

REPORT DOCUMENTATION PAGE

Public reporting burden for this collection of information is estimated to average 1 hour per response, including gathering and maintaining the data needed, and completing and reviewing the collection of information collection of information, including suggestions for reducing this burden, to Washington Headquarters Service, Paperwork Project (0704-0100), Washington, DC 20503.

0115

3 sources,
act of this
Jefferson

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE March 2000	3. REPORT TYPE AND DATES COVERED Final Technical Report 1 Sep 94 to 30 Nov 97	
4. TITLE AND SUBTITLE Application of the Matrix Pencil Method for Estimating the SEM (Singularity Expansion Method) Poles of Source Free Transient Responses From Multiple Look Directions			5. FUNDING NUMBERS F49620-94-1-0421	
6. AUTHOR(S) Tapan K. Sarkar, Sheeyun Park and Jinwan Koh (Syracuse Univ) Sadasiva M. Rao (Univ of Alabama)				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Department of Electrical Engineering and Computer Science 121 Link Hall Syracuse University Syracuse, NY 13244-1240			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR/NM 801 N. Randolph St, Rm 732 Arlington, VA 22203-1977			10. SPONSORING/MONITORING AGENCY REPORT NUMBER F49620-94-1-0421	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION AVAILABILITY STATEMENT Approved for public release; distribution unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) In this paper, the matrix pencil method has been utilized for estimating the natural resonances from different transient responses recorded along multiple look directions as a function of time after the incident field has passed the structure. The novelty of this article is that a single estimate for all the poles are done utilizing multiple transient waveforms emanating from the structure along multiple look directions. The SEM poles are independent of the angle at which the transient response is recorded. The only difference between the various waveforms are that the residues at the various poles are of different magnitudes. Some of the residues may even be zero for some of the poles indicating that the contribution from certain SEM poles may not be significant along that look direction. Here all the waveforms are utilized providing a single estimate for the poles without performing an arithmetic mean of the various waveforms.				
14. SUBJECT TERMS			15. NUMBER OF PAGES 21	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

**APPLICATION OF THE MATRIX PENCIL METHOD FOR ESTIMATING
THE SEM (Singularity Expansion Method) POLES OF SOURCE FREE TRANSIENT
RESPONSES FROM MULTIPLE LOOK DIRECTIONS**

Tapan K. Sarkar, Sheeyun Park and Jinwan Koh
Department of Electrical Engineering and Computer Science
121 Link Hall
Syracuse University
Syracuse, New York 13244-1240

Sadasiva M. Rao
Department of Electrical Engineering
University of Alabama, Auburn

ABSTRACT: In this paper, the matrix pencil method has been utilized for estimating the natural resonances from different transient responses recorded along multiple look directions as a function of time after the incident field has passed the structure. The novelty of this article is that a single estimate for all the poles are done utilizing multiple transient waveforms emanating from the structure along multiple look directions. The SEM poles are independent of the angle at which the transient response is recorded. The only difference between the various waveforms are that the residues at the various poles are of different magnitudes. Some of the residues may even be zero for some of the poles indicating that the contribution from certain SEM poles may not be significant along that look direction. Here all the waveforms are utilized providing a single estimate for the poles without performing an arithmetic mean of the various waveforms.

1. INTRODUCTION: It is well known in the electromagnetics literature that after the incident field had crossed the structure of interest, the time domain responses can be modelled by a sum of complex exponentials [1-2]. In the Laplace domain this is equivalent to modelling the transfer function of the system by the poles along with its residues or in terms of a ratio of two polynomials whose roots provide the poles and zeros of the system.

Many methods exist in the published literature to carry out such a parameterization of the source free transient responses of the system. A partial survey of such techniques is available in [3,9,10]. Out of most of the techniques, the matrix pencil method had proved to be quite useful [4,5] because of its low sensitivity to background noise and its computational ease and efficiency.

