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SMARTweave: An Electrical NDE System

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SMARTweave: An Electrical NDE System

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Abstract

SMARTweave (SW) was patented in May 1993 as an electromagnetic method to monitor the flow of resin in composite manufacturing processes. It has been found to be very rapid and effective for this purpose, and its uses have expanded since this date. Using a Labview software package and 16 conductive nodes, both processes and properties of composite materials can be characterized. SW has specifically been used at our laboratory to investigate the resin-transfer molding (RTM) process. The speed of entry of the resin for different composite fabrics can be visually studied and adjusted. Composites are typically difficult to examine with nondestructive evaluation (NDE), so this new technique is a valuable addition. There are eight excitation probes and eight sensor probes, unlike the usual one excitation probe and one sensor probe.

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1. Introduction

The SMARTweave (SW) system was invented to study the flow characteristics and cure rate in resin-transfer molding (RTM) of composite materials. It has been very effective, in this case, and this success has warranted expanding its scope to more general nondestructive evaluation (NDE) applications. The purpose of this report is to compare and contrast SW with the other more conventional NDE methods. The "'SMART" in "SMARTweave" is an acronym for "Sensors Mounted as Roving Threads." Of "The Big Five" NDE methods (penetrant testing [ET], magnetic-particle testing [MT], eddy-current testing [ET], ultrasonic testing [UT], and x-ray radiographic testing [RT]), only the last three (ET, UT, and RT) are sensor-based methods. ET uses electric energy to generate eddy currents. The impedance to these eddy currents is the critical parameter. UT uses sound energy, and RT uses x-ray energy. SW is like ET in this respect, in that it is powered by electric current, The sensors in the SW system are simply overlapping, nonintersecting, electrically conductive strands. It seems unusual that a sensor can be as simple as a strand of carbon fiber, but this is precisely what makes SW so effective and versatile. By comparison, the conventional NDE methods often require complex and expensive, yet very limited, sensors.

SW is a very flexible technique because almost any number (1, 4, 9, 16, ... 64, 81, ...) of nodes can be created. The two threads at each node are separated by the composite fabric in our experiments or by the unknown specimen in the general case. This fabric creates an infinite resistance before the resin flows through and is absorbed by it. In this instance, the open circuit is closed and a box lights up on the SW pictorial screen. This box is a voltage measurement, and its intensity determines its magnitude. This intensity will change over time, which leads to the question, "When is the node actually excited or activated?" This question is very crucial to a fundamental understanding of what is actually going on in the system and to getting all of the information one can about the material being examined, as well as the process. Advanced automation and intelligent signal processing have been used to delve into this problem and analyze the data objectively. A statistical pattern emerges from the data in the form of two "moving averages." The analysis is complicated because the nodes do not respond in isolation.

What happens at every node affects what happens at every other node-a sort of Hartree Fock phenomena. Each node has a history. These are complications that result in much additional relevant information when studied mathematically using a finite-element model. A reconstruction (smoothing) algorithm with 9 degrees of freedom (DOF) determined the time solution for every node in the finite-element model given the times that sensors are activated. Thus, data from a few points is extrapolated to get results for a large number of points to determine the flow front at discrete time intervals.

Scanning is required in ET and UT (i.e., either the probe or the specimen must move). This is not so in RT or SW testing. These later two can be called stationary methods. Therefore, SW testing can examine a moving liquid, such as resin in an RTM process, while UT, ET, and RT cannot. SW testing can examine processes, while UT, ET, and RT can only examine properties. Also, in ET and UT, only one point is examined at a time, while, in RT and SW testing, many points are examined at a time. So, in terms of energy used, SW testing is paired with ET, while in terms of points examined, SW testing is paired with RT. Since SW testing is a stationary method, it can examine a moving liquid, while UT and ET cannot.

2. Theory

Whenever dynamic fluid flow is being dealt with, as in this case, the governing mathematics is Darcy's Law:

$$V = -\frac{k}{\mu}\left(\frac{\partial P}{\partial z}\right),$$

where v is macropore resin velocity, k is macropore permeability, μ is resin viscosity, and $\frac{\partial P}{\partial z}$ is the axial-pressure gradient. Resin viscosity was always kept at 200 centipoise. Macropores are the regions between pores, and micropores are the regions within a tow. In our experiments, we were almost always comparing the relative velocities of resin-wetting two fabrics with very different macropore permeabilities. This caused the flow velocity to be about twice as large for one fabric as for another. Bleeder cloth was always used as the baseline material with a “fast” velocity. By having a baseline material with such a high permeability, the variations in parameters were more pronounced and a consistent baseline condition was established.

