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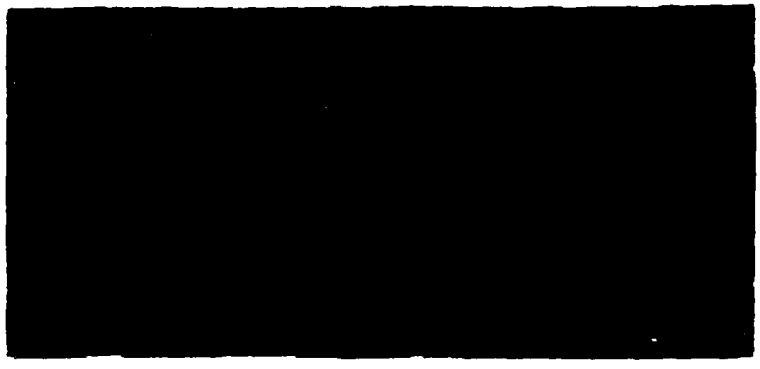

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FINAL REPORT FOR

MODEL-BASED PARAMETER ESTIMATION IN ELECTROMAGNETIC COMPUTER MODELING

CONTRACT N00014-86-K-0326

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RSL Technical Report 7360-5

April 1989

Supported by:

Office of Naval Research
Arlington, Virginia 22217-5000

and Department of the Army

Contract N00014-86-K-0326

Introduction

Modeling in Computational Electromagnetics (CEM) can be a numerically demanding exercise. There are essentially two factors that contribute to this situation. One is the need to describe the propagation of the electromagnetic field via the Maxwell curl equations, a Green's function, mode expansions, or ray and geometrical optics. It is in this part of the problem that a source-field relationship is quantitatively developed. The other is the subsequent need to invert the source-field relationship to proceed from prescribed existing fields and known sources to the induced sources that result and the fields they consequently produce. A moment-method solution, based on an integral equation formulation, embodies both of these factors.

There are basically two paths by which the computer times involved in CEM applications might be reduced. One would be the development of alternate formulations that reduce the time required for either of the activities listed above, or that eliminate the need for it completely. The geometrical theory of diffraction (GTD) is one example of this path. The other would be the development of more efficient numerical approaches for implementing the moment-method model. Under this contract we have investigated several means of reducing the computation time involved in the application of integral equation, moment-method modeling.

Two of the topics covered can be considered to be Model-Based Parameter Estimation (MBPE) approaches. Simply stated, MBPE is any technique that attempts to model a phenomenon, not from the most general physical model, but rather by observing the phenomenon itself. A well-established example is the method of evaluating the Sommerfeld field values developed by Miller, Brittingham, and Okada [1]. Here, even though the Sommerfeld integral itself is very difficult to evaluate, the spatial variation of this integral is rather smooth and easy to approximate. Thus, although it may appear very elegant to evaluate this integral from first principles, it is in fact much more efficient to use a "curve-fitting" model.

The first use of MBPE discussed in this report involves the efficient modeling of the Green's functions associated with rectangular waveguides and enclosures. It is well known that when using an integral equation technique to calculate the scattering of a target within an enclosure, the use of the Green's function appropriate for that enclosure can lead to a great reduction in the number of unknowns necessary to make this calculation [2]. However, the difficulty in actually evaluating these Green's functions often detracts from this approach. The technique described can be implemented in standard moment-method computer codes and greatly decreases the computational times for both scattering and antenna calculations within such enclosures.

The second MBPE application addressed in this work involves improvements in a well-known MBPE technique--Prony's method [3]. As is well known, Prony's method is a simple and powerful method of modeling the complex transfer functions often found in engineering disciplines in terms of sampled values of the transfer function, either in the time or frequency domains. This report suggests two different extensions of the frequency domain Prony's method that address some inherent weaknesses of the technique when modeling transfer functions containing large numbers of poles, such as those typically found

when dealing with radiating structures. These enhancements make Prony's method more robust and will find application in such diverse applications as target identification and wide-band frequency-domain CEM codes.