Now when the transient responses from the object of interest whose SEM poles need to be found out is looked at from different angles both in azimuth and in elevation, the residues of the poles are angle dependent whereas the SEM poles modeling the time domain waveforms are

not angle dependent. In addition, for each look direction there are two possible polarizations. One could also use both polarizations to increase the number of waveforms available. Conventionally, to estimate the SEM poles from multiple look angle data one takes the average of all the various look directions waveforms and then obtains a single waveform. Then a sum of complex exponentials is used to fit the single waveform and an estimate of the SEM poles is obtained along with the averaged values of the residues. However, this is not a good approach if the signal-to-noise ratios of the different waveforms are different - namely in some of them the transient response dies down quite fast whereas in some of the responses this may continue to ring for a long time. Hence taking an average of those two classes of waveshapes actually deteriorates the signal-to-noise ratio of the data. This is because by taking an average of the signal along with waveforms where the signal has died down may lead to an unnecessary contamination of the signal by noise. In this paper the matrix pencil approach is applied to obtain a single estimate for the SEM poles utilizing simultaneously all the transient waveforms from multiple look directions and without averaging them.

In the next section the matrix pencil method is presented for the simultaneous estimation of all the SEM poles from multiple look directions without averaging. In section 3, the computational procedure utilizing the total least squares singular-value decomposition based approach is presented for the estimation of the SEM poles from multiple look directions. This approach has been found to be most robust in obtaining estimates for the poles in the presence of random noise [6-8]. Section 4 provides some numerical examples utilizing sample simulated data followed by conclusion and a selected set of references where additional materials are available.

2. Application of the Matrix Pencil Method for Simultaneous Estimation of the SEM-Poles Utilizing Waveforms from Multiple Look Directions

Let us denote the transient response of length $N+1$ along a particular look direction $-k$ by the set $[Y_k]$. So that the column vector $[Y_k]$ is represented by

$$[Y_k]_{(N+1) \times 1} = [y_k(0); y_k(1); \dots; y_k(N)]_{1 \times (N+1)}^T \quad (1)$$

where T denotes the transpose of a matrix. The elements $y_k(j)$ represents the values of the transient response at the j th time sample, so that

$$y_k(j) = \sum_{i=1}^M A_k(i) \exp[s_i j \Delta T] \dots \text{ for } j = 0, 1, 2, \dots, N \quad (2)$$

where ΔT is the sampling time. Each transient response consists of the same M SEM poles s_i which are to be solved for along with their amplitudes $A_k(i)$ for a particular look direction k . Please note that M is also an unknown along with the SEM poles and their residues. The SEM poles s_i are look direction independent but not their residues $A_k(i)$. In the sampled domain, (2) can be rewritten as

$$y_k(j) = \sum_{i=1}^M A_k(i) z_i^j \quad \text{for } j = 0, 1, 2, \dots, N \quad (3)$$

where

$$z_i = \exp[s_i \Delta T] \quad (4)$$

It has been further assumed that all the waveforms for different look angles $k = 1, 2, \dots, K$, have been sampled uniformly at the same sampling rate ΔT and that each waveform contains the same number of samples $N+1$.

Next we consider two matrices $[B_1]$ and $[B_2]$ defined as:

$$[B_1]_{N \times K} = \begin{bmatrix} y_1(0) & y_2(0) & \dots & y_K(0) \\ y_1(1) & y_2(1) & \dots & y_K(1) \\ \vdots & \vdots & & \vdots \\ y_1(N-1) & y_2(N-1) & \dots & y_K(N-1) \end{bmatrix}_{N \times K} \quad (5)$$

$$[B_2]_{N \times K} = \begin{bmatrix} y_1(1) & y_2(1) & \dots & y_K(1) \\ y_1(2) & y_2(2) & \dots & y_K(2) \\ \vdots & \vdots & & \vdots \\ y_1(N) & y_2(N) & \dots & y_K(N) \end{bmatrix}_{N \times K} \quad (6)$$

Now, it can be shown that the two matrices $[B_1]$ and $[B_2]$ can be decomposed as follows:

$$[B_1]_{N \times K} = [Z_1]_{N \times M} [I]_{M \times M} [A]_{M \times K} \quad (7)$$

$$[B_2]_{N \times K} = [Z_1]_{N \times M} [Z_0]_{M \times M} [A]_{M \times K} \quad (8)$$

where

$$[Z_1]_{N \times M} = \begin{bmatrix} 1 & 1 & \dots & 1 \\ z_1 & z_2 & \dots & z_M \\ z_1^2 & z_2^2 & \dots & z_M^2 \\ \vdots & & & \\ z_1^{N-1} & z_2^{N-1} & \dots & z_M^{N-1} \end{bmatrix}_{N \times M} \quad (9)$$

