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COMPUTER ALGORITHMS AND ARCHITECTURES FOR THREE-DIMENSIONAL EDDY-CURRENT NONDESTRUCTIVE EVALUATION

Contract No. N 00019-86-C-0219

with

Sabbagh Associates, Inc.
4639 Morningside Drive
Bloomington, IN 47401

for

Naval Air Systems Command

20 January, 1989

Volume I

EXECUTIVE SUMMARY

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19. ABSTRACT

In this report, we develop an electromagnetic model for three-dimensional inversion of eddy-current data, an inversion algorithm based on the conjugate gradient technique, and a special purpose computer that we estimate can execute this algorithm in times comparable to high speed main-frames. This computer has a pipeline architecture and is designed around our parallel implementation of the inversion algorithm and makes use of high-speed DSP chips. The inversion process achieves a higher performance measure when more than one data set is inverted. The sequential order of the inversion scheme restricts the number of active elements in the pipe for a single problem. When more than one inversion problem enters the pipe, then more than one element could be active to improve the overall performance of the system.

The basic electromagnetic model starts with the integral equations for electromagnetic scattering, which are then discretized by means of the method of moments. This gives us the fundamental inversion model, which is then solved using the conjugate gradient algorithm. In order to accomplish the three-dimensional inversion, we acquire data at a number of frequencies; therefore, our inversion process is called a multifrequency method. The choice of frequencies, and the number of frequencies to be used, depend upon the conductivity of the host material, and the depth resolution sought.

The method of conjugate gradients has a number of attractive features for our purposes. Chief among them is that it allows a large problem to be solved efficiently, and, because it is an iterative algorithm, it allows us to take advantage of the special Toeplitz structure of the discretized model. We also derive an algorithm that allows us to constrain the solution, use preconditioning and a Levenberg-Marquardt parameter. Preconditioning is often useful in improving the convergence of the conjugate gradient algorithm, and the Levenberg-Marquardt parameter is needed to stabilize the solution against the effects of noise and modeling inaccuracies.

The inversion algorithms may require *a priori* information about the flaw regions. The information can be used to concentrate the inversion efforts on regions of interest rather than unflawed regions. Statistical pattern recognition and computer vision techniques have been examined to achieve this goal. The purpose of applying statistical pattern recognition techniques, is to detect the flaw regions and the background regions in the spatial domain. In addition, a graphical tool can be used to analyze the raw data when used as input features, and evaluate the classifiability of the measurement (any two features).

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EXECUTIVE SUMMARY

PHASE II STATEMENT OF WORK

The principal objectives of the Phase II work are to develop algorithms for eddy current flaw reconstruction and to design an overall NDE system for detection and reconstruction. This work is to prepare for the commercial development of the system during Phase III.

The work to be performed consists of the following tasks:

1. Make a thorough study of the Alliant FX multiprocessor computer.
2. Develop a parallel version of our reconstruction algorithm so that the parallelism is fully exploited.
3. Develop the model algorithm based on convolutions and transform it into a parallel version.
4. Using computer simulated flaws, execute the reconstruction process for verification. Fine tune the algorithm and note those changes that would enhance performance. Refine the multifrequency reconstruction algorithm and enhance its robustness in the presence of noise or corrupted data.
5. Using laboratory data, reconstruct the size and shape of three dimensional flaws.
6. Design the computer component of our NDE system and design its integration into the overall system.
7. Prepare quarterly progress reports.
8. Prepare final report.

SUMMARY OF WORK PERFORMED DURING THIS PROJECT

This final report contains a complete account of the work that was performed during this project. This section summarizes the report; the interested reader should consult the appropriate chapters for technical details.

Chapters I to IV deal with the development of the electromagnetic model for inversion of eddy-current data, and the application of the conjugate gradient technique to the inversion process. Chapter I uses many of the ideas that were originally developed in our SBIR contract with the Naval Surface Weapons Center (White Oak Labs), and that have been explained in the final reports for Phases I and II of that effort. We recommend that a reader who is interested in knowing the origins of our approach to electromagnetic modeling of advanced composite materials study those final reports.