The final topic discussed in this report addresses the problem of the solutions times associated with the large systems of equations typically encountered in large moment-method CEM applications. As is well known, as the electrical size of a scatterer increases, the number of unknowns necessary to model the geometry increases when using an integral-equation technique, such as the method of moments. When solving such a system of equations, the computational time needed to invert the resulting matrix increases as N^3, where N is the number of unknowns.

A well-known approximation that is sometimes used in the solution of large systems of equations is the so-called Near Neighbor Approximation (NNA), which involves approximating the true impedance matrix with a sparse or banded approximation [4]. Under this contract, we closely investigated the solution errors incurred with various versions of the NNA. Our intent was to develop a priori predictions of solution errors and develop a greater understanding of how the solution accuracies degrade as more and more couplings are ignored.

This final report is a summary of the various research efforts conducted under contract N00014-86-K-0326. Each of the topics identified above is summarized in the sections to follow. More detailed expositions of each of these topics are offered in separate reports, which are referenced in the appropriate sections to follow.

Numerical Green's Function Studies

A common problem encountered in CEM is that of a primary scatterer (or target) enclosed by or in the presence of a secondary scatterer (or enclosure). Such a situation is depicted in Fig. 1. Here, a known field or source distribution illuminates both the primary and secondary scatterers. In problems of this type, although one is generally interested in the fields scattered by the target, the presence of the secondary scatterer can significantly alter both the incident and scattered fields.

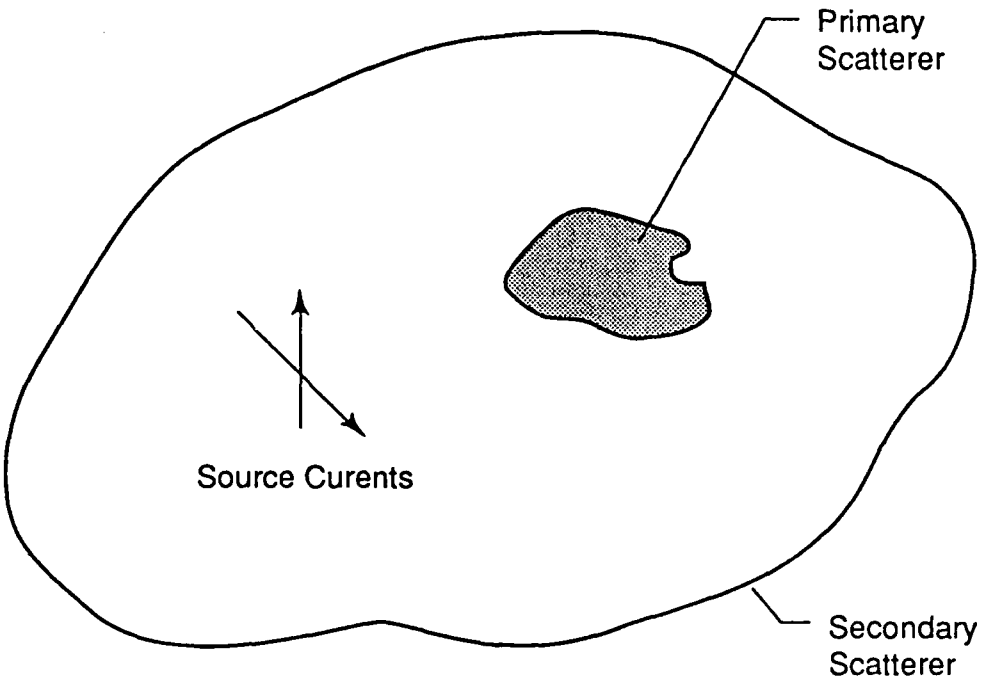

Figure 1. A primary scatterer enclosed by a secondary scatterer.

When using integral equation techniques to determine the fields associated with situations such as that depicted in Fig. 1, there are two basic techniques that can be used to solve the problem. First, the secondary enclosure/scatterer can be modeled in the same way that the test scatterer is. In the case of the method of moments (MoM), this constitutes solving for the appropriate current distribution on both the primary and secondary scatterers. An advantage of this technique is that a broad class of secondary scatterers can be considered, but this comes at great expense; i.e., that the total number of unknowns in this formulation is the sum of those on the test and secondary scatterers. For some secondary scatterers, the number of unknowns needed to model them will far exceed those needed for the primary scatterer.