$$[I]_{M \times M} = \text{is a diagonal matrix} = \text{Identity matrix} \quad (10)$$

and a diagonal matrix $[Z_0]$ containing the SEM pole set

$$[Z_o]_{M \times M} = \begin{bmatrix} z_1 & & & 0 \\ & z_2 & & \\ & & \ddots & \\ & & & 0 \\ & & & & z_M \end{bmatrix}_{M \times M} \quad (11)$$

with

$$[A] = \begin{bmatrix} A_1(1) & A_2(1) & \dots & A_k(1) \\ A_1(2) & A_2(2) & \dots & A_k(2) \\ \vdots & \vdots & & \vdots \\ A_1(M) & A_2(M) & \dots & A_k(M) \end{bmatrix}_{M \times k} \quad (12)$$

Now if we consider the matrix pencil

$$[B_2] - \lambda [B_1] \quad (13)$$

then we observe

$$[B_2] - \lambda [B_1] = [Z_o] \{ [Z_o] - \lambda [I] \} [A] \quad (14)$$

This matrix pencil becomes linearly dependent when λ is one of the system poles as then the rank of $\{ [Z_o] - \lambda [I] \}_{M \times M}$ is reduced by one as $\lambda = z_i$. Equation (14) can be transformed into a computationally palatable form by considering the ordinary eigenvalue problem in either of the following forms:

$$[B_2] [B_1]^+ - \lambda [I] \quad (15)$$

$$[I] - \lambda [B_1] [B_2]^+ \quad (16)$$

where the superscript + is the pseudo inverse of the respective matrices. The pseudo inverse is

defined in terms of the singular value decompositions of the respective matrix. Let

$$\begin{aligned}
 [B_1]_{N \times K} &= [U_1]_{N \times N} \begin{bmatrix} \sigma_1^2 & & & 0 \\ & \sigma_2^2 & & \\ & & \ddots & \\ & & & \sigma_k^2 \\ 0 & & & & \ddots \\ & & & & & 0 \end{bmatrix}_{N \times K} [V_1]_{K \times K}^H \\
 &= [U_1] [\Sigma] [V_1]^H
 \end{aligned} \tag{17}$$

where $[U_1]$ and $[V_1]$ are two orthogonal matrixes, i.e.

$$[U_1]^{-1} = [U_1]^H \tag{18}$$

$$[V_1]^{-1} = [V_1]^H \tag{19}$$

where the superscript H denotes the conjugate transpose of a matrix. Here $[\Sigma]$ is a rectangular matrix whose diagonal elements are related to the singular values of $[B_1]$. In summary, we have the following relationship

$$[B_1]_{N \times K} [V_c]_{K \times 1} = \sigma_c [U_c]_{N \times 1} \quad \text{for } c = 1, 2, \dots, K \tag{20}$$

and

$$[U_1]_{N \times N} = [\{u_1\}_{N \times 1} : \{u_2\}_{N \times 1} : \dots : \{u_N\}_{N \times 1}]_{N \times N} \dots \tag{21}$$

$$[V_1]_{K \times K} = [\{v_1\}_{K \times 1} : \{v_2\}_{K \times 1} : \dots : \{v_K\}_{K \times 1}]_{K \times K} \dots \tag{22}$$

Now the pseudo inverse of $[B_1]$ can be computed from

$$[D_1]_{(L+1) \times K \cdot (N-L)} = [P]_{(L+1) \times M} [I]_{M \times M} [R]_{M \times (L \cdot M)} [Q]_{(K \cdot M) \times [K \cdot (N-L)]} \quad (30)$$

and

$$[D_2]_{(L+1) \times [K \cdot (N-L)]} = [P]_{(L+1) \times M} [Z_0]_{M \times M} [R]_{M \times (K \cdot M)} [Q]_{(K \cdot M) \times [K \cdot (N-L)]} \quad (31)$$

where

$$[P]_{(L+1) \times M} = \begin{bmatrix} 1 & 1 & \dots & 1 \\ z_1 & z_2 & \dots & z_M \\ z_1^2 & z_2^2 & \dots & z_M^2 \\ \vdots & \vdots & & \dots \\ z_1^L & z_2^L & \dots & z_M^L \end{bmatrix}_{(L+1) \times M} \quad (32)$$

