampled data used for interpolation and extrapolation and the interpolated and extrapolated results of order 650 for the ground bounce problem. (a) Time domain. (b) Frequency domain.

multaneous interpolation and extrapolation algorithm, some results for different order of expansion are obtained. Fig. 2 shows the comparisons for different order of approximations 10, 20, 30, and 40 and the original signal in both time and frequency domains. Obviously, these interpolation and extrapolation results do not agree well with the original signals. This is because the original time-domain signal is not smooth at the time points $t = 0.50$, 1.75, and 2.50 and has a wider time support; thus, it is necessary to choose a larger expansion order. Fig. 3 shows the expansion results of order 150 in the time and frequency domains. We can find that the interpolation and extrapolation results agree very well with the original signals in both the time and frequency domains.

Example 2: From a practical standpoint, there is noise associated with the sample values of the data. Therefore, it is very important to verify whether the interpolation and extrapolation algorithm is valid for the given data contaminated with noise. In this example, we choose the following function as the unknown time-domain signal:

$$x(t) = \begin{cases} 0, & t \le 0 \\ \sin\dfrac{8\pi t}{3}\exp\left[-\dfrac{16(t-2.5)^2}{9}\right], & t > 0. \end{cases}$$

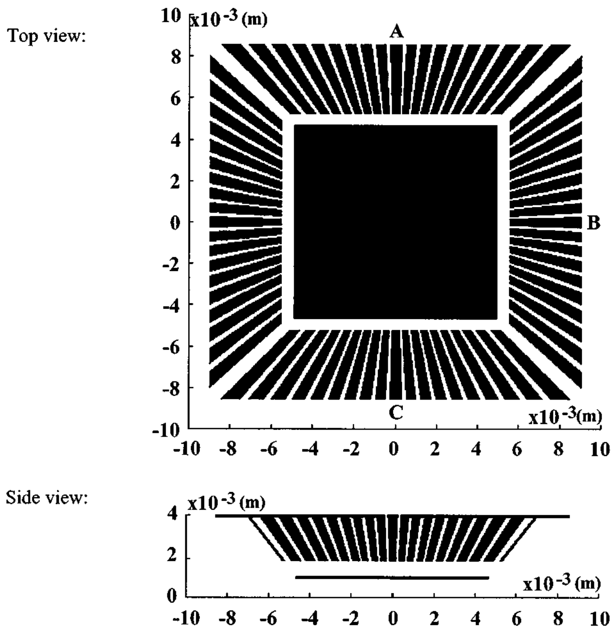


Fig. 9. Geometry of the lead frame problem.

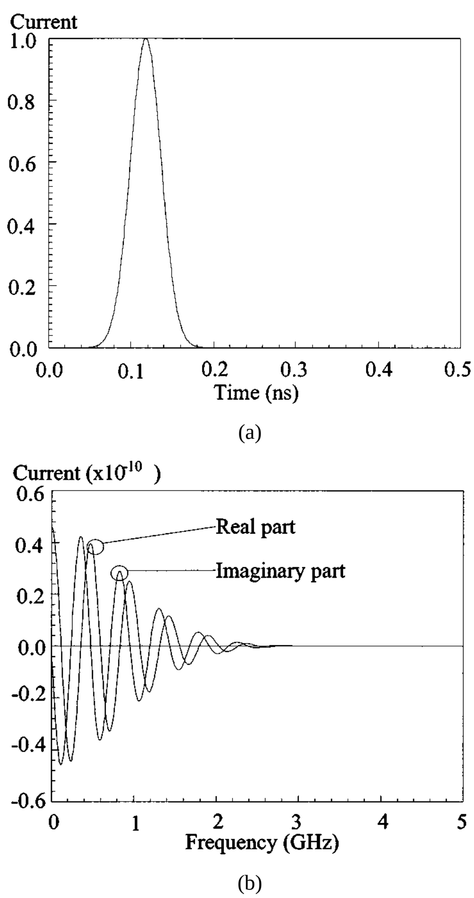


Fig. 10. Current excitations in the: (a) time and (b) frequency domains.