There are two components of the pressure gradient, an axial component, $\frac{\partial P}{\partial z}$, and a radial component, $\frac{\partial P}{ar}$. The axial component is a measured quantity, while the radial component is derived, either from the gradient for axial tows,

$$\left(\frac{\partial P}{\partial r}\right)=\frac{p-P_a}{r\ln\left(\frac{r_o}{r_f}\right)},$$

or the gradient for transverse tows,

$$\frac{\partial P}{\partial r}=\frac{P-P_a\left(\frac{r_o}{r_f}\right)^2}{r\ln\frac{r_o}{r_f}},$$

where P_a is the ambient mold pressure, r_o is the tow radius, and r_f is the radial front position within the tow [1].

3. Experimental Procedure (Methods)

In our experiments, 16 such carbon (graphite) strands were used. Eight of these were “excitation” leads, and eight were “sense” leads. An excitation lead is a graphite (or other material) fiber that carries an electric current to the inspection point. A sense lead is one that carries the altered electric current from the inspection point to the SW computer system. The excitation leads were orthogonal to the sense leads, forming a grid with 64 points of intersection (or nodes or junctions) as shown in Figure 1.

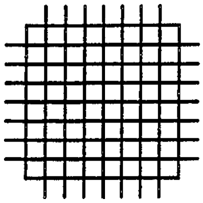

figure **1. Grid** Showing 64 **Points of Intersection for Excitation and Sense Leads.**

Electronic diagrams for UT and ET are quite common. A similar diagram for SW testing is found in Figure 2 (Figure 8 of Walsh [2]). The electrically conductive leads are arranged in a nonintersecting grid-like fashion in the RTM box. The function of the Keithley 160 is to obtain the raw electrical signals from the sensor grid. Thorough integration of the sensor grid is done by the Isaac Card Cage by multiplexing through the sensing threads. Data acquisition is accomplished by the Isaac 91-I, power is supplied by the Isaac power supply, and the data are recorded and displayed by the IBM personal computer (Figure 8, column 12 of Walsh [2]). This is only one configuration of an SW scanning system; substitutions for each component can be made, even within the RTM box, the heart of the SW concept.

Flow-front patterns and the rate of resin transfer in RTM have been the main application of SW, This includes approximately 35 such experiments. Four plies of 9-in x 18-in bleeder cloth are placed next to four plies of 9-in x 18-in chopped strand mat. Chopped strand mat is a 40% volume fraction (under vacuum) E-glass-composite fabric. Under vacuum, it is 40% glass and 60% resin. It is 30% or less glass when made under wet lay-up conditions with no vacuum (compaction). The reinforcement is basically random, but continuous, and the sizing is compatible to vinyl ester. The eight sensor leads are placed below the top three plies of each fabric, while the eight excitation leads are placed on top of all four plies to separate them and create an open circuit for the resin to close. The leads are connected electrically to the SW computer system.

