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Rotating Electric Field Sensor for Nondestructive Evaluation of Nonmetallic Engineered Components

Jim L. Novak

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-94AL85000

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SAND96-1029
Unlimited Distribution
Printed May 1996

Distribution
Category UC-706

Rotating Electric Field Sensor for Nondestructive Evaluation of Nonmetallic Engineered Components

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Abstract

The improvements in the performance of products incorporating nonmetallic engineered materials are obtained at the expense of increases in the complexity of the product design, manufacture, and maintenance. Subsequently, a wide variety of NDE techniques has been developed to permit the verification of design models, the identification of manufacturing flaws, and the assessment of service-related damage. This project involved developing a new nondestructive evaluation (NDE) sensing technique that provides additional information about components made from these materials. The sensor measures changes in an imposed electric field to obtain electrical impedance images of a component. The effective sensing volume (ESV) and the orientation of the imposed electric field may be varied to optimize field interaction with the internal structure of a part. These interactions are combined into multidimensional impedance images that reflect variations in the mechanical geometry and internal structure of a part. The location of an impedance anomaly may be correlated with the location of a flaw.

*This LDRD Final Report is provided under Contract 3513160.

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Acknowledgments

The authors would like to thank Tom Rudnick and Leonard Casaus of the Microsensors Research and Development Department (1315) for their technical input to this project, and to Robert Waldschmitt of the Intelligent System Sensors and Controls Department (9611) for laying out and assembling the sensor prototypes.

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Acronyms

ESV	Effective Sensing Volume
GPIB	General Purpose Interface Bus
HIRCIS	High Resolution Capacitance Imaging Sensor
HP	Hewlett-Packard
NDE	Nondestructive Evaluation

Introduction

Ceramics, composites, textiles, and other nonmetallic engineered materials are superior to traditional materials in many applications with demanding performance specifications. For example, the properties of some nonmetallic materials can be varied to produce anisotropic component structural properties that improve strength to weight ratios. The use of these new materials allows the composition of a component, in addition to its physical geometry, to be spatially altered to perform to the given specifications.

The additional performance potential of these engineered materials greatly increases the complexity of component design, manufacture, and use. It is widely recognized that no single nondestructive evaluation (NDE) technique is capable of fully evaluating component performance¹. Subsequently, a wide variety of NDE techniques have been developed to permit the verification of design models, the identification of manufacturing flaws, and the assessment of service-related damage. For example, previous work has determined that the complex permittivity (proportional to impedance) of a bulk nonmetallic material can be used to assess its chemical state². Variations in the chemical bonding versus time are calculated from the complex dielectric constant using empirically determined relationships. However, these measurements are very sensitive to the geometry and physical configuration of the sample, as well as the spatial distribution of the imposed electric field. For these reasons, large, uniform samples of the nonmetallic material are required, and only gross material properties may be determined.

More sophisticated techniques rely fundamentally on forming spatial maps of a particular material property, such as ultrasonic propagation velocities (C-scans), material density (CT scanning), or surface conductivity (eddy currents). The measurement of the spatial variation of a material property allows the coupling between composition, geometry, and performance to be evaluated.

This project involved the development of an NDE technique that measures geometry and structural variations in nonmetallic engineered materials by an impedance mapping technique. Unlike previous impedance-based experiments², this new effort focuses on the performance of the final, cured component and not on the material properties of the bulk material. Spatial variations in the impedances measured in this technique reflect differences in geometry and structure such as thickness, arrangement of reinforcing plies, and inhomogeneities such as voids and delaminations. This technique is applicable in a variety of manufacturing operations that form a material into a component, rather than material property analyses that focus on the material itself.

Prototype Sensor 1 Design

Through appropriate design of sensing element electrodes, time-varying, spatially restricted, airborne electric fields may be created to interact with the material under test³. By placing the sensing elements in contact with a nonmetallic component, the imposed potential will result in an electric field that will interact with various internal structures. The amplitude and phase of the

resulting electric current can be used to measure the complex value of the local impedance. Resistive structures, such as reinforcing carbon fiber, were expected to enhance the real impedance component, while the imaginary component should be altered to differing degrees by the presence of voids, delaminations, or intact resin. In addition, because of expected electrical nonlinearities in the materials, the excitation frequency and amplitude will be independently varied to provide a multidimensional image.

