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Automated Eddy Current Analysis of Materials

by

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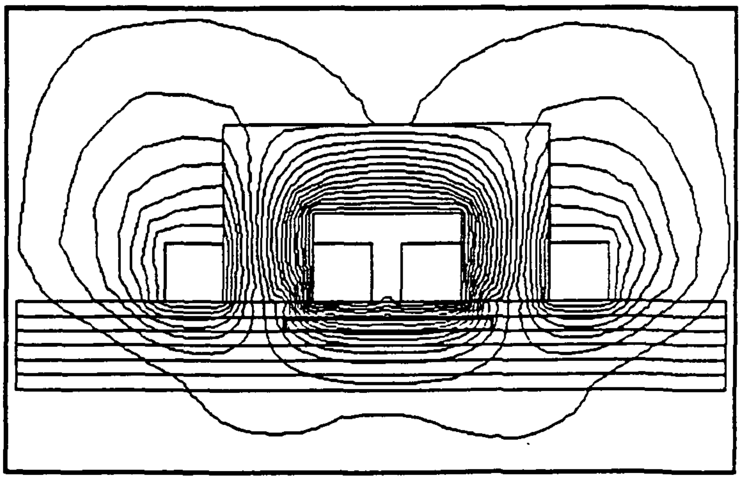

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1.0 INTRODUCTION

The nondestructive testing of aerospace components provides a challenging research activity for the evaluation of new technologies. Graphite based composites are becoming more accepted in critical structures which require a high strength-to-weight ratio. The primary disadvantages, at this time, are the lack of senstivity of most eddy current transducers and the inability to characterize a fabricated part as to its intended service capabilty; i.e. given known defect information, what will be the service life of the part? Attempts to answer these questions can be approached in two steps. First one needs to characterize defects in the material using some nondestructive evaluation technique and then be able to predict the service life of the component with the known defects. Metallic structures have traditionally been handled very well using NDE and fracture mechanics; however, there is still a lot of work to be done to be able to accomplish similar tasks with composite structures.

Since graphite is conducting to a small degree, i.e. the resistivity can vary anywhere from 500 to 1000 •_-cm, eddy current inspection techniques are applicable to determining certain flaws in graphite fiber based structures. Uniformity in resistivity in the normally manufactured products does currently present difficulties; however, it is anticipated that these can be overcome.

1.1 APPROACHES TO EDDY CURRENT SIGNAL INTERPRETATION

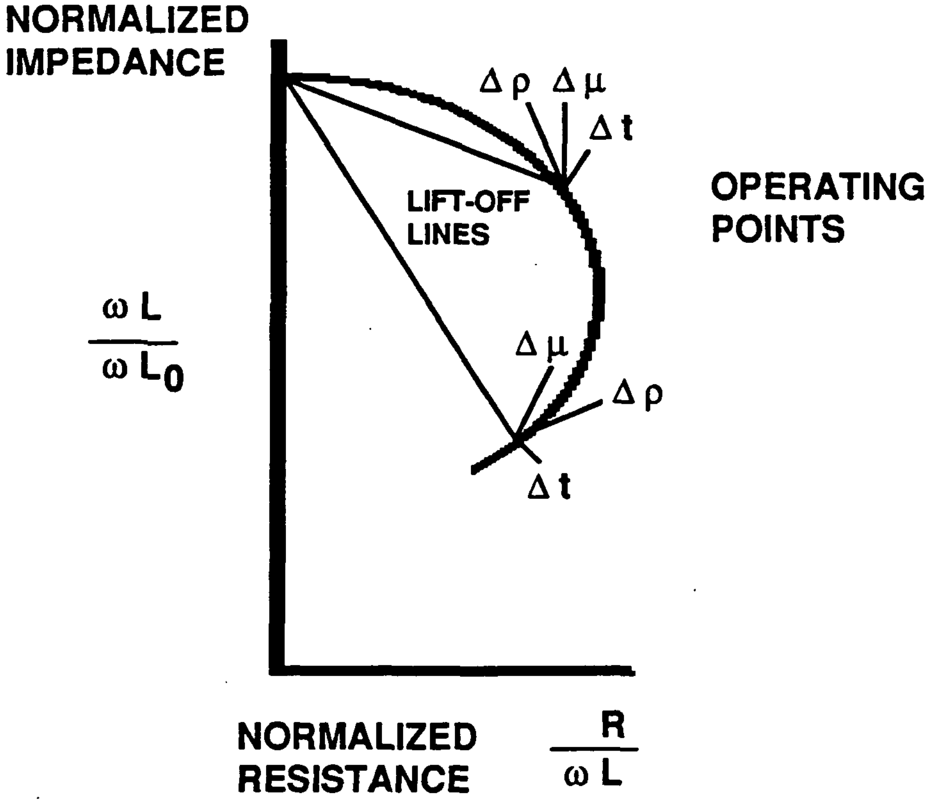
Although the use of expert systems to interpret eddy current signals is very new, concepts using feature extraction for defect identification have been around for awhile. The use of statistical pattern recognition, for example, has shown merit. An excellent paper on this technique is given in reference 1. Their work was concerned with characterizing flaws in austenitic steels used in power plant environments, which is a significantly different material from graphite fibers. However, the analysis performed in that work does show the utility of feature abstraction and statistical techniques based upon signal characterization of known defect types. Some of these ideas are useful in developing knowledge based reasoning systems for defect characterization also.