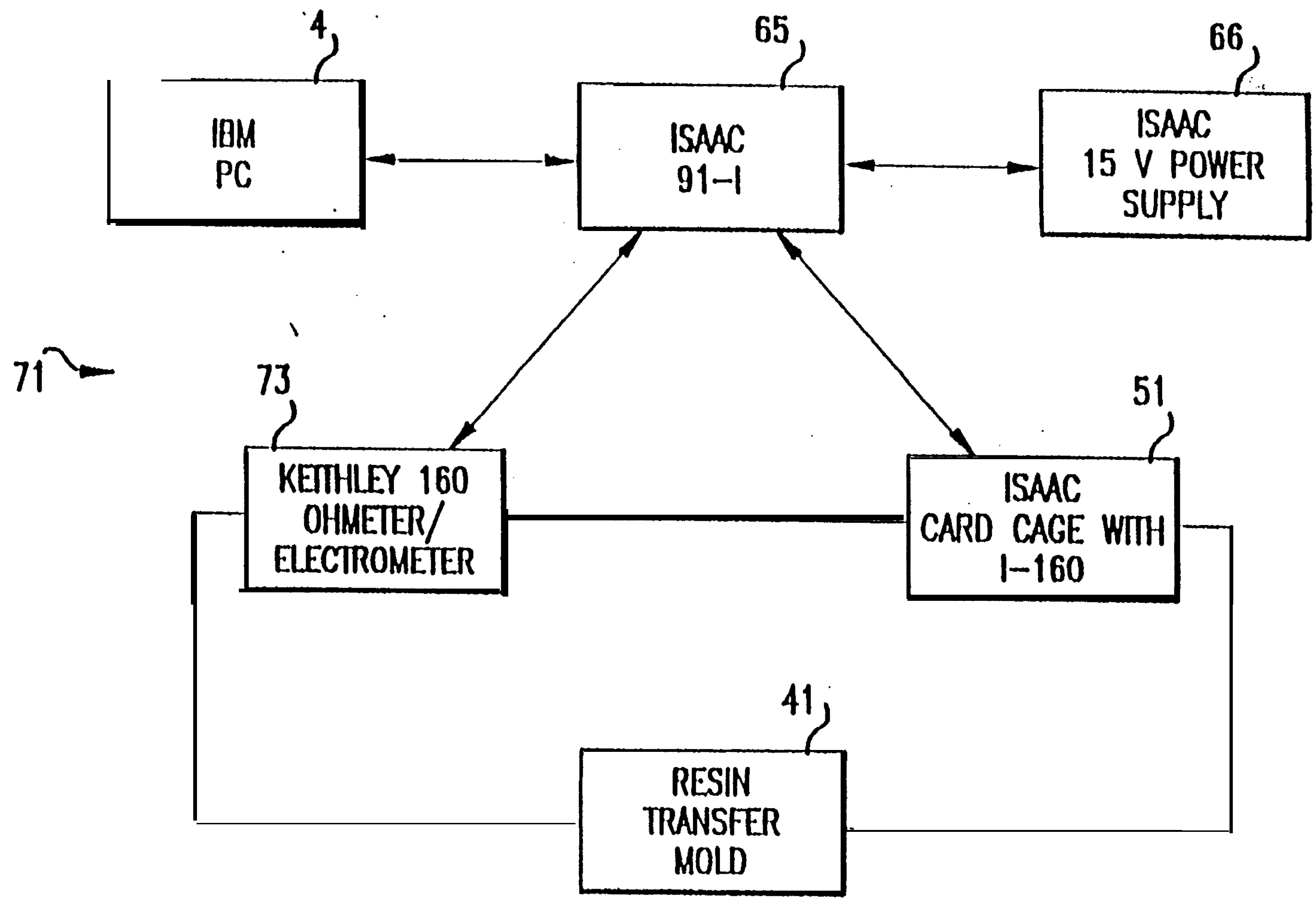

Figure 2. Diagram for SW.

In each experiment, there were resin sources and vacuum outlets. In our earlier experiments, a line source at the base of the component part was used. This allowed resin to enter the bagged system all along the 18-in base at once. A line source was also used for the vacuum. Later, the line sources were changed to point sources in both cases. The point source was first put in the corner and then (in later experiments) in the center. It was found that the rate of flow of the resin was the same in each case, and only the shape of the flow front was different: a straight-line flow front emanating from a line source and a circular flow front emanating from a point source, with the source as center of the circle. The flow was several times greater for the bleeder cloth than for the chopped strand mat. Therefore, multiple sources were tried only on the chopped strand mat side of the plate to try to make the flow rate as fast as the bleeder cloth side. Two SW computer systems (one manual and one controlled) were used. The controlled system would start the second and/or third source at a programmed time (e.g., when the second row of excitation sensors were covered with flowing resin). Channeling is a phenomenon that was very relevant. Channels were introduced into our vacuum system unintentionally, at times. However, channels can be used in a very positive way, if designed into the system properly since the resin will flow much faster through them than through the normal area.

After performing approximately 30 experiments in two dimensions, experiments in three dimensions were begun. Instead of one layer of excitation and sense leads, the new configuration had three layers of excitation and sense leads, with several (seven) layers of fabric between them. This was done because the three-dimensional (3-D) case was what was had in real parts and systems. It was necessary to have three disconnected sets of sense leads, but the excitation leads needed to be connected between the three layers in five, long, continuous strands of graphite, which wound through and around the fabric in an s-shape.

4. Results

Another process, other than RTM, where SW has been successful is bleeder-type composite processing. In Figure 3 (Figure 9 of Walsh [2]), an example of this is given. Here, there are two