$$[R]_{M \times (K \cdot M)} = \begin{bmatrix} A_1(1) & & 0 & \vdots & A_2(1) & & 0 & \vdots & \dots & \vdots & A_K(1) & & 0 \\ & A_1(2) & & \vdots & & A_2(s) & & \vdots & \dots & \vdots & & A_K(2) & \\ 0 & & A_1(M) & \vdots & 0 & & A_2(M) & \vdots & \vdots & & 0 & & A_K(M) \end{bmatrix}_{M \times M} \quad (33)$$

$$[Q]_{(K \cdot M) \times [K \cdot (N-L)]} = \begin{bmatrix} [Q_1]_{M \times (N-L)} & & & \\ & [Q_1]_{M \times (N-L)} & & \\ & & \ddots & \\ & & & [Q_1]_{(K \cdot M) \times [K \cdot (N-L)]} \end{bmatrix} \quad (34)$$

and

$$[Q_1]_{M \times (N-L)} = \begin{bmatrix} 1 & z_1 & z_1^2 & \dots & z_1^{N-L-1} \\ 1 & z_2 & z_2^2 & \dots & z_2^{N-L-1} \\ \vdots & \vdots & \vdots & & \vdots \\ 1 & z_M & z_M^2 & \dots & z_M^{N-L-1} \end{bmatrix}_{M \times (N-L)} \quad (35)$$

In addition $[I]$ and $[Z_0]$ are two diagonal matrices which have been defined by (10) and (11), respectively. Now if we consider the matrix pencil

$$[D_2] - \lambda[D_1] \quad (36)$$

and their equivalent ordinary eigenvalue form of the type

$$[D_2] [D_1]^* - \lambda[I] \quad (37)$$

or

$$[I] - \lambda[D_1] [D_2]^* \quad (38)$$

then when λ becomes an eigenvalue of either (29) or (30), and its value is equivalent to a system pole.

Once all the poles $z_i, i=1, \dots, M$ have been computed the residues at the poles can be computed from the following equation:

$$\begin{bmatrix} y_1(0) & y_2(0) & \dots & y_k(0) \\ y_1(1) & y_2(1) & \dots & y_k(1) \\ \vdots & \vdots & & \vdots \\ y_1(N) & y_2(N) & & y_k(N) \end{bmatrix}_{(N+1) \times K} \quad (39)$$

$$= \begin{bmatrix} 1 & 1 & \dots & 1 \\ z_1 & z_2 & \dots & z_M \\ z_1^2 & z_2^2 & \dots & z_M^2 \\ \vdots & \vdots & & \vdots \\ z_1^N & z_2^N & \dots & z_M^N \end{bmatrix}_{(N+1) \times M} \cdot \begin{bmatrix} A_1(1) & A_2(1) & \dots & A_k(1) \\ A_1(2) & A_2(2) & \dots & A_k(2) \\ \vdots & \vdots & & \vdots \\ A_1(M) & A_2(M) & \dots & A_k(M) \end{bmatrix}_{M \times K} \quad (40)$$

or equivalently

$$[Y] = [Z] \cdot [A]$$

The various residues can now be computed from the least squares solution of (31) from

$$[A] = [Z]^+ [Y] = \{[Z]^H [Z]\}^{-1} [Z]^H [Y] \quad (42)$$

3. COMPUTATION OF THE SEM POLES UTILIZING THE TOTAL LEAST SQUARES

In order to deal with noisy data, the formulation of the previous section is made more robust to noise. We now consider the composite matrix [D]

$$[D] = \begin{bmatrix} y_1(0) & y_1(1) & \dots & y_1(N-L-1) & y_2(0) & y_2(1) & \dots & y_2(N-L-1) & \dots \\ y_1(1) & y_1(2) & \dots & y_1(N-L) & y_2(1) & y_2(2) & \dots & y_2(N-L) & \dots \\ \vdots & \vdots & & \vdots & \vdots & & & \vdots & \\ \vdots & \vdots & & \vdots & \vdots & & & \vdots & \\ y_1(L) & y_1(L+1) & \dots & y_1(N-1) & y_2(L) & y_2(L+1) & \dots & y_2(N-1) & \dots \\ y_1(L+1) & y_1(L+2) & \dots & y_1(N) & y_2(L+1) & y_2(L+2) & \dots & y_2(N) & \dots \end{bmatrix}$$