This research effort has focused on the use of eddy current techniques for characterizing flaws in graphite-based filament-wound cylindrical structures. A major emphasis has also been placed upon incorporating artificial intelligence techniques into the signal analysis portion of the inspection process. Developing an eddy current scanning system using a commercial robot for inspecting graphite structures (and others) has been a goal in the overall concept and is essential for the final implementation for expert systems interpretation. Manual scans, as performed in the preliminary work here, do not provide sufficiently reproducible eddy current signatures to be easily built into a real time expert system.

The expert systems approach to eddy current signal analysis requires that a suitable knowledge base exist in which correct decisions as to the nature of a flaw can be performed. In eddy current, or any other expert systems used to analyze signals in real time in a production environment, it is important to simplify computational procedures as much as possible. For that reason, we have initially chosen to utilize the measured resistance and reactance values for the preliminary aspects of this work. A simple computation, such as phase angle of the signal, is certainly within the real time processing capability of the computer system. In the work described here, there has been a balance between physical measurements and finite-element calculations of those measurements. As described earlier, the goal is to evolve into the most cost-effective procedures for maintaining the correctness of the knowledge base.

The impedance plane representation for eddy current signals is used througout this report because of the simplicity of the display information. However, time varying functions of eddy currents signals are not easily coded in that representation. Figure 1 shows the salient points of the impedance plane display and how various material changes affect the resulting R and X components.

Figure 1. Impedance Plane plot showing how changes in conductivity, permeability and thickeness affect the eddy current signal.



1.2 Eddy Current Transducer Characterization

Another major activity performed in this work was to develop eddy current transducers specifically designed to inspect graphite fiber components. A number of relevant papers have been published in the last few years defining some of the problems in using eddy current probes to inspect components containing graphite[2-10]. The E-probes and horseshoe probes developed here provide large signals for both cut tows and impact damage. Major increases in the coupling efficiency with carbon fibers and in the sensitivity of flaw detection are desirable. The use of finite element models to predict eddy current signatures has also been a major activity within this work. Using the Ansoft Maxwell software, values of the impedance changes for various defects are computed using both the E-probe and the horseshoe probe. It is anticipated that verification of this procedure as heuristic inputs into the expert system being developed for interpretation of the eddy current signals will be a continuing activity, however, logistically it is still more economical than preparing all possible flaws for signature characterization.

2.0 EXPERIMENTAL

Two new thicker filament wound graphite cylinders, one with prefabricated defects, as shown in Figure 1 were prepared by MSFC contractors in support of the M&P Laboratory. Eddy current scans are then able to produce a representative signal for this type of defect. The types of eddy current probes currently available at MSFC were normally pancake type probes, which are useful for finding surface and sub-surface cracks in metallic specimens. Initial measurements with the available probes indicated that very little coupling between the probe and the specimen was occurring. This observation motivated us to experiment with the finite element model to better understand the physics of the eddy current measurements.

The Ansoft Maxwell software allows axisymmetric solution of electromagnetic fields in various geometries. The normal pencil probe used so often in eddy current testing does not work well with graphite fibers. Several factors are responsible for this ineffectiveness. Firstly, the overlap between the toroidal field emanating from the transducer is extremely small, resulting in a very small impedance change between air and the graphite fibers. Even with a number of fibers located parallel to each other in the filament wound cylinder do not provide sufficient coupling to differentiate between the resistivity changes in going from air to the graphite sample.

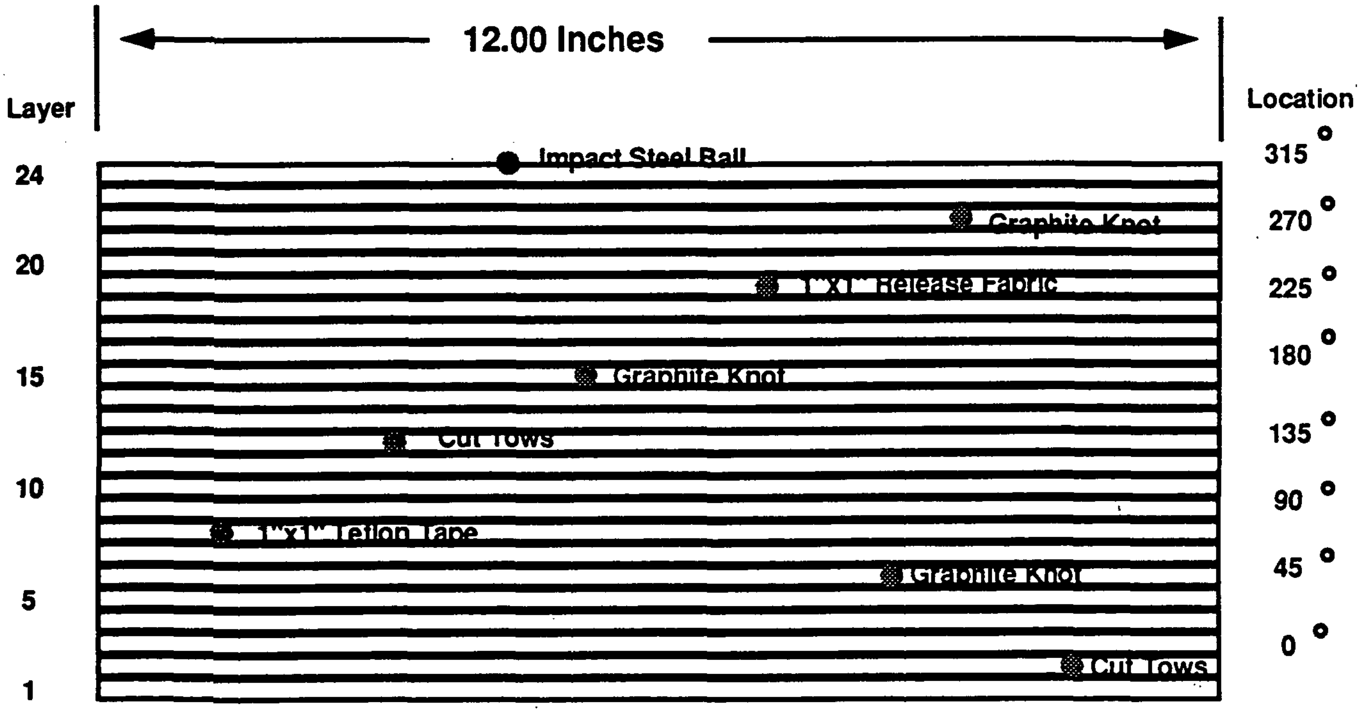
Two others types of probes were used in this work. E-probes and horseshoe probes were also used, with much better success. In addition some experimental work with a pot-core probe has been performed. The E-probe can be modeled axis-symmetrically with the finite element programs so that a solution can be obtained. More importantly the electromagnetic field is unidirectional and in the proper orientation, providing excellent coupling with the fibers.
The horseshoe probe is not axis-symmetric, but it has been modeled as half of an E-probe. Experiments verifying that half an E-probe can model a horseshoe probe allows the use of defect