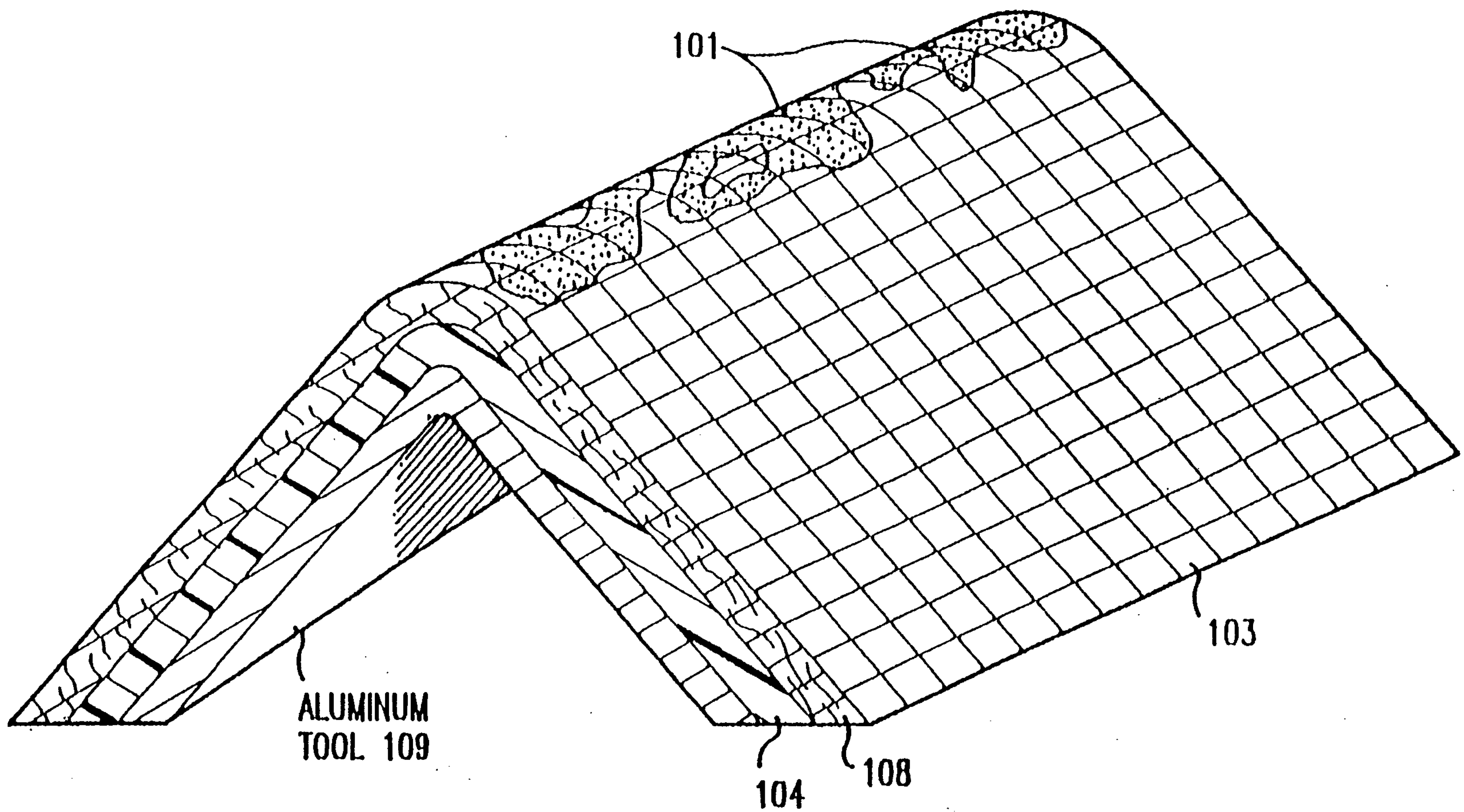

Figure 3. Bleeder-Type Composite Processing.

layers of material on an aluminum tool. The first layer (104) is graphite epoxy, and the second is bleeder material, such as absorbent glass and burlap. The graphite/epoxy layer is bled through the bleeder layer and comes into contact with the sensing grid on the aluminum part. Here, the flow of the resin is based on the principles of permeation, as opposed to pressure or injection. The SW grid monitors the progress of bleed-through epoxy resin, as in section 10% of the figure. The SW system is capable of indicating where excessive and mild bleeding of resin occurs in the laminate (Figure 9, column 12 of Walsh [2]).

Graphs for two separate nodes are shown in Figure 4 [3]. Each graph is constructed with three curves on it: (1) the SW signal, (2) the change in the difference of two moving charges, and (3) the sum of the change in the difference of two moving charges. It turns out that the node is not turned on (excited) at the peak of the "sum of the change in the difference of two moving averages" curve, but somewhere on the upward ramp (side). It can also be seen that the SW signal is more dragged out in the bottom figure, and stronger on the positive side in the top. The more dragged-out signal means that it took more time to "excite" the node, while the stronger signal means that the wetted fabric at this node has more resistance than it does at the other node. In conclusion, the amplitude and width of these three curves give us much information about the nature of the phenomena at these nodes much as they do in other forms of spectra, such as magnetic-resonance (MR) spectra.