Because many nonconductive engineered materials are anisotropic, the measured impedances will vary depending on the spatial orientation of the electric field. We exploited this property by developing a rotating electric field using segmented electrodes driven at different phases. An illustration of such a device using a four-quadrant field is given in Figure 1. The overall diameter of the device is about 1 mm (0.040"). The outer four driving electrodes are activated in sequence, resulting in an electric field that "rotates" about the center axis.

A rotating field sensing element was mechanically scanned over the surface of the component to acquire an impedance image. By monitoring the impedance as a function of rotational "position," we obtained multidimensional maps of the complex impedance, Z , versus spatial location (x, y) and field orientation (ϕ). Additional modifications to the test apparatus, not performed in this project, could allow varying the excitation frequency (ω) and amplitude (A) as well.

Figure 1. Four-Quadrant Sensing Element for Generating a Rotating Electric Field.

This design for the rotating field sensor has a number of advantages with respect to interfacing with the supporting electronics. The outer drive electrodes are sequentially activated to produce a rotating field about the center sense electrode. This device is relatively simple to implement, as it requires only one multiplexer for the segmented drive electrodes. Also, by operating with one sense electrode common to all fields, a single charge amplifier may be used. This configuration minimizes the number of interconnecting wires between the sensor and the required signal processing electronics.

Prototype Sensor 1 Results

This sensor concept was evaluated rapidly and inexpensively by modifying an existing High Resolution Capacitive Imaging Sensor (HIRCIS), which had been developed for use in measuring metallic burrs. In the modified HIRCIS, the four drive electrodes are disks of the same diameter (0.020") as the sense electrode. The center-to-center spacing between electrodes is 0.010". Because of the design of the HIRCIS, however, it was not possible to electronically switch the drive signals. Therefore, the electric fields were switched manually for these preliminary tests. This technique provided exactly the same information as an electronically switched system, but at a significantly slower rate.

The sensor output was connected to an HP4194A Gain/Phase Analyzer to measure the resulting amplitude and phase of the output signal. The sensor was mechanically mounted on an X-Y translation stage and the nonmetallic part to be imaged was rigidly positioned beneath the sensor. A computer controlled the motion of the mechanical platform to provide precise spatial scanning of the part under test. At each X-Y location, the gain and phase of the sensor signal was acquired from the HP4194A via a GPIB interface.

The results of an experiment that involved imaging a sample of carbon/epoxy composite material from Bell Helicopter Textron are given in Figure 2. The gain and phase images cover a 4 by 4 mm area, for a single orientation of the modified sensor. The weave pattern of the carbon fiber reinforcing material is clearly visible. The gain and phase images, while similar, contain unique information. For example, note the "spot" near the center. The gain amplitude levels off, essentially forming a plateau in this region, while the phase image clearly indicates variability in this area. The origin of anomalous spots visible near the upper left corner of the gain and phase images is unknown.

Gain Image

Phase Image

Figure 2. Impedance Images Recorded from Carbon/Epoxy Composite Sample.

Prototype Sensor 2 Design

The results of the Prototype 1 experiments demonstrated that the impedance imaging technique provides unique information in both the amplitude and phase measurement. Modifying an existing sensor allowed rapid demonstration of the concept without incurring fabrication costs. However, further experimentation required a more sophisticated design, designated Prototype 2. A schematic diagram of the new device is given in Figure 3. Because we had some difficulty aligning Prototype 1 with the orthogonally woven fabrics used in structural materials, this new sensor uses eight segments. By subdividing each rotation into eight orientations, we expected to be better able to electrically orient the fields to the major axes of the material.

Figure 3. Prototype 2 Rotating Electric Field Sensor Design.