signatures to be computed using the Maxwell software. After some experimentation with the software, we were able to model horseshoe probes by placing the excitations coil axisymetrically and obtain solutions in that manner. During the time of this reporting period, most of the solutions obtained were for the horseshoe probes.

Samples of cylindrical components fabricated from resin 55A and fiber AS4-W-12K were provided by EH43 and the Thiokol contractors at the filament winding facilities at Marshall Space Flight Center. Eddy current measurements were obtained from these samples using the E-probes and horseshoe probes decribed in our earlier report. The maximum specimen thickness available to us was 0.168 and .25 inches.

The layout of defects embedded in the thin graphite samples were given in our previous report. The thicker speciment, 0.25 inches had defects as shown in Figure 2.

Figure 2. Geometrical layout of second graphite-epoxy fiber sample .



2.1 ROBOT CELL DESIGN CONSIDERATIONS

The robotic workcell has been designed and implemented in Building 4702 at the Marshall Space Flight Center. The commercially acquired components are:

- a.) Intellidex 550 robot arm
- b.) Hewlett-Packard 4193A Impedance Meter
- c.) DCI Turntable
- d.) Symbolics MacIvory Workstation
- e.) FAA SmartEddy System

Several interfacing actions were performed to get all the systems to communicate with each other. An architectural concept is presented in Figure 3.