In Chapter I, we describe mathematical models that make use of a bulk conductivity model of an anisotropic material. The bulk conductivity approach and the associated Green's functions for a flat plate are described in the previous final reports mentioned above. Here we develop direct and inverse models based on a whip source probe and a ring source probe. In laboratory tests these probes have been used successfully to detect flaws; thus we develop these models to allow for the reconstruction of three-dimensional flaws.

Making use of previously developed internal and external Green's functions for the bulk conductivity, flat plate model, we develop expressions for the incident and scattered fields due to these source probes. The resulting transfer functions will become the basis for our multi-frequency inversion algorithms.

The basic electromagnetic model starts with the integral equations for electromagnetic scattering, which are then discretized by means of the method of moments. This gives us the fundamental inversion model, which is then solved using the conjugate gradient algorithm. In order to accomplish the three-dimensional inversion, we acquire data at a number of frequencies; therefore, our inversion process is called a multifrequency method. The choice of frequencies, and the number of frequencies to be used, depend upon the conductivity of the host material, and the depth resolution sought. These matters are discussed in Chapter III.

Chapter II reviews the method of conjugate gradients, which has a number of attractive features for our purposes. Chief among them is that it allows a large problem to be solved efficiently, and, because it is an iterative algorithm, it allows us to take advantage of the special Toeplitz structure of the discretized model. In this chapter we derive an algorithm that allows us to constrain the solution, and we also discuss the use of preconditioning and the Levenberg-Marquardt parameter. Preconditioning is often useful in improving the convergence of the conjugate gradient algorithm, and the Levenberg-Marquardt parameter is needed to stabilize the solution against the effects of noise and modeling inaccuracies.

Chapter III deals with reconstructions using simulated and laboratory data. Here, we make use of a number of the ideas that were developed in Chapter II. In addition we show how the application of estimation theory (in particular, linear classification theory) leads to a type of preconditioner that aids considerably the convergence of the inversion process. We believe that this chapter indicates that the conjugate gradient algorithm, as we are implementing it, is a viable approach to three-dimensional quantitative nondestructive evaluation (NDE). In addition, the effort that was put into this chapter has suggested additional adaptive (or 'smart') algorithms that ought to be worthy of future research.

In Chapter III we test the conjugate gradient (CG) inversion algorithm using simulated data. The data was generated using the direct models developed in Chapter I. All tests used the whip source probe. These tests were performed to determine how the CG algorithm performs as a function of the frequency range of the data and the degree of overdeterminedness of the system. Also, since we know we are trying to solve a set of relatively ill-conditioned equations, we need to know if acceptable solutions can be expected. Also, if acceptable solutions are possible, we need to know how many iterations we should expect to perform.

First, a set of tests was performed with a test 'flaw patch' in only one layer. The slab was partitioned into four 'layers' and five sets of emf data from 1 MHz to 9MHz were used. The unconstrained version of the CG algorithm was used. The purpose of these tests was to see if the algorithm isolates the solution to the proper layer. The results of the first set of tests suggested a second set of tests involving flaws in two of four layers. The purpose of these tests was to see if the additive effect of the two flaws would falsely indicate flaws in another layer. In these tests, three additional runs were made. First, a wider range of frequencies (1 MHz to 30 MHz) was used. Then, nine frequencies from 1 MHz to 9MHz were used. Finally, the constrained version of the CG algorithm was used.

The results of the tests indicated that perhaps some post-filtering based on linear classification theory might be used to improve the solution. A 'training set' was used to define a threshold value for acceptance of a flaw. Some of the solutions were then filtered using this threshold.

In addition to simulated data, we reconstructed laboratory data using the algorithms discussed previously. The explanation of the experiments and results are given, and show that our techniques are very promising.

Throughout this research our approach to inversion has been to linearize the problem through what may be called a 'Born-like' approximation. At this time we believe that this approach is the more commercially attractive. Nevertheless, it is worthwhile to develop the rigorous, nonlinear inversion model, which does not require the Born approximation, and which, therefore, should produce a model that is more accurate and consistent with laboratory data; this is done in Chapter IV. This chapter is based on work done elsewhere in the field of seismic inversion operators by Stephen Norton. We have extended Norton's work to a fully three-dimensional, vector, electromagnetic model, that is discretized to make it computationally feasible. We believe that with the development of special purpose computer architectures, the solution of the rigorous model will become commercially attractive for NDE.