$$\begin{array}{ccc}
 y_k(0) & y_k(1) & \dots y_k(N-L-1) \\
 y_k(1) & y_k(2) & \dots y_k(N-L) \\
 \vdots & \vdots & \vdots \\
 \vdots & \vdots & \vdots \\
 y_k(L) & y_k(L+1) & \dots y_k(N-1) \\
 y_k(L+1) & y_k(L+2) & \dots y_k(N)
 \end{array} \Bigg]_{(L+2) \times [K \cdot (N-L)]} \quad (43)$$

Please note that $[D_1]$ is obtained from $[D]$ by eliminating the last row and $[D_2]$ is obtained from $[D]$ by eliminating the first row. We now perform a singular value decomposition of $[D]$ according to (17) as follows:

$$[D]_{(L+2) \times [K \cdot (N-L)]} = [U]_{(L+2) \times (L+2)} [\Sigma]_{(L+2) \times [K \cdot (N-L)]} \cdot [V]_{[K \cdot (N-1)] \times [K \cdot (N-L)]}^H \quad (44)$$

To combat the effects of noise and to determine the order M , we perform a singular value filtering of $[\Sigma]$ by retaining its M dominant singular values. The details are available in [4-8] and is omitted in this paper. Also it can be seen that the ordinary eigenvalue problem of

$$[D_2] - \lambda[D_1] \quad (45)$$

can be transformed into the following

$$\begin{aligned}
 & [U_2]_{(L+1) \times (L+2)} [\Sigma]_{(L+2) \times [K \cdot (N-L)]} [V]_{[K \cdot (N-1)] \times [K \cdot (N-L)]}^H \\
 & = \lambda [U_1]_{(L+1) \times (L+2)} [\Sigma]_{(L+2) \times [K \cdot (N-L)]} [V]_{[K \cdot (N-1)] \times [K \cdot (N-L)]}^H
 \end{aligned} \quad (46)$$

or

$$[U_2] - \lambda[U_1] \quad (47)$$

where $[U_2]$ and $[U_1]$ of (44) are obtained from $[U]$ by eliminating the first and the last row,

respectively.

Then the poles are obtained from the solution of either one of the following four ordinary eigenvalue problem

$$\begin{aligned} [U_2]^H [U_2] - \lambda [U_2]^H [U_1] \\ [U_2] [U_2]^H - \lambda [U_1] [U_2]^H \end{aligned} \quad (48)$$

$$\begin{aligned} [U_2] [U_1]^H - \lambda [U_1] [U_1]^H \\ [U_1]^H [U_2] - \lambda [U_1]^H [U_1] \end{aligned} \quad (49)$$

Once the poles are obtained the residues at the poles due to different signals measured at various look directions are obtained from the solution of (32) through the use of (31).

4. NUMERICAL RESULTS

As an example consider a square plate of dimensions $1\text{m} \times 1\text{m}$ (lying in the x - y plane) irradiated by an electromagnetic pulse which is of $6\ell\text{m}$ (light-meters) in duration and is oriented along the E_0 direction with magnitude -377V/m . We are observing the current at the center of the plate. The waveforms are sampled every $\Delta T = 0.11875 \ell\text{m}$ and the incident pulse dies down after $12 \ell\text{m}$. The waveshape for the y -directed current is observed after 130 time samples so as to ensure that the incident field has passed the metal plate. The next 50 samples are taken to estimate the SEM poles for the plate by observing the transient field arriving from different angles of incidence. It has been observed that only 5 poles are required as the singular values drop-off beyond 10^{-8} in evaluating $[D]$ of (43). In the first table we present the SEM poles along with their residues for seven separate incident angles of θ and ϕ .

Case I; $\theta = 0$ and $\phi = 90^\circ$

$$\begin{aligned} s_{1,2} &= -1.2 \pm j1.73 & A_{1,2} &= .45/\underline{\pm 130^\circ} \\ s_{3,4} &= -.49 \pm j.721 & A_{3,4} &= .37/\underline{\pm 18.5^\circ} \\ s_5 &= .703 & A_5 &= .0083 \end{aligned}$$

In this case the incident electric field E_θ of amplitude -377V/m is impinging on the plate from $\theta = 0^\circ$ and $\phi = 90^\circ$. There are two sets of complex conjugate poles and one growing exponential which is of small amplitude. The growing exponential is non physical however, it is the error due to curve fitting of the data.