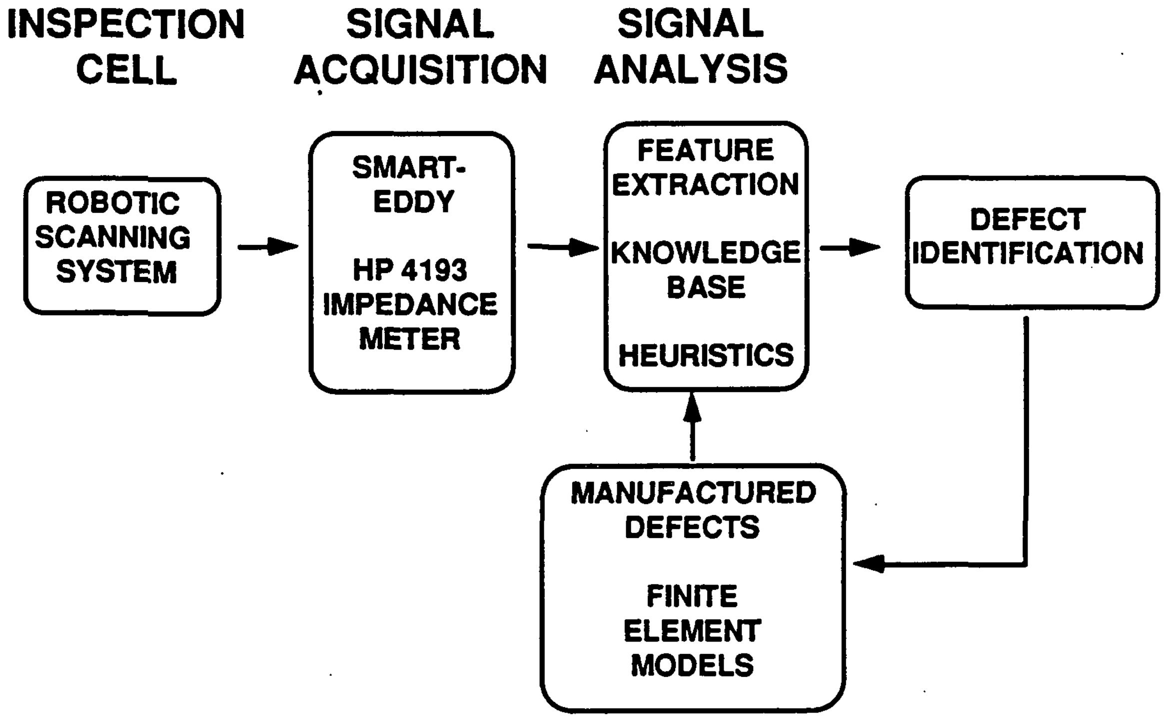


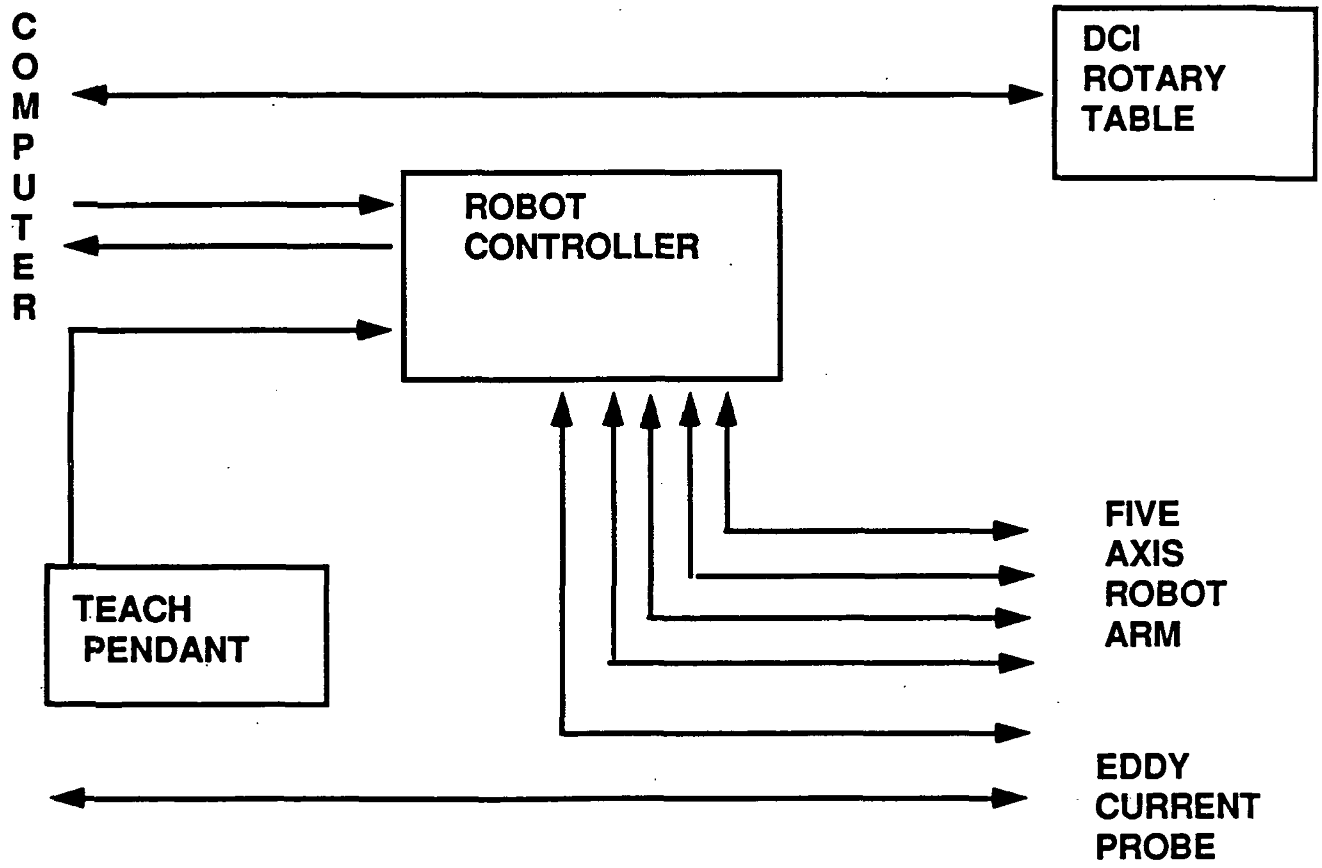
Figure 3. Architecture for Eddy Current Expert System with robotic scanning.

2.2 Description of Workcell Components

2.2.1. Intellidex 550 robot arm

The Intellidex 550 robot has been used extensively in industries which require clean room facilities for tasks such as microelectronics fabrication and hard disc assembly. The robot is well built and is programmed in a control language based on Basic. The ease of programming tasks for the robot was a major factor in its use for scanning purposes in this work. In addition a hand teach pendant is available to program the robot for more tedious tasks.

Figure 4. Block diagram of robot cell using Intellidex robot and DCI rotary table for eddy current scanning of graphite fiber components.



The eddy current scanning task is easily handled by remote instruction through an RS-232 communication link as shown in Figure 4. The communication link between the MacIvory and the robot was also accomplished during this phase of the project.

2.2.2. DCI Turntable

The scanning mechanism for cylindrical components is supplied with the rotary table manufactured by DCI, Incorporated. The rotation actuator is a two-phase stepping motor which can operate up to 25000 pulses per second. The arrangement used in this set of experiments was to operate the motor speed through an RS232 link with the MacIntosh computer. Other modes of control are available, however, the RS232 communications link provides the most potential for automated scanning.

The block diagram shown in Figure 3 also illustrates the communications links with both the Intellidex robot and the DCI rotary table.

2.2.3 Hewlett-Packard 4193A Vector Impedance Meter

Very accurate eddy current measurements from 10 - 100 kiloohms in the frequency range of 400 kilohertz to 110 Megahertz are possible with this instrument. The resolution over this range is approximately 0.1% in both magnitude and phase. A major attraction of this instrument is its accuracy over a broad frequency range and its versatility in output devices with both a recorder output (0 - 1 Volt dc) and a HP-IB interface for remote control and data output. A major attribute for scanning systems is rapid data acquisition and the 4193A does not provide a really rapid mode of operation with 7 readings per second as the maximum data rate.

Since the major philosophy of this effort has been to optimize upon the real-time data acquisition and analysis of eddy current signals, we have therefore sought to increase the data readings per second to as high a value as possible. In order to determine if the HP 4193A could process data any faster, we investigated fairly thoroughly how the instrument worked by looking at the waveforms generated in the instrument up to the analog-to-digital conversion in the system.