In Chapter V, we report experimental results, data storage techniques, hardware and software used in the project, and methods of interfacing laboratory data with the computational processes of flaw reconstruction and field prediction.

Laboratory data were collected towards the completion of technical objective of reconstruction of flaws. The emphasis in collecting the data was on interfacing the data collection process with the rest of the NDE system. A significant portion of the effort in integrating laboratory data and the computer model was verification that the computer program was actually modeling the events measured in the laboratory. The theory provided a means for calculating magnetic and electric fields, while sensors and amplifiers allowed us to measure EMF values. The magnetic field was used to calculate EMF by an integration over the sensor area, but that EMF was dependent on a number of parameters: excitation current, sensor cross-sectional area, and excitation geometry, to mention a few. Some of these parameters were difficult to measure and varied from experiment to experiment.

In our laboratory experiments, we obtained sufficient data, in addition to the EMF measurements, to characterize the experiment so that the model could be accurately used. For each test, we kept records of sensor sizes and geometries, experimental setup, software and hardware used for acquisition, and other parameters that could influence the interaction of laboratory data with the computer model. The complexity of keeping track of the data and the required documentation demanded innovative techniques for storage, retrieval, and documentation. Some of the techniques developed were useful primarily in a prototype environment, such as this project; other techniques were applicable to a wider range of problems.

The inversion algorithms may require apriori information about the flaw regions. The information can be used to concentrate the inversion efforts on regions of interest rather than unflawed regions. Statistical pattern recognition and computer vision techniques have been examined to achieve this goal. In this Chapter VI, we present the pattern recognition approach, while the second approach is presented in Chapter IX.

Our goal of applying statistical pattern recognition techniques, is to detect the flaw regions and the background regions in the spatial domain. The regions identified as flaws are the projection of the three-dimensional flaw onto the measurement plane. These regions correspond to the three-dimensional flaw in the measurement plane and do not indicate the depth of the flaw. The three-dimensional conductivity profile is obtained by inversion of the measurements. The decision is then based on a feature vector for each sample point. If the features show sufficient separability then the detection scheme would have low detection errors.

We applied a multi-class classifier to the eddy current data when the number of classes is two. The multi-class can then be used (we have not pursued this idea) to detect and classify flaws among flaw classes. We believe that the feature set extracted from a flaw region, would contain sufficient information to identify flaws from one another. Such a system, in principle at least, would isolate the flaw regions into separate regions where each region would be associated with one type of flaw. The multi-class scheme was also motivated by the need to isolate the tows present in the eddy current scan of some material. The tows were introduced as a third class in addition to flaws and background.

A graphical tool was developed to analyze the raw data when used as input features, and evaluate the classifiability of the measurement (any two features). The two-dimensional scatter diagram of any two features could also be obtained. Furthermore, each cluster of the data is represented by an ellipse reflecting the cluster relative size and orientation. Graph theory is used to obtain the class boundaries in the two-dimensional case by eliminating segments that do not belong to the classification boundary.

Chapters VII and VIII deal with a parallel implementation of the inversion algorithm, based on the conjugate gradient technique, an efficient scheme for inversion and uses the characteristics of the inversion algorithm to design a specific machine, which we call the PWP machine. In addition, we estimate the inversion time to be comparable to high speed main-frames.

Chapter VII starts with the basic sequential inversion algorithm. Ordering the execution steps implies that the overall performance depends on the time and space complexity of each step. Furthermore, each step usually provides input for its successor, which prevents the execution of two or more sequential steps simultaneously. This imposes a natural limit on the time complexity. The overall time complexity can be improved only if the time complexity of each step is minimized, or in our case optimized. The optimization is thus restricted to each step of the sequential process which can be performed by parallelizing that particular step. The architecture proposed depends, in general, on the algorithm being implemented. The inversion algorithm via conjugate gradient is essentially sequential. If an alternate non-sequential algorithm inverts the data, the proposed architecture may or may not be efficient.