Case II; $\theta = 10^\circ$ and $\phi = 80^\circ$

$$\begin{aligned} s_{1,2} &= -1.35 \pm j1.71 & A_{1,2} &= .27/\underline{\mp 38.2^\circ} \\ s_{3,4} &= -.276 \pm j1.241 & A_{3,4} &= .19/\underline{\mp 150^\circ} \\ s_5 &= .204 & A_5 &= .113 \end{aligned}$$

Case III; $\theta = 30^\circ$ and $\phi = 50^\circ$

$$\begin{aligned} s_{1,2} &= -1.06 \pm j1.75 & A_{1,2} &= .37/\underline{\mp 32^\circ} \\ s_{3,4} &= -.281 \pm j1.18 & A_{3,4} &= .29/\underline{\mp 143^\circ} \\ s_5 &= .041 & A_5 &= .219 \end{aligned}$$

Case IV; $\theta = 50^\circ$ and $\phi = 75^\circ$

$$\begin{aligned} s_{1,2} &= -.941 \pm j1.82 & A_{1,2} &= .44/\underline{\mp 30^\circ} \\ s_{3,4} &= -.283 \pm j1.17 & A_{3,4} &= .36/\underline{\mp 138^\circ} \\ s_5 &= .07 & A_5 &= .325 \end{aligned}$$

Case V; $\theta = 20^\circ$ and $\phi = 70^\circ$

$$s_{1,2} = -1.57 \pm j1.49 \quad A_{1,2} = .9/\underline{\mp 55.3^\circ}$$

$$s_{3,4} = -.278 \pm j1.22 \quad A_{3,4} = .35/\underline{\mp 158^\circ}$$

$$s_5 = .14 \quad A_5 = .454$$

Case VI; $\theta = 10^\circ$ and $\phi = 170^\circ$

$$s_{1,2} = -.963 \pm j4.11 \quad A_{1,2} = .145/\underline{\mp 55^\circ}$$

$$s_{3,4} = -.282 \pm j1.18 \quad A_{3,4} = .212/\underline{\mp 112^\circ}$$

$$s_5 = .023 \quad A_5 = .208$$

Case VII; $\theta = 30^\circ$ and $\phi = 140^\circ$

$$s_{1,2} = -.999 \pm j2.42 \quad A_{1,2} = .116/\underline{\mp 31^\circ}$$

$$s_{3,4} = -.282 \pm j1.19 \quad A_{3,4} = .139/\underline{\mp 126^\circ}$$

$$s_5 = .316 \quad A_5 = .068$$

As it can be seen from the various results that only one set of poles around $-.28 \pm j1.2$ is stable and the others move around. The various poles are marked in Figure 1 through the various numerals representing the seven cases described above by roman numerals.

Next we utilize all the seven data sets to obtain a single estimate for the poles. Again as before 5 poles are obtained. This single estimate of the poles is marked by '*' in Figure 1.

$$s_{1,2} = -1.13 \pm j1.95$$

$$s_{3,4} = -.28 \pm j1.17$$

$$s_5 = .039$$

However the estimates for the residues are different for different look angles.