The high accuracy in phase measurement is obtained by using phase-sensitive detection scheme to determine the difference in phase between the normal signal and the shifted signal for the unit under test. An intermediate frequency generated for the phase sensitive detection provides a 14 hertz frequency, which is too small for rapidly digitizing the magnitude and phase information. Hence 7 readings per second are maximum for the instrument.

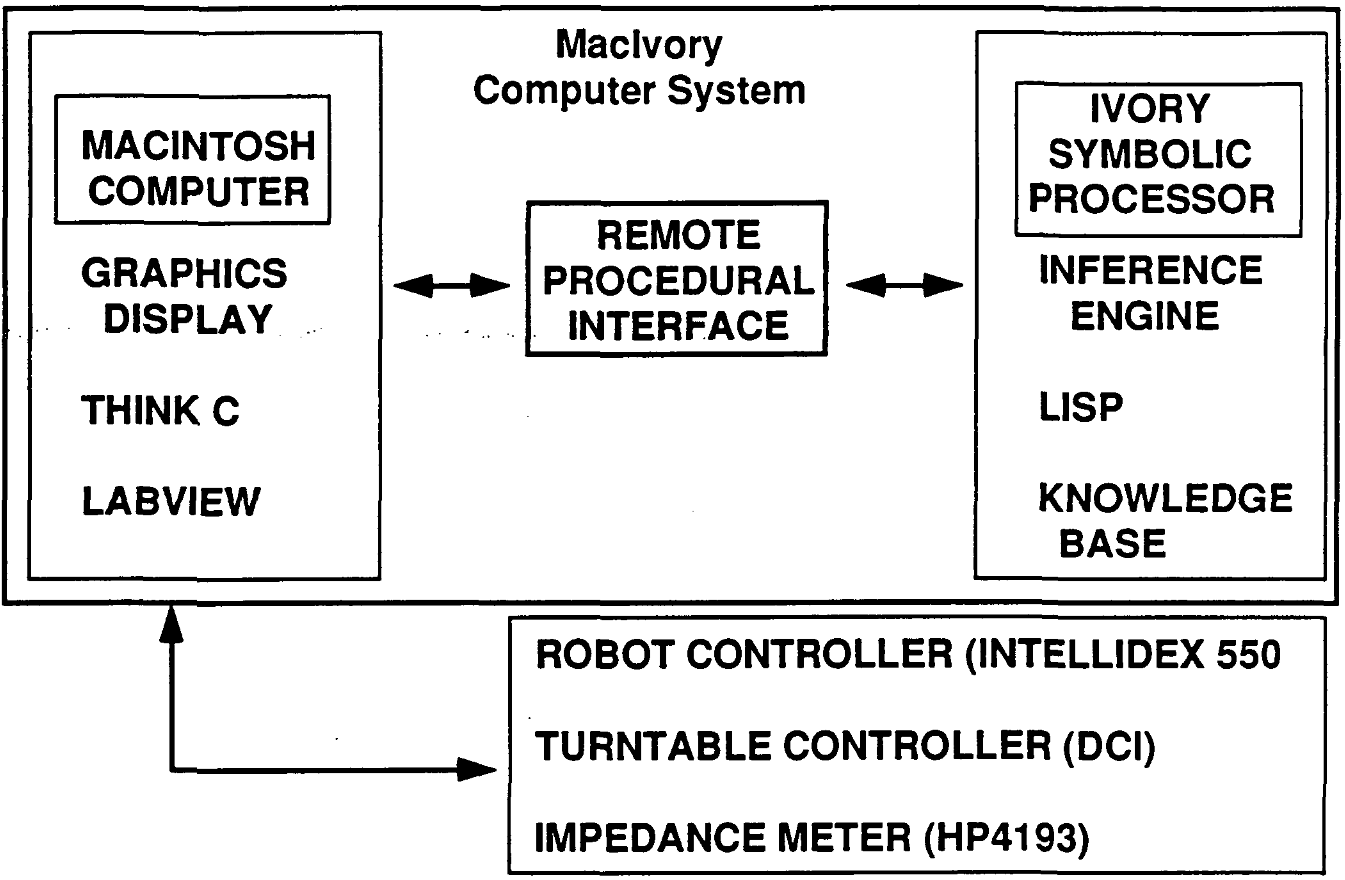
2.2.4 FAA SmartEddy System

The smarteddy was used in the previous study to charaterize the eddy current signals for graphite fiber components. It is an IBM PC clone (early Texas Instruments portable version with high resolution color graphics) and performs well. The frequency range available is 100 hertz up to 1 Megahertz. We were able to use the Smarteddy system in conjunction with the robot scanning system; however, the MacIvory is not usable as a real time expert systems platform in that role.

2.2.5 Symbolics MacIvory Workstation

The Symbolics MacIvory Workstation is an Apple MacIntosh computer which uses the Symbolics Ivory boards for symbolic processing. Ms. Mary Beth Cook made a number of advancements in getting the MacIvory portion of the system to communicate with external devices through the Remote Procedural Interface. She and Morgan Wang were also successful in getting Labview up on the MacIntosh platform and transferring data between the two platforms through the creation of data files which could then be read and processed by either system. Here again, the question of real time processing then becomes more difficult to perform. A number of routines were developed in both MacIvory and Labview to read (acquire) data and perform smoothing routines and averaging routines.

Figure 5. MacIvory Workstation and its elements used for robotic eddy current inspection.