The machine architecture is a pipeline architecture. It achieves a higher performance measure when more than one data set is inverted. The sequential order of the inversion scheme restricts the number of active elements in the pipe for a single problem. When more than one inversion problem enters the pipe, then more than one element could be active to improve the overall performance of the system.

Two conjugate gradient schemes are currently being used: (1) unconstrained inversion, and (2) constrained inversion. An appendix to Chapter VII discusses a version of the constrained technique that eliminates internal looping. This version is better for the PWP machine and is supported by a theoretical and numerical discussion.

The factors that will determine the performance of the inversion are the size of memory and task partition. The first involves the space complexity of a given inversion scheme, while the second involves the dynamics of the inversion. Both aspects are studied in order to design a parallel machine that will execute the inversion with good performance.

In designing the PWP machine, an estimate of the memory requirement is obtained in order to evaluate the feasibility of our design. The requirement depends on the inversion problem and it varies linearly in each of the inversion parameters to give an overall requirement of the fourth order. Even with this requirement, the size is reasonable for typical problems encountered in NDE. If the problem of interest is large relative to the available memory, then the problem must be partitioned on the PWP machine, a condition that is inherent in all computers when the memory requirement is larger than the memory resources.

An architecture for a pipeline configuration is discussed along with techniques for improving the convergence using this architecture. The pipeline is composed of computational layers with several computing elements in each. The task sequencing scheme can be used to determine the number of computing elements for each layer in the pipe.

The design utilizes DSP chips and a multiple bus architecture so that I/O problems can be reduced. The overall speed of the system depends on the speed of the individual DSP chips used to integrate the system. Furthermore, as more advanced DSP chips become available, the system could be upgraded with minimal changes.

We consider a scheduling scheme to assign tasks in order to execute the conjugate gradient. The sequencing scheme is applied to our inversion algorithm, and we obtain estimates of the completion times. The completion time per iteration is six time units for $2\ N_z$ computing elements, five for $N_f\ N_z$ processors and four units for $2\ N_f\ N_z$, where N_z is the number of layers and N_f is the number of frequencies. The cost of the computing elements becomes very high when the desired completion time is four units. When cost, scheduling and speed are considered, $2\ N_z$ processors would be the trade off number of processors to use. A speed-up factor of 1100 is attained, when compared to the Alliant FX/1.

Having chosen a number of processors for a particular inversion problem, the scheduling scheme discussed minimizes the completion time of an inversion problem given a fixed number of processors. The completion time for the new problem depends on its parameters.

Finally, a simulation tool for concurrent systems is presented. By simulating the PWP machine architecture, we can evaluate its performance and improve the design. The goal of the simulation is to minimize the completion time and cost.

In Chapter VIII, we discuss Digital Signal Processing (DSP) integrated circuits as primary components of the computing elements for our proposed special-purpose parallel machine. DSP chips are now available that can operate on floating-point data, making DSP's an excellent choice for doing the calculations in the forward and inverse problems. A number of DSP chips are reviewed, and the tradeoffs are discussed of choosing a particular DSP over another. We discuss which features of the DSP's are important for building a parallel machine around a number of DSP's. The design of the machine, its controlling CPU, algorithms, memory, and communication protocols are closely related to the architecture of the DSP chips used in the design.

In this Chapter IX, we summarize the image processing techniques developed for the analysis of eddy current images. One the most useful scheme was the segmentation of images which was used to estimate the classifier parameters in Chapter VI. In addition, the statistical properties of the flaw and background regions were used to obtain an estimate of the regularization parameter which preconditions the inversion data.

Various techniques of image processing related to NDE were studied. These included edge detection, image segmentation, planar extraction, connected component analysis, and run length coding for image compression.

In Chapter X, a theoretical study for the possibility of using systolic architectures to represent different steps of the Conjugate Gradient method is presented. The realization of such arrays, trees, and vectors is possible with the available VLSI technology. Optimal Systolic architectures are presented for matrix arithmetic with substantial speed-up ratios and reasonable processor-utilization. The design of such architectures is achieved by transforming the time efficiency into a constrained optimization problem,and then solving it using standard techniques.