Figure 5 also gives information on when a node is excited. Each vertical jump indicates that a node has been excited. These jumps are distinct and precise. This is a graph of time vs. voltage. It can be seen that, once the node is excited, the voltage drop across it remains relatively constant, except for the unexplained drop in voltage for all of the nodes at approximately 2,647 s.

It was found that channeling, or "racetracking," is a major concern in the RTM process. This is the creation of long, thin gaps in the vacuum bag when the vacuum is pulled. They are approximately 1 mm or less in width and approximately 3 in or 4 in in length on average, but they can basically have any width or length. They are the result of bagging material that is

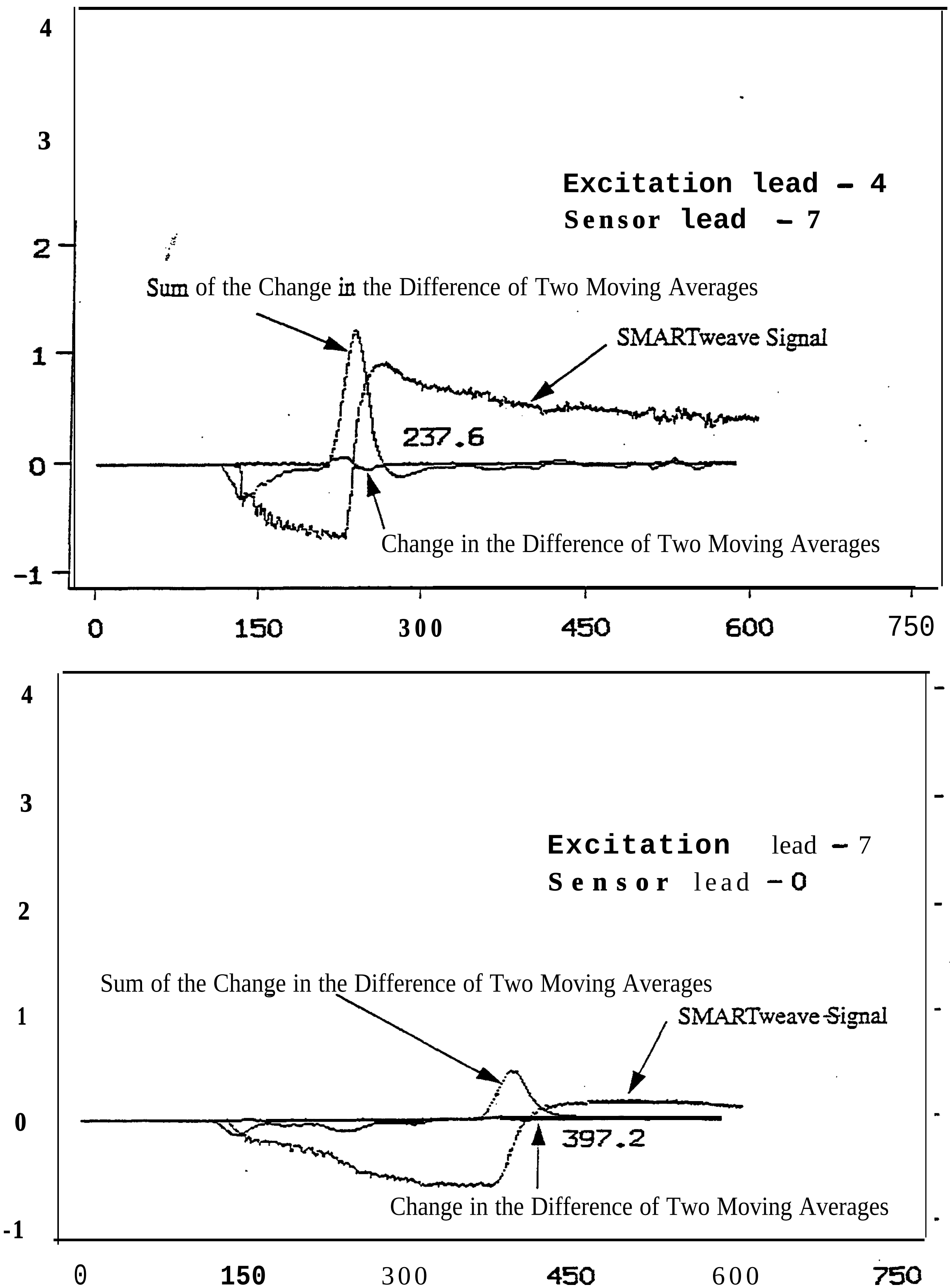

Figure 4. **Graphs for** Two **Separate Nodes.**

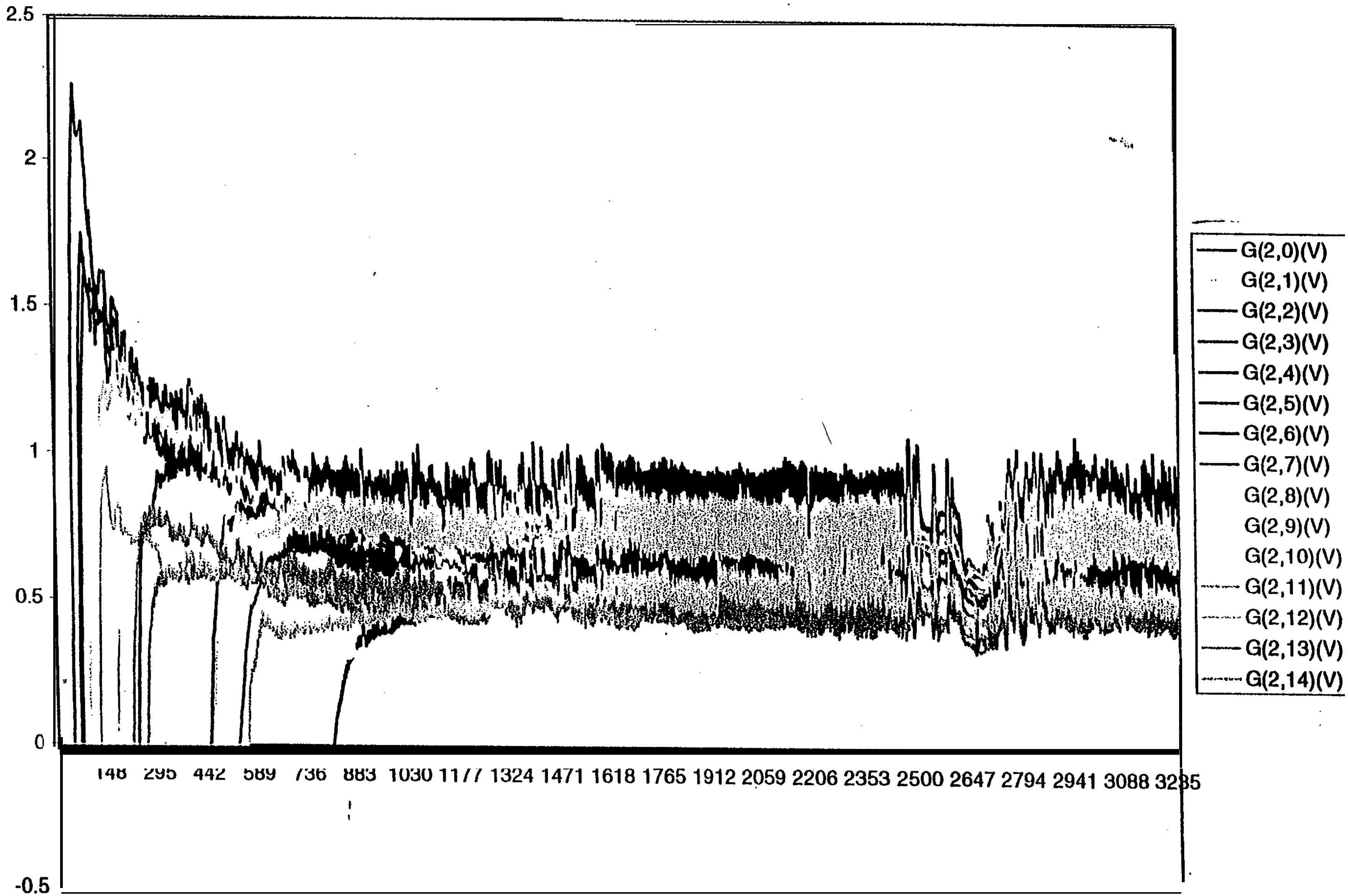

Figure 5. Information on When a Node Is Excited.

creased or results in some other phenomenon in the manufacturing process, such as not smoothing out the bagging material before pulling the vacuum. Often, there are gaps around the edges of the preform, which are also a type of channeling. These are harder to eliminate. Channeling is usually an undesirable phenomenon, but it can sometimes be desirable. Channels can be controlled and intentionally introduced, in order to get resin to a particular area of the configuration. The main undesirable property of channels is that they can cause areas of the preform to be overfilled with resin Undesirable channels must be removed prior to the start of an experiment, for once an experiment has begun, it is virtually impossible to remove them. Through experimentation, many have been observed and studied. They can be removed before an experiment by smoothing out the bagging manually, by gently pulling on the bagging, or by rebagging. It was found that channels can branch off in a vee shape, like veins. With attention to detail and careful design, channels can be eliminated completely or controlled for a positive effect. These are some observations from many experiments using SW with RTM.