The procedure that was developed was to make two scans around the upper section of the cylinder and average the readings to obtain an average value for the eddy current values of the graphite in that cylinder. Any strong anomalies would then be deleted from the averaging process and indentified as defect indications. Then the robot would index down the cylinder making each revolution on scan. A data file of the eddy current values was stored on disk for data interpretation following the scan. Consequently the goal for real time processing was not achieved at this time.

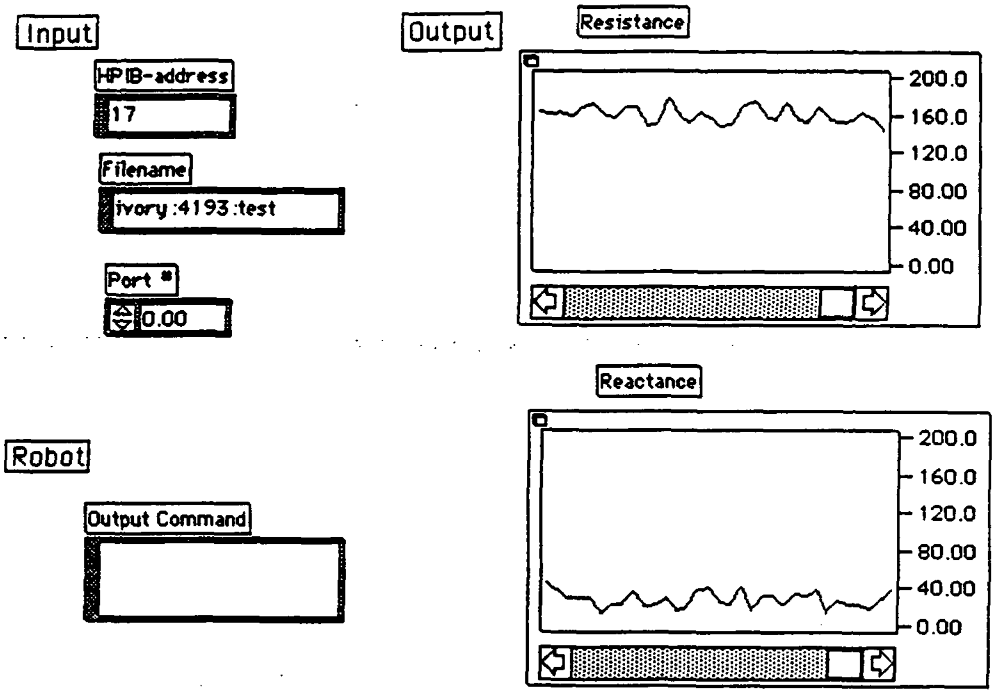
3.0 RESULTS

The data were obtained using both the MacIvory and the SmartEddy for the data following the scan. Consequently the goal for real time processing was not achieved at this time.

3.0 RESULTS

The data were obtained using both the MacIvory and the SmartEddy for the data acquisition in order to compare each platform. The SmartEddy system provides decomposition into resistance and reactance for the time aplitude plots, while we had to develop routines to perform the same function on the MacIvory. The Labview does allow for the creation of the plots. Examples of the type of data obtained from are shown in the next charts. Both impedance plane plots and amplitude displays of resistance and reactance are shown here. Impedance plane displays of the signals can be more informative in that the phase angle changes which occur for a given defect are consistant with the type of defect and the defect depth. Figures 6 and 7 show the types of output that are available from the MacIvory at this time. More work still needs to be done to bring them up to the SmartEddy type of presentation[17]. However for the purposes of the expert system analysis, we are still trying to determine if reactance and resistance changes can be used for interpretation of the data.

Figure 6. MacIntosh screen display of eddy current scan on graphite cylinder using Labview. This example shows a portion with no defect using the horseshoe probe.

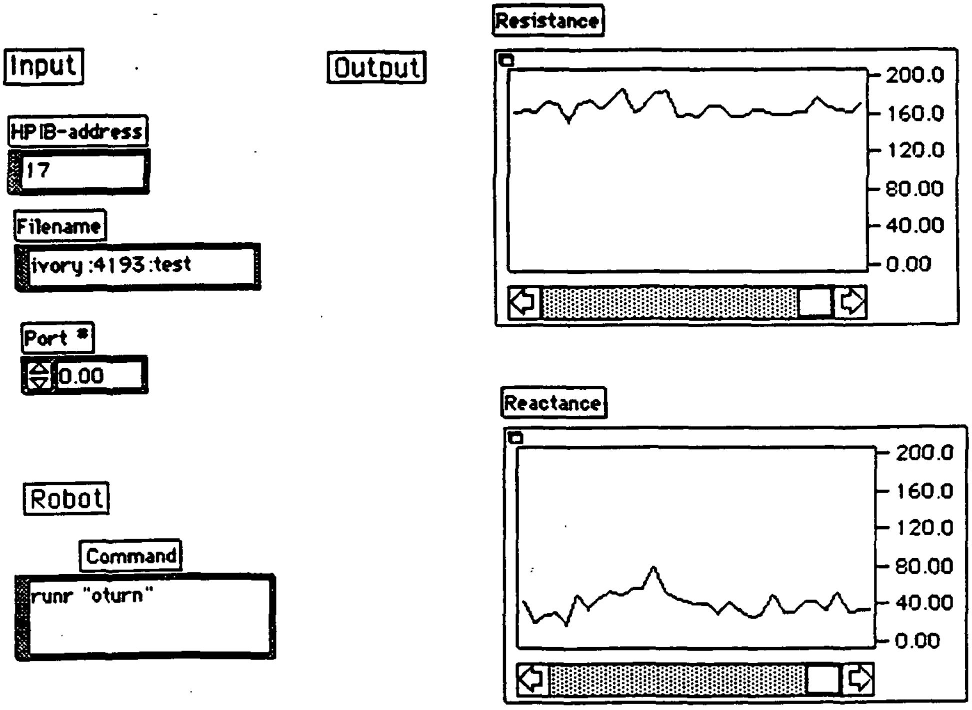

HPIB-address
17

Filename
ivory:4193:test

Port #
0.00

Output Command

Figure 7. MacIntosh screen display of eddy current scan on graphite cylinder with graphite knot near surface of specimen.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ivory:4193:test