The electric fields in the new device are also designed to generate rotating electric fields that encompass approximately the same sample volume for all orientations. It was clear that images acquired using Prototype 1 using other orientations (not shown in Figure 2) were shifted spatially by the center-to-center spacing between adjacent electrodes. These shifts are undesirable, and could lead to improper flaw characterization. By designing the electrodes to generate electric fields that occupy nearly identical volumes, the data from different orientations may be directly compared. Prototype 2 is a significantly more complex sensor design, and incorporates surface mount components and multilayer printed circuit boards.

Prototype Sensor 2 Results

A Prototype 2 sensor incorporating rotating electric fields and different size effective sensing volumes (ESV) was fabricated using printed-circuit board techniques. The electrode pattern is as shown in Figure 3. To form individual sensors, pairs of electrodes were electronically selected using an on-board multiplexer. Sensor A, for example, was activated by electronically connecting electrode A1 to an oscillator, and electrode A2 to the input of a charge amplifier. The

directional electric field generated between A1 and A2 formed the sensing field. Another smaller sensor was electronically selected by using electrodes B1 and B2. This field, while in the same rotational orientation as sensor A, exhibited a smaller ESV due to the small electrode diameter and reduced spacing. The orientation of the field relative to the part being analyzed could be changed by selecting electrodes E1 and E2. Sensors A and E have the same ESV, because the electrode diameter and spacing are identical. However, these sensors have fields that are offset by 90 degrees. Using this property, electronic multiplexing between sensors A, C, E, and G, would effectively produce a rotating field with a fixed ESV. Similarly, sensors B, D, F, and H could be used to produce a rotating field sensor with a smaller ESV.

The Prototype 2 sensor was tested on the sample of graphite-epoxy composite material as in previous tests. The sensor was mechanically scanned over a 20 by 20 mm region of the sample in 0.250 mm increments. At each point, four impedance values corresponding to electrode pairs A, B, E, and F (as shown in Figure 3) were recorded. The four 40 by 40 arrays of impedance values are plotted as greyscale images A, B, E, and F in Figure 4. The images were taken from identical regions of the sample -- differences in the data are strictly due to variations in the size and orientation of the respective sensor's electric field.

A)

B)

E)

F)

Figure 4. Impedance Images of Composite Sample Using Prototype 2.

Sensor A (electrode pair A1 and A2) produces an electric field that is relatively long and directional, extending from the upper left to the lower right in Figure 4. This field interacted more strongly with fibers in the composite sample running at this same orientation. This led to the dark stripes running from upper left to lower right in image A. Because the interelectrode distance between electrode pair B1 and B2 is smaller than the weave of the fabric, Sensor B produces a more radially-symmetric electric field. This field interacted with the fiber web more uniformly, and produced the evenly spaced crosshatched pattern in image B.

The difference between images A and B is due to the difference in the effective sensing volume (ESV) for Sensors A and B. While the electric fields used in these two sensors have the same rotational orientation, they differ in size due to the different center-to-center separation and electrode size in image B. By modeling the extent of the associated ESVs, the two images may be processed to generate new information about the composite material that is either located in the common volumes, or located in the volume "shell" comprising the difference between the

two ESVs. This allows one to identify properties of the composite as functions of the depth into the material.

Image E was acquired using Sensor E, which generates an electric field rotated 90 degrees with respect to Sensor A. The directional field of Sensor E interacts more strongly with fibers running from the lower left to the upper right of Image E, producing dark bands. These bands are oriented 90 degrees from those in Image A. The smaller ESV of Sensor F results in the cross-hatched Image F. Notice that while Images B and F are different and resemble negatives of one another. Although the ESVs of Sensors B and F are the same, the difference in their orientation allows a measurement of the relative alignment of the individual fibers making up the woven fabric.

Discussion

These data demonstrate that the shape and orientation of the electric fields used for impedance imaging dramatically affects the information acquired. Sensors with identical orientations with respect to an anisotropic material, but with different ESVs produce images that may be used to measure material properties versus depth into a sample. By rotating the sensor electric field, the impedance measurement can detect oriented features, including the directionality of embedded reinforcing fibers. Finally, by creating a pattern of electronically-switched electrodes to form different sensors, a single array device can quickly acquire information from differently shaped fields, producing information about many aspects of a part under test.