The designs of our experiments also yielded several results about the configurations and feed lines. Initially, experiments were run with a single-line source along one entire edge, with a single-line vacuum on the opposite edge. It took about 20 min for the vacuum to draw the Karo-syrup resin substitute (200 centipoise) from one edge to the other on an 18-in x 18-in preform lay-up. After a few experiments, a point vacuum was tried, with the point being in the middle of the back edge. This did not slow down the filling of the mold (preform), so the point vacuum was continued in further experiments. Similarly, a point source was used in the center of the baseline edge. Again, the fill time was not slowed, but, now, the flow front was circular instead of linear. It was seen that the geometry of the part, RTM system, and of the mold are very important factors in the process. Next, multiple sources were employed. It was thought that multiple sources would speed up the process and facilitate the filling of comers and other hard-to-access areas. These additional sources, usually in the form of lines, were placed on the chopped strand mat side (slow side), but not on the bleeder cloth (fast side), in order to attempt to make the fill rates similar on both sides. This did prove to be effective in shortening the fill time and making hard-to-reach areas more accessible.

Controlled, as opposed to manual, sources were next employed. A different SW system-one that contained the proper software to operate the automatically controlled resin sources-needed to be used here. One or two controlled sources were added on the chopped strand mat side at intervals of 6 in from the baseline edge, where a line or point resin source was located. This design worked quite well and indicated that controlled openings of resin sources could be a real benefit to the efficiency of RTM in industry.

The data from the first 3-D experiment was analyzed, and the results are shown in Figure 6. The 3-D flow front is shown in the figure by the five separate walls of resin There are. five because there were five excitation and five sense leads at each of the three SW levels. The figure shows that SW can give just as precise and detailed depiction in three dimensions as it can in two, if the data are processed correctly, as in this figure. The resin source was in the exact center of the specimen. This is why concentric circles are formed as the resin is pulled upward (z direction). In reality, there are no gaps between concentric circles, but, rather, just one continuous mass of rising resin. The gaps are the result of spaces between the SW nodes (junctions). Therefore, if more closer nodes are employed, the gaps can be narrowed to practically any desired space.

5. Discussion

The fundamental properties of materials that affect eddy currents are as follows: conductivity of the material, dimensions of the material, and permeability of the material. The fundamental properties that affect ultrasonics are acoustical impedance and dimensions of the material. The fundamental property of materials that affects x-ray radiography is density of material. Finally, the fundamental property that affects SW is the dielectric constant. A dielectric material is one that responds to the application of an electrical field by acting both as a capacitor (storing charge) and a conductor (transmitting charge). There are five properties of dielectric materials, which can thus be studied by SW data: (1) ionic conduction, (2) dipoles