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Command
runr "oturn"

Three major points need to be discussed here. Firstly, the resistivity of graphite fibers are not consistent throughout the sample. Hence the materials point keeps changing throughout a scan. This will have to be taken care of during the expert system analysis. Secondly, the theory and most eddy current specialists don't believe that eddy currents can provide an indication of delaminations. Our samples were fabricated using a graphite knot for a delamination (See Figures 4 and 6) and we were able to observe the embedded delamination (although the signal was small). A kissing debond, which is obviously more difficult to fabricate would not have given such an obvious indication of a defect. We currently feel that we were able to see a volume change since the delamination was caused by inserting a dielectric material between two graphite layers. The third point is the surface characteristics change from one specimen to another. The filament topology affects the surface, as well as any manufactured defects, since volume changes do occur within the material. Consequently the robotic scan measurements have all been affected by the surface topology of the speciment.

Measurements have been made with both E-probes and horseshoe probe. Similar results were obtained for both cases. In the robot workcell, we have implemented the E-probe in the vertical direction or lengthwise with respect to the cylinder. This allows for more complete coverage of the cylinder during each rotation of the component under test.

3.1 FINITE ELEMENT MODELING

We have continued to use the Ansoft software Maxwell to compute the interaction between the various eddy current transducers and the materials. As described in the previous report, the program allows one to generate a three dimensional model and solve for the electromagnetic fields in an axisymmetric environment. Mr. Morgan Wang has been the student who has been performing the finite element modeling with this software. The computation is a two-dimensional finite element model and the results can only be displayed in two dimensions. Obviously the interaction between the magnetic fields produced by an eddy current transducer and the graphite fiber material is a three-dimensional phenomenon. One of the possible research projects for Mr. Wang's thesis for his Master's Degree is the problem of taking the two-dimensional solution from Maxwell®and obtaining the three dimensional value for reasistance and reactance.

In order to obtain a representation of how the eddy current signal should change with respect to the scanning motion of the eddy current transducer, Maxwell modules were developed for simulation of scans across a particulare defect. For instance, Figures 8 - 10 show simulated values for resistance and reactance when displaced from the defect and then scanning over the defect for a cut tow. Note that the changes are small, nonetheless they are observable.

Figure 8. Finite Element Model of Horseshoe Probe on Graphite Fiber at 3 MHz. Calculated values are R = 5.26 ohms and X = 5.63 ohms.

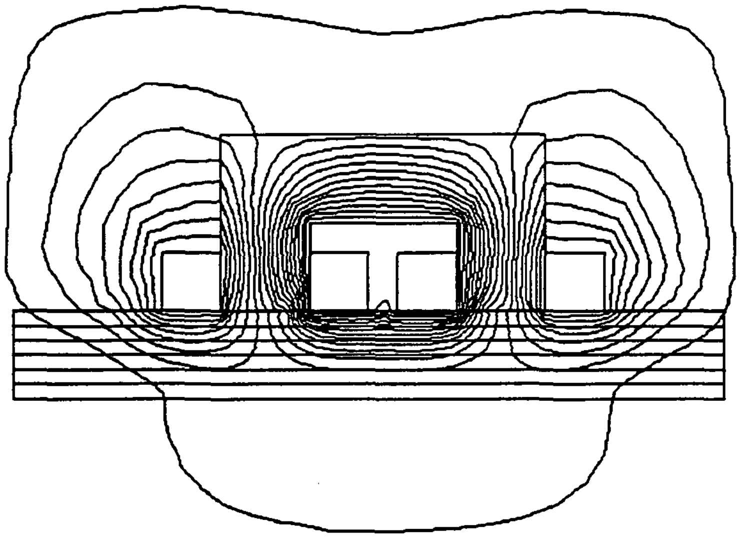


Figure 9. Finite Element Model of Horseshoe Probe scanning graphite fiber with defect with the probe just coming up on the defect.. Calculated values are R = 5.30 ohms and X = 5.63 ohms.

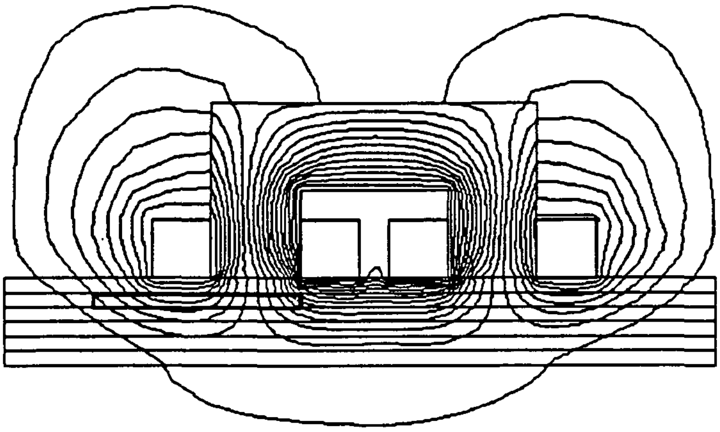
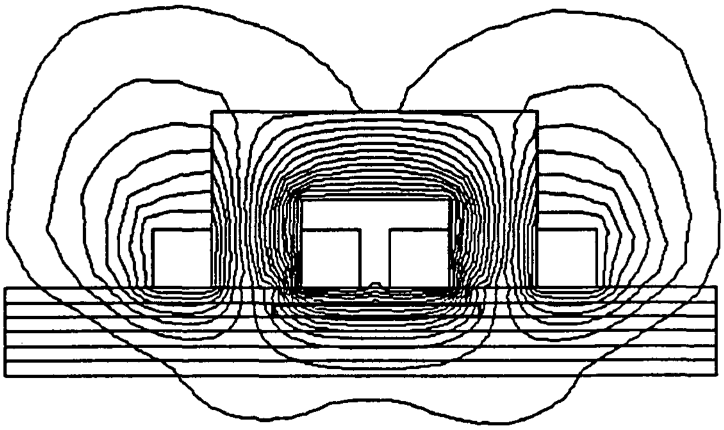