Case I; $\theta = 0^\circ$ and $\phi = 90^\circ$

$$A_{1,2} = .35/\underline{\mp 37.6^\circ}$$

$$A_{3,4} = .273/\underline{\mp 139^\circ}$$

$$A_5 = .218$$

Case II; $\theta = 10^\circ$ and $\phi = 80^\circ$

$$A_{1,2} = .29/\underline{\mp 30.1^\circ}$$

$$A_{3,4} = .252/\underline{\mp 131^\circ}$$

$$A_5 = .211$$

Case III; $\theta = 30^\circ$ and $\phi = 50^\circ$

$$A_{1,2} = .125/\underline{\mp 45.2^\circ}$$

$$A_{3,4} = .152/\underline{\mp 91.1^\circ}$$

$$A_5 = .13$$

Case IV; $\theta = 50^\circ$ and $\phi = 70^\circ$

$$A_{1,2} = .126/\underline{\mp 55^\circ}$$

$$A_{3,4} = .143/\underline{\mp 86^\circ}$$

$$A_5 = .117$$

Case V; $\theta = 20^\circ$ and $\phi = 70^\circ$

$$A_{1,2} = .195/\underline{\mp 11.7^\circ}$$

$$A_{3,4} = .213/\underline{\mp 118^\circ}$$

$$A_5 = .186$$

Case VI; $\theta = 10^\circ$ and $\phi = 170^\circ$

$$A_{1,2} = .077/\underline{\mp 47.7^\circ}$$

$$A_{3,4} = .05/\underline{\mp 152^\circ}$$

$$A_5 = .036$$

Case VII; $\theta = 30^\circ$ and $\phi = 140^\circ$

$$A_{1,2} = .236/\underline{\mp 46^\circ}$$

$$A_{3,4} = .159/\underline{\mp 149^\circ}$$

$$A_5 = .117$$

From the theory presented in this paper where only one set of poles has been estimated using all the waveforms, it appears that there is a possible harmonic relationship between the two decaying exponentials, at least in the imaginary part and as expected the higher frequency is damped more. However such a relationship is missing when the poles are estimated from each waveshape separately.

5. CONCLUSION

The matrix pencil method is presented for estimating the SEM poles due to different transient responses. The novelty of this approach is that only one set of the SEM poles are estimated from the multiple waveforms. However the residues at the pole sets are different for different waveshapes. It is hoped that such a single estimate for the SEM poles will be more accurate and robust to different orientation of polarizations of the incident fields and due to various effects introduced by noise.

6. **ACKNOWLEDGEMENT:** Grateful acknowledgement is made to the reviewers for enhancing the readability of the manuscript.

REFERENCES

1. C. E. Baum, "The Singularity Expansion Method" in *Transient Electromagnetic Fields*, L. B. Felsen, Ed., New York: Springer-Verlag, 1976.
2. E. K. Miller, "Time Domain Modelling in Electromagnetics", *J. Electromagn. Waves Applicat.*, Vol. 8, Nos. 9-10, pp. 1125-1172, 1994.
3. O. M. Pereira-Filho and T. K. Sarkar, "Using the Matrix Pencil Method to Estimate the Parameters by a Sum of Complex Exponentials", *IEEE Antennas and Propagat. Mag.*, Vol. 37, pp. 48-55, 1995.
4. Y. Hua and T. K. Sarkar, "Matrix Pencil Method for Estimating Parameters of Exponentially Damped/Undamped Sinusoids in Noise", *IEEE Trans. Acoust. Speech Signal Processing*, Vol. 38, pp. 814-824, May 1990.
5. Y. Hua and T. K. Sarkar, "Generalized Pencil-of-Functions Method for Extracting the Poles of an Electromagnetic System from its Transient Response", *IEEE Trans. on Antennas and Propagation*, Vol. 37, No. 2, pp. 229-234, February 1989.
6. Y. Hua and T. K. Sarkar, "A Perturbation Property of the TLS-LP Method", *IEEE Trans. on Acoustics, Speech and Signal Processing*, Vol. 38, pp. 2004-2005, 1990.
7. Y. Hua and T. K. Sarkar, "On the Total Least Squares Linear Prediction Method for Frequency Estimation", *IEEE Trans. Acoust. Speech Signal Processing*, Vol. 38, No. 12, pp. 2186-2189, Dec. 1990.

8. Y. Hua and T. K. Sarkar, "On SVD for Estimating Generalized Eigenvalues of Singular Matrix Pencil in Noise", *IEEE Trans. Acoust. Speech Signal Processing*, Vol. 39, No. 4, pp. 892-900, April 1991.
9. D. A. Ksienski, "Pole and Residue Extraction from Measured Data in the Frequency Domain Using Multiple Data Sets", *Radio Science*, 1985, pp. 13-19.
10. D. A. Ksienski, "Numerical Methods of Noise Reduction for Frequency Domain SEM", *Electromagnetics*, 1984, pp. 393-405.
11. Y. Hua and T. K. Sarkar, "Parameter Estimation of Multiple Transient Signals", *Signal Processing*, Vol. 28, 1992, pp. 109-115.

List of Figures

Figure 1. Clustering of the poles