Another technique for dealing with problems of this type involves the use of the Green's function associated with the secondary scatterer. The representation of this Green's function can either be analytical or numerical. Since the Green's function contains all of the scattering characteristics of the secondary scatterer, its use (in place of the free-space Green's function)

allows the MoM to model only the primary scatterer. This can result in a significant reduction in the number of unknowns necessary to solve for the fields and currents produced by the primary scatterer.

These Green's functions are typically found in one of two ways. The most direct is to derive them analytically from first principles. This method has the advantage of being "exact," but cannot be applied to all geometries. A more general technique is to use an integral equation solution technique, such as the MoM, to calculate the Green's function numerically. Although this method is less straightforward, it can be applied to a very broad class of secondary enclosures and scatterers. In either case, however, the Green's function techniques are often encumbered by the sheer volume of numerical operations necessary to calculate these functions for all the source/observation points required by the MoM modeling of the total problem. In some cases, the computational effort necessary to evaluate these Green's functions within MoM codes becomes greater than that necessary to use the free-space Green's function and treat the secondary scatterer just as the primary scatterer.

We have applied an MBPE technique to the Green's function method of calculating scattering in the presence of secondary scatterers or enclosures. The specific class of problems chosen for analysis was the scattering of targets enclosed by rectangular waveguides and cavities. Our intent was to demonstrate how MBPE can be applied to greatly enhance the speed by which the Green's functions associated with these secondary scatterers could be calculated.

Our analysis proceeded by first developing the Green's functions for these enclosures in terms of the infinite number of images of a source current within them [5]. These expressions, which consist of single, double, or triple infinite sums (for one-, two-, and three-dimensional enclosures, respectively), were then rearranged so that the fields of a source current perceived by an observer within the enclosures could be interpreted as those radiated by two identical, infinite, and periodic arrays that are displaced with respect to each other. This simplification allows each component of the dyadic Green's function to be written as the sum of two (identical) subfunctions, each of a single argument. This is in contrast to the fact that the Green's function itself is a single function of two arguments--both the source and observation positions.

Although the simplified Green's function formulations identified above do not in and of themselves reduce the computational effort necessary to evaluate them, they are an ideal springboard for MBPE since the Green's function subfunctions are relatively slowly varying functions of their single argument. Thus, these subfunctions can be very easily and accurately modeled by using polynomial regression techniques. Once the regression coefficients have been determined from the rigorous calculation of the subfunctions over a relatively course grid within the enclosure, the entire Green's function can be reconstructed by the evaluation of a low order polynomial function.

This technique was applied to the case of a parallel plate waveguide enclosure with great success. A moment-method computer code specific for this problem was written in two versions--one with a "brute force" numerical Green's function and the other with an MBPE Green's function. These codes were then compared in both accuracy and run times for a variety of wire scatterers within

the waveguide. These tests concluded that the MBPE Green's function values were not only accurate but, just as important, required less than one twentieth the computational time. Although tests were not conducted for two- and three-dimensional enclosures, even more time savings would be realized for these problems since the MBPE technique would be largely unchanged as the dimension of the enclosure is increased, whereas the "brute force" Green's functions contain double and triple infinite sums of terms, respectively.

A detailed formulation of this technique is given in [6,7]. Results quoted demonstrate the dramatic increases in numerical efficiency that MBPE can afford in numerical Green's function modeling.

Transfer Function Modeling

The characterization of linear systems by their system functions has been a keystone of engineering analysis for decades. Disciplines such as control systems and circuit theory have long depended upon such analysis. Their use in the area of electromagnetic scattering, however, is a more recent idea. This concept has stirred considerable interest in areas such as scatterer analysis, synthesis, and identification.