Figure 10. Finite Element Model of Horseshoe Probe scanning Graphite Fiber at 3 MHz with probe over defect. Calculated values are: R = 5.47 ohms and X = 6.08 ohms.



The major difficulty we have experienced so far is the number of layers which can be modelled using the Ansoft software which we currently are using. Since the second sample has 24 layers and we can only model about 6 to 8 layers, we are not modelling that sample properly. We hope to improve upon that in future activities.

It is anticipated that for the final expert system implementation, a series of these calculations would provide the simulated time varying amplitude impedance of the eddy current transducer moving over the defect. This feature would then be added to the knowledge base to provide predictive capability for that type of flaw. The time-averaged data will also have to be correlated to the finite-element models.

3.2 EXPERT SYSTEMS APPROACH TO EDDY CURRENT SIGNAL ANALYSIS

The goal in using an expert system for interpretation of eddy current signals relies upon the use of heuristics and efficient strategies for sorting through the decision trees in identifying the type to defect being observed. If these goals can be satisfied, then the arduous computation required for statistical pattern recognition can be reserved for the difficult interpretations and the envisioned expert system can handle the real time inspection requirements.

To demonstrate the foundation upon which statistical interpretations are based, it is interesting to reconsider the procedures described in Reference 1. Feature extraction, as described in that reference are useful considerations for applying expert systems also. In considering an alternative methodology, Figure 3 displays the expert systems model planned here. There are several features contained in this concept which are significant. In the DATA INPUT section, note that the use of a robotic scanning system will enable consistent time-varying amplitudes to be obtained. Manual scanning, as has been performed in this phase of the work, does not provide consistent results. The implementation is being performed in several phases as instrumentation becomes available. An anticipated application of neural networks is obvious to the defect identification problems in eddy current inspection[11]. The build-up of the knowledge base is also occurring in stages using finite element models and fabricated defects to generate decision criteria

ABST.

for the expert system. The only other work reported previously dealt with metallic components and primarily developed a heuristic for deteriming crack depths and widths[12-13].

Inputs into the knowledge base are defined by calibrated defects and finite element models. We anticipate that finite element modeling, once complete verification that the models are as good in predicitng impedance changes as real defects, will be much more economical and faster methodolgy for construction of the knowledge base.

The MacIvory computer was chosen for the expert system platform, providing both user friendly interfaces and symbolic processing. Note that as shown in Figure 6, the interface between the Symbolics engine and the MacIntosh is the RPC Interface. RPC stands for Remote Procedural Call, i. e. the two processors operate independently of each other and provide remote calls to the other processor to handle a particular function which can only be handled by the processor. Lisp is the language used by the MacIvory and Genera is the operating environment. Of course the MacIntosh environment is standard to that computer system. Evaluation of this platform will obviously become more strenous as this work continues.

In the first few months working on the project, several programs and interfaces to call up eddy current data; i.e. to display several types of plots (i.e. emulate the SmartEddy to a degree) and perform some smoothing routines have been developed. Due to the nature of the manually scanned data obtained from early measurements of the test specimens, we are not able yet to uniquely characterize the signals from the defects. Now that the robot scanning system is in place, that task will become more easily accomplished. A major effort will be needed to overcome the variable resistivity and the surface variability problems. Also several discussions with Ms. Sue Vernon indicate that using larger eddy current probes would allow more consistent coverage of near and far wall defects in the thicker specimens.

4.0 CONCLUSIONS

This work has resulted in the development of a robotic workcell using eddy current transducers for the inspection of carbon filament materials with improved sensitivity. Improved coupling efficiencies achieved with the E-probes and horseshoe probes are exceptional for graphite fibers[14-15]. The eddy current supervisory system and expert system have been partially developed on a MacIvory system. Continued utilization of finite element models for pre-determining eddy current signals has been shown to be useful in this work, both for understanding how electromagnetic fields interact with graphite fibers, and also for use in determining how to develop the knowledge base.

Sufficient data has been taken to indicate that the E-probe and the horseshoe probe can be useful eddy current transducers for inspecting graphite fiber components. The lacking component at this time is a large enough probe to have sensitivity in both the far field and the near field of a thick graphite epoxy component. END

5.0 ACKNOWLEDGEMENTS

This work has been benefitted by a number of helpful discussions with several researchers in the field, in particular Ms. Susan Vernon of the Naval Surface Weapons Laboratory and Ken Woodis and Lisa Hediger at the NDE Laboratory at MSFC. Also we are indebted to the filament winding group for preparing our specimens and to Magnetics Corporation for the ferrite samples. Gratitude is also expressed to the students from UAH who worked on this project, Morgan Wang and Mary Beth Cook. Best of luck to Mary Beth in her new civil service career.

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