This sensing technology differs from existing impedance-based NDE techniques in that it relates the electrical properties of nonmetallic engineering materials with the part geometry. It has been well established that bulk impedance measuring techniques can be used to control material manufacturing processes. This proposal develops a sensing technology that may be used during the manufacture and use of components fabricated from these specialized materials.

Small breaks in reinforcing fibers, the presence of voids, and service-induced delamination, are examples of flaws that are likely to result in measurable changes in the electrical properties of the component under test. By measuring small, local, impedance variations in these parts, real-time NDE can be performed, permitting modification to the manufacturing process or field component replacement.

The ability to rotate the imposed electric field is a unique feature of the proposed impedance sensor design. By varying the angle between the imposed electric field and the surface of the component under test, anisotropies can be observed. This will allow directional flaws such as fiber breakage to be observed. The rotation angle, the spatial location, the frequency, and the amplitude of the applied electric field, will provide the independent variables for multidimensional maps of the electrical properties.

Conclusions and Recommendations for Future Work

This work advanced Sandia's capabilities in NDE technologies that may be used in agile manufacturing of high performance products. The overall life cycle cost of products utilizing nonmetallic engineered materials can be reduced through the use of this technology for in-

process and in-service inspection. Product tolerances can be maintained through feedback control, resulting in reduced waste. Field inspection of components, such as panels on aircraft, will permit repair or replacement based upon structural integrity, rather than on a predetermined maintenance schedule.

With directional impedance images such as those described above, the location of an impedance anomaly may be correlated with the location of a flaw in the component under test. Because the individual data elements are related spatially, distributed effects such as propagating forms of delamination can be examined and their origin determined. Image processing techniques may also be used to enhance features not readily identifiable using single-point measurements. For example, correlations between different areas of an image could be used to detect manufacturing flaws or fatigue-induced damage.

Additional experiments should be performed to compare the performance of this technology to that of existing techniques. The data from the impedance sensor should be compared with that acquired by ultrasonic C-scan techniques, for example. Further, model-based image analysis techniques can be applied to understand the fundamental interaction between the sensor electric field and the part under test. This comparison could test different types of nonmetallic parts, include fiber-reinforced materials, plastics, and engineered ceramic materials.

Questions remain about the "sensitivity" of this impedance measurement to changes in the mechanical structure of nonmetallic materials. While the experiments describe here demonstrate the utility of the rotating field concept, additional testing is required to determine specific performance limits and design tradeoffs. Sensor performance should be quantified to evaluate the electrical-mechanical relationship in a variety of materials and structures. For example, the ability to detect a flaw is likely to decrease with the flaw depth. Small voids deep inside a thick portion of a component may result in impedance variations that cannot be measured using a single-surface impedance measuring technique. However, since many practical nonmetallic components are relatively thin (< 10 mm), it is expected that our technique will be useful in most cases.

Other adaptations of this impedance imaging technique, such as a through-mode measurement that may be more suitable for deep flaws, could be explored for these configurations. This research would allow the development of "design rules" that will permit the specification of sensor size and geometry based upon the desired sensitivity and component types. At this point, it will be possible to intelligently develop an array of rotating electric field sensors, to reduce the current requirement for mechanical scanning.

References

- ¹ Shadwell, P. W. and Daniels, D. J., "Critical Survey of Non-Destructive Testing Techniques for Non-Conducting Materials," ERA Technology Limited Report 92-0109R, May 1992.
- ² Kranbuehl, D. E., "In-situ on-line measurement of composite cure with frequency dependent electromagnetic sensors," *Plastics, Rubber, and Composites Processing and Applications*, 16:213-219, 1991.
- ³ Novak, J. L., and Wiczer, J. J., "A high resolution capacitive imaging sensor for manufacturing applications," *Proc. IEEE Int. Conf. Robotics and Automation*, 1991.

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