Within the area of CEM, transfer functions are of great importance in frequency domain techniques as most quantities calculated in these codes can be interpreted as transfer or driving point functions. This interpretation can be of great importance when wide-band calculations are performed. If, for example, a method-of-moments code is used to analyze a scatterer over a wide bandwidth, it would be much more efficient if the impedance or admittance matrix element transfer functions could be predicted over a considerable bandwidth, rather than simply evaluating them at the frequencies of interest. Such a technique is possible, however, only if the poles and residues of these functions can be accurately calculated from a minimum of sampled data.

A persistent challenge within the subject of transfer function modeling is reconstructing the transfer function of a given system from sampled frequency domain data. This problem has received a great deal of attention in the literature [8,9]. The most well-known technique, Prony's method, has shown itself to be capable of predicting the poles and zeros of a wide variety of system functions for a modest number of frequency domain data points per pole.

In spite of the well-known capabilities of Prony's method, it still has limitations. One limitation is its inability to model transfer functions that contain an analytic (i.e., nonpole) component. This, of course, stems from its initial assumption that the sampled data can be expressed as a simple pole series. Because of this assumption, Prony's method also experiences difficulties in predicting the correct poles and residues when the transfer function being modeled contains poles that lie outside the sampled data. Although this can be avoided when modeling systems with a finite number of poles (such as a lumped circuit), it cannot be avoided in distributed systems.

Another limitation of Prony's method is that it cannot make use of more than a fixed number of data points per pole. This causes two problems. First, it may not be known a priori how many poles a particular system contains. Second, techniques that converge to a correct answer as the number of sample points extends toward infinity require less attention to use in practice. We have attempted to address the above shortcomings by augmenting Prony's technique in two different ways. Each technique addresses a different shortcoming.

The first technique involves adding nonpole (i.e., polynomial) terms to the typical Prony pole series. This addition has two positive effects. First, transfer function poles that lie outside of the data bandwidth can now be accounted for by the polynomial terms. Thus, although the actual values of these particular poles and residues still cannot be determined, the fact that their effect on the transfer function over the bandwidth of the data can be modeled by the polynomial terms means that the actual poles can be better modeled by the pole terms of the Prony series. Another positive effect of

this addition is that the polynomials allow the use of more sampled data terms as the number of polynomial terms increases.

A rigorous development and the test results of this technique are contained in [10]. Here, the addition of the polynomial terms is shown to greatly increase the ability of Prony's method to correctly predict the poles and residues of the complex resonances of transfer functions that contain poles outside the data set. This augmentation would appear to make Prony's method much more capable of predicting the transfer functions of actual radiation systems from either numerically or experimentally derived sampled data.

The second augmentation of Prony's method involves the use of frequency derivative samples. In this scheme, N derivative samples (i.e., first, second, ..., Nth derivatives) of the transfer function at a particular frequency are used (in contrast to using N samples of the function itself at N frequencies). The standard pole series is then matched to this data set to obtain the poles and residues of the transfer function.

This frequency derivative technique is fully developed in [11] Here, it is shown that complex transfer functions, even those with closely spaced resonances, can be well predicted by this technique. This method is particularly attractive when modeling transfer functions from data obtained from frequency domain integral equation codes. It has been shown, [12], that frequency domain derivative samples can be obtained for a very modest computational cost once the system has been solved at a particular frequency. Thus, the N data samples necessary to calculate the poles and residues of the transfer function can be obtained much more cheaply than calculating the transfer function at N frequencies.

It appears to us that a particularly attractive method of modeling transfer functions in the future will be a combination of the two techniques outlined above. It may be that an optimum mix of polynomial terms in the Prony series and frequency derivative samples at a small number of frequencies within the passband of interest will allow the most efficient modeling of a particular transfer function. This will continue to be a topic of continued research at the University of Kansas.

Studies in Large Systems of Equations

A constant challenge in the numerical modeling of electromagnetic structures is the solution of the extremely large systems of equations that result from integral equation techniques, such as the method of moments. In general, as the electrical size of an object increases, the number of unknowns necessary to model it grow in a linear, quadratic, or cubic fashion for linear, planar, and volumetric scatterers, respectively. This growth in the number of unknowns places serious strain on computational facilities, both in CPU time and storage, and ultimately sets limits on the size and complexity of the scatterers that can be accurately modeled.