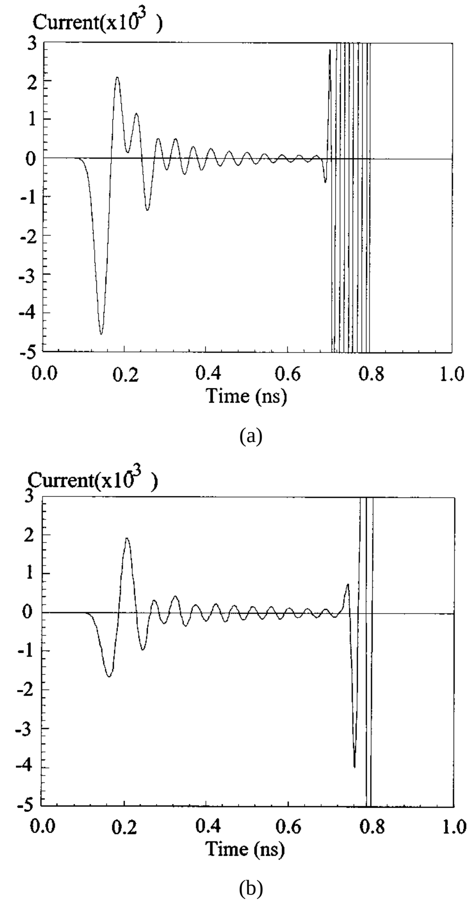
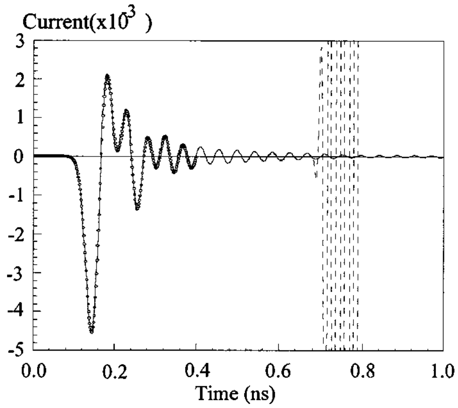


Fig. 11. Time-domain responses calculated by using MOT in: (a) Lead B and (b) Lead C.

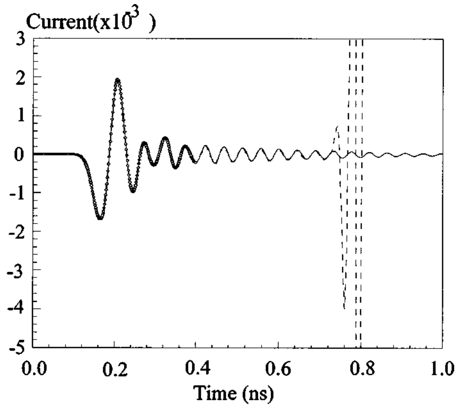
This signal $x(t)$ and its Fourier transform $X(f)$ are plotted in Fig. 4 (solid line). Assuming that, in both time- and frequency-domain signals, only some portions of the sampled data are known, and 20% random noises are added. Fig. 4 (dotted line) shows the known sample points with 20% noise added to the time-domain signal $x(t)$ and the frequency-domain signal $X(f)$. In the time domain, the information at $t < 1.25$ and $t > 3.25$ must be extrapolated, and the information at $2.00 < t < 2.75$ must be interpolated. In the frequency domain, the information at $f > 3.00$ must be extrapolated, and the information at $1.00 < f < 1.50$ must be interpolated. By utilizing our adaptive optimal simultaneous interpolation/extrapolation algorithm, we interpolate and extrapolate these time and frequency signals. Fig. 5 shows the expansion results for order 20. From Fig. 5, it can be found that the agreement between our interpolation and extrapolation results and the original signals in both time and frequency domains is still excellent. This demonstrates that our interpolation and extrapolation algorithm is valid for given sampled data with noise. Although not shown, excellent results are obtained with an expansion order of 150 when 20% random noise is added to the sampled data in Example 1.

Excellent results for Examples 1 and 2 demonstrate that our adaptive optimal simultaneous interpolation/extrapolation algorithm can be used to analyze the complex problem. In the next two examples, we consider the ground bounce and lead frame problems in electronic packaging.