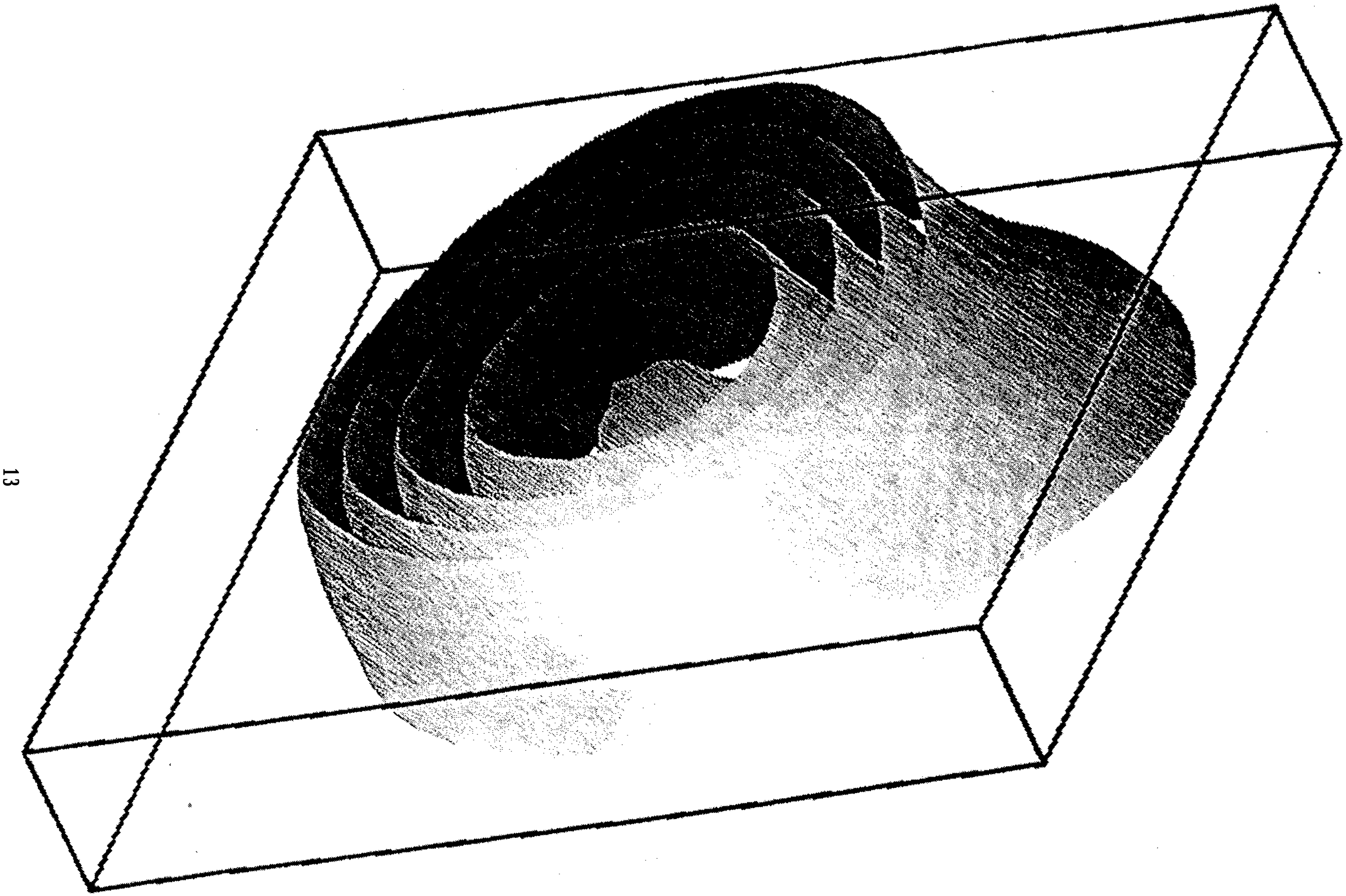

Figure 6. Results of First 3-D Experiment.

(both inherent and induced), (3) electronic conduction, (4) electrode polarization, and (5) inhomogeneities (Maxwell-Wagner effect).

Transducers are materials (devices) that convert one form of energy into another. Ultrasonic transducers are made up of a piece of piezoelectric material that changes sound (mechanical) energy into electrical energy and back again Neither the sensors in ET nor SW testing can be called transducers because the type of energy is' not changed during their use. In ET, the energy is changed from electrical to magnetic and back again, but this is considered to be the same form of energy, electromagnetic. In SW testing, the form of energy is electrical throughout. The form of energy in RT, of course, is x-rays and is not changed.

As far as couplants are concerned, only UT, among the three sensor-based methods, needs to be intimately coupled to the specimen. Either water or gel is used. ET only needs a protective Mylar or other flexible sheath. SW testing requires no couplant and would be classified as a contact method. There is no immersion in the SW method as in UT. UT and RT can examine virtually any solid substance, since practically all solid substances can be penetrated by sound waves or x-rays. Here again, SW testing is similar to ET, in that it can only examine electrically conductive materials. In RTM, for example, the starting materials are not electrically conductive, so there is no SW signal. As the starting materials are wetted with the resin, they become conductive and the SW signals begin to appear. So, when should one use SW as an NDE tool? Typically, it should be used whenever a conductive material flowing through a nonconductive substrate needs to be examined. It should not be used, however, to locate defects smaller than the distance between a group of nodes. Of course, by using more nodes, one can shrink this distance considerably, keeping in mind that there are physical limits to this approach.

6. Summary and Conclusions

The NDE of composites is more difficult than that of most materials. ET and UT can be used to inspect them, but in very limited ways. ET can only look at a portion of the composite (i.e., the electrically conductive part). For example, in graphite epoxy, it can only detect breakage of the graphite fibers. UT, on the other hand, is very limited depth wise, since sound energy attenuates very quickly with depth in a composite material due to the heterogeneous nature of composites. RT is expensive, bulky, and hazardous. SW supplements and complements these effective but limited methods by looking at composites in a new and different way.

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