The most common method of solving the linear systems of equations encountered in integral equation modeling is to use a direct matrix solver, such as LU decomposition, to calculate an inverse of the impedance (or interaction) matrix. However, although direct methods of solution are desirable in that they produce "exact" solutions in a known number of computational steps, they come at a great cost in computational storage and time. Solution times associated with these techniques vary as N^3, where N is the number of unknowns.

It is well known that the impedance matrices for a large class of scatterers are highly diagonally dominant. This occurs because the coupling between distant members of a scatterer are usually quite weak. Because of this, it is tempting to approximate these impedance matrices by setting to zero all couplings below a certain threshold, thus creating a sparse (or, even more desirable, a banded) matrix, since it is well known that these types of systems of equations can be solved with far less solution time. This is often called a near neighbor approximation (NNA). As an indication of the time savings that can be afforded an NNA technique, the solution time of a banded system varies as NB^2, where B is the bandwidth of nonzero terms about the main diagonal.

Whereas the time savings associated with the NNA are well know, the degradation in accuracy is not. It is to this question that our effort was expended. Our intent was to study the effects of various NNA schemes on the solutions of a variety of simple scattering structures. The structures chosen were long straight wires, loops, and very large cylindrical arrays of wires. In all cases, our interest was in electrically large scatterers, typically greater than 10 wavelengths in linear dimension. The wire and loop tests were conducted using the Ohio State thin wire scattering code [13], and the cylindrical arrays were modeled using the Numerical Electromagnetics Code (NEC) [14].

One finding of this study was that the NNA is capable of producing accurate solutions for long straight wires, even when the couplings between segments as close as a wavelength are ignored. Also, it was found that the errors in the currents, input impedance, and far field patterns more or less track each other, meaning that the solutions start to experience significant errors at about the same point as more and more couplings are ignored.

On the other hand, the NNA was found to be not nearly so successful for loops. Although it is possible for an NNA approximation of the impedance matrix to produce good solutions for these geometries, the decrease in error as a function of retained terms was found to be not monotonic. Thus, there would be an a priori uncertainty that an acceptable solution would be obtained for a given problem.

Generalizing, it appears that the NNA can be expected to produce acceptable results, at greatly reduced computational costs, for scatterers that are basically long and narrow. On the other hand, as the geometry exhibits greater tendencies to support circumferential currents, the predictability of the technique starts to degrade.

Our findings indicate that the NNA by itself is not a particularly attractive method of solution, in spite of its well-known gains in solution costs[15]. This conclusion is not surprising and is echoed by other investigators [16]. However, findings of our study have shown that in spite of the large errors often produced by the NNA, there are aspects of the solution that are in fact very accurately predicted and thus can be useful in developing new iterative solution methods. This is consistent with the fact that the NNA has been shown to be useful within at least one iterative scheme for solving large problems [15]. This finding has spawned a new research effort at the University of Kansas to identify mechanisms by which information obtained from NNA solutions can be efficiently fed back to iteration problem solvers. Results from these studies will be the subject of future publications.

Concluding Remarks

The ultimate goal of any engineering discipline is to model or synthesize all possible design possibilities with the maximum possible accuracy and the minimum possible cost. The computational electromagnetics discipline is no exception. Since the introduction of the digital computer, giant strides have been made in this direction. Nevertheless, it is also obvious from looking at the trends in the years since the computer's introduction that, while the gains have been impressive, the class of problems that is beyond our ability to model remains enormous.

The goal of the work conducted under this contract was to investigate a number of ways of implementing MBPE techniques within relatively standard CEM techniques. In each case, the intent was to exploit whatever could be observed about the phenomenon being modeled and then use this insight to effect a more computationally efficient solution. In each case, the computational gains were dramatic.

We feel that there is much yet to be accomplished in this area. The success that we encountered in this research leads us to believe that general problem solvers are always the most desirable. For those cases where one knows in advance the class of problems to be addressed, MBPE techniques have definite advantages

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