Example 3: The ground bounce problem [8] is considered in this example. For the structure depicted in Fig. 6, the voltage (V) is assumed to be 5 V. A current of 1 mA is injected with a delay. The time variation of the voltage disturbance is recorded for 50 000 time steps, which is shown in Fig. 7. The finite-difference time-domain (FDTD) method [9] is employed to calculate this voltage disturbance. The frequency response of the voltage

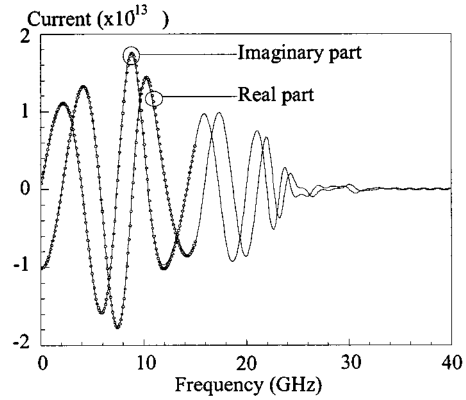


(a)

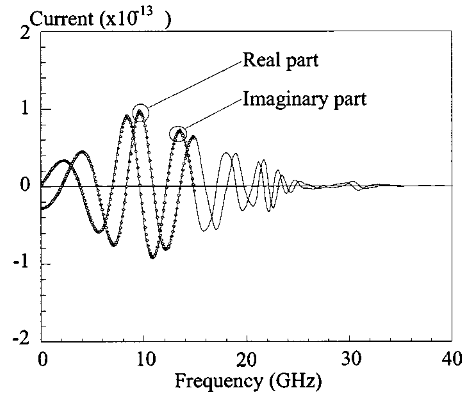


(b)

Fig. 12. Extrapolated results and comparison of the time-domain response in: (a) Lead B and (b) Lead C. Dotted line: early-time responses used to extrapolatrion. Solid line: extrapolated results. Dashed line: MOT results.



(a)



(b)

Fig. 13. Extrapolated results and comparison of the frequency-domain responses for: (a) Lead B and (b) Lead C. Dotted line: low-frequency MoM results used for extrapolation. Solid line: extrapolated results.

is obtained by taking the Fourier transform of the time-domain data. Fig. 8 shows the sampled data used and the generated interpolation/extrapolation results. Excellent agreement is obtained. In this example, we need a large order of Hermite expansion as the time duration we want to match is very long. The proposed algorithm, however, remains stable for a large order $N = 650$.

Example 4: In this last example, we consider the lead frame problem [10]. The structure of the lead frame is shown in Fig. 9. When Lead A is excited by a current, the current distributions in the lead frame both in the time and frequency domains will be evaluated. The current excitation in time domain is a Gaussian pulse, and the current excitation in frequency time is the Fourier transformation of the above Gaussian pulse. Current excitations for the two domains are shown in Fig. 10. Obviously, the FDTD with uniform discretization cannot be used because of the effect of the uniform discretization. In addition, when using the MOT with triangular patching [11], there exists late-time instabilities. Fig. 11 shows the curves of the time responses in Leads B and C, respectively.

In order to apply our adaptive optimal simultaneous interpolation/extrapolation algorithm to analyze this problem, the time responses from $t_0 = 2.549834$ to $t = 0.4$ ns in the above MOT results are chosen as the early-time signal, shown in Fig. 12 (1000 data points). The low-frequency signal (Fig. 13, 150 data points) from $t_0 = 2.549834$ to $f = 15.0$ GHz in Leads B and C are obtained by using the MoM [12], and the same triangular patching is utilized to eliminate the effect of discretization between the frequency-domain MoM and MOT methods. Using those data, the time-domain responses are extrapolated up to $t = 1.0$ ns, which are shown in Fig. 12 (real line), and the frequency-domain responses are extrapolated up to $f = 40.0$ GHz, which are shown in Fig. 13 (real line). The orders of the AH expansion for Leads B and C are 160 and 150, respectively.

The computational cost of this algorithm scales as $O(N^2(M_1 + 2M_2))$. In Example 1, $M_1 = 250$ and $M_2 = 500$, the CPU runtime is 220 min in the same computer for $N = 150$. In Example 2, $N = 20$, $M_1 = 250$, and $M_2 = 200$, and the CPU runtime is 2 min on a Pentium 133 MHz PC.

V. Conclusions

An adaptive optimal simultaneous interpolation and extrapolation algorithm in the time and frequency domains has been presented. By using the AH expansion, the time-domain signal and its corresponding frequency-domain transform can be simultaneously interpolated and extrapolated from the given sample data of the two signals. In this algorithm, the optimal choice for the origin of the expansion and scaling factor can be obtained by using the approximation error as a criterion. A suitable expansion order can be chosen by an adaptive procedure. Four numerical examples are presented to demonstrate the efficiency of our method. The algorithm is still especially efficient for the sampled data with random noise. This scheme has been successfully applied to data obtained from the ground bounce and lead frame problems in electronic packaging. The proposed algorithm remains stable when a long duration time is simulated in which the order of the expansion becomes large.

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