In Chapter XI, as an alternative to the quantitative methods typically used for nondestructive evaluation of materials here at Sabbagh Associates, we explored the possibility of using qualitative methods to detect and classify flaws. The tact used was to examine electromagnetic fields for features which would yield information as to the presence and nature of flaws. We use the term "artificial intelligence" to describe the techniques tried since the programs developed mimic the way a human being might detect and classify a flaw by examining a graph of a magnetic field.

Models for examing EMFs of two types of materials were developed, on for stainless steel and one for graphite composite. The stainless steel version was developed more extensively, since accurate computer models for depicting an EMF of a field for a specified flaw exist. These models, developed at Sabbagh Associates, allow the user to define the size, shape, and location of a flaw in a material, as well as the frequency the data was gathered at and the nature of the material used. The techniques developed using the computer model were also test on laboratory data, with favorable results.

Only lab data was used in developing the program for graphite composite since accurate models for graphite composite were developed after this study terminated. As a result the effect of flaw size and depth on the EMF could not be tested fully, since the physical materials can not be easily manipulated to test for different flaws. However, the groundwork is laid for further refinement once the computer models for graphite composite materials are developed.

We believe that the effort reported herein has significantly advanced the state-of-the-art in the application of eddy-currents to the quantitative nondestructive evaluation. The Green's functions developed for various configurations of graphite-epoxy are quite novel. They can be used for solving other problems in electromagnetic interactions with advanced composites, such as radar scattering from advanced-composite structures. The three-dimensional inversion algorithms that are based on these models are also quite novel, and could serve as the basis for a host of other remote sensing technologies. The electronic instruments and sensors that have been developed, or improved upon, during this project have been successfully applied to eddy-current NDE of materials other than graphite-epoxy. The classification techniques and image processing techniques are based on solid theoretical methods and have allowed us to detect defects and structures not previously seen by current methods. Finally, the design of the PWP computer gives us a machine that could be used with many problems where the solution algorithm is iterative.

We are confident that eddy-current technology will continue to grow and become a vital part of the NDE of conventional materials, graphite-epoxy, and other advanced composites, and that the spin-offs just described will evolve into their own technologies, as well.

THE TECHNICAL STAFF

Those members of Sabbagh Associates' technical staff who worked on this project are:

- L. David Sabbagh, PhD, Principal Investigator (Executive Summary, II, III, IV)
- Harold A. Sabbagh, PhD, Co-Principal Investigator (I,II,III,IV)
- Denis J. Radecki, MS (I, III)
- Sina Barkeshli, PhD, (III, IV)
- Jeffrey C. Treece, MS (V, VIII)
- Bishara F. Shamee, MS (VI, VII, IX)
- Fouad T. Mrad, MS (VII, X)
- Matthew P. Melchert, MS (XI)

The numbers in parentheses indicate the chapters of this report that the person work on and/or wrote.

PUBLICATIONS

The following is a list of publications and presentations that resulted from the work performed under this contract:

- L. D. Sabbagh, T.M. Roberts, D. J. Radecki, J. C. Treece, H. A. Sabbagh, *A Computational Model for Electromagnetic Interactions with Advanced Composites,*

Proceedings of the Fourth Annual Review of Progress in Applied Computational Electromagnetics at the Naval Postgraduate School, Monteray, CA, (1988).

- H. A. Sabbagh, D. J. Radecki, S. Barkeshli and S. A. Jenkins, *Inversion of Eddy-Current Data and the Reconstruction of Three-Dimensional Flaws,* To be presented at 12th World Conference on Non-Destructive Testing, Amsterdam, The Netherlands, April 23rd-28th 1989.
- H. A. Sabbagh, D. J. Radecki, S. Barkeshli and B. F. Shamee, *Inversion of Eddy-Current Data and the Reconstruction of Three-Dimensional Flaws,* To be presented at Seventh COMPUMAG Conference, Tokyo, September 3–7, 1989.
- This work on computational methods will serve as a basis for a series of lectures to be given at Fifth Annual Review of Progress in Applied Computational Electromagnetics at the Naval Postgraduate School, Monteray, CA, (1986).