EDDY CURRENT INSPECTION of
THICK CARBON FIBER REINFORCED COMPOSITES

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INTRODUCTION

Eddy current nondestructive evaluation (NDE) is usually associated with the detection and measurement of surface defects in metal and with the through-thickness inspection of thin-wall metal tubing. The greater electrical resistivity of carbon fiber reinforced composites (CFRCs), excluding metal matrix composites, results in much greater skin depths or standard depths of penetration, thereby providing for the through-thickness inspection of much thicker components than are usually associated with eddy current NDE. For example, skin depths in copper and 304 stainless steel at 10 kHz are 0.026 inch** and 0.168 inch, respectively. Assuming typical resistivity values for carbon/carbon and graphite epoxy, skin depths in these materials at 10 kHz are 0.56 and 1.98 inch, respectively.

In single-sided eddy current inspection, the skin depth should be on the order of the thickness of the material. In through-transmission eddy current inspection, it appears that thicknesses much greater than a skin depth can be inspected with off-the-shelf equipment and with no loss in phase detection accuracy. This paper presents our initial work in through-transmission eddy current NDE with emphasis on the inspection of thick-wall, filament-wound graphite epoxy cylinders.

The resistivity characteristics (usually high and sometimes frequency dependent) of CFRCs are a consequence of the structure of this class of composites. It is also the structure which determines the anomalies to which eddy current is sensitive. CFRCs consist of conducting graphite or carbon fibers in a matrix. The matrix may be more conducting than the fibers (metal matrix composites, which will not be addressed), less conducting (carbon/carbon), or non-conducting (graphite epoxies). Since it is the fibers which carry most or all of the current, eddy current is sensitive to variations in the fibers which affect the localized resistivity of the material. Since fiber breakage has the greatest effect on the current-carrying capability of the fibers, eddy current is most

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**1 inch = 25.4 millimeters
sensitive to fiber breakage. This typically is associated with service-incurred damage resulting from impact and fatigue. Fabrication-related anomalies such as wrinkled fibers, variations in fiber density and/or amount of inter-fiber contact also cause local variations in resistivity which may be detected by eddy current. It is possible that variations in carbon matrix continuity due to voids may also be detected.

Impact damage can consist of a combination of delamination, matrix cracking and broken fibers. Which of these types of damage predominates in the damaged region depends on the force of impact, the velocity of the impact and the size of the impactor. A damaged region containing broken fibers is characterized, in part, by the remaining ligament or the amount of material containing unbroken fibers which remains to bear the load. The possible distribution of the remaining ligament is illustrated in the drawing shown in Figure 1. Single-sided eddy current inspection is most sensitive to the thickness of the ligament nearest the scanned surface, even when the damaged region is enclosed in the material. In contrast, through-transmission is sensitive to the total amount of undamaged material, independent of its through-thickness location.

The goal of the work to be described is the development of a through-transmission eddy current method to detect broken-fiber damage and to measure the remaining ligament in large, filament-wound graphite epoxy cylinders. These cylinders may have wall thickness as great as 10 inches and diameters on the order of 100 inches. A significant factor in the development work is the present unavailability of such large cylinders. A system developed to address the available "small" cylinders (wall thicknesses < 1.0 inch and diameters < 10 inch) must be equally applicable to cylinders that are larger by a factor of 10. Careful consideration must be given to the scale-up potential of the system.

Three coil design combinations were evaluated (Figure 2): 1) opposed surface probes, 2) opposed circumferential coils, and 3) the combination of a circumferential driver coil and a horseshoe receiver. The three combinations were compared with respect to their material responses, apparent scale-up potential including both the axial and the circumferential resolution provided, and defect sensitivity.

![Fig. 1. Illustration of possible distributions of remaining ligament.](image)

![Fig. 2. Three transmitter/receiver combinations: a) opposed surface probes, b) opposed circumferential coils, c) circumferential transmitter and horseshoe receiver.](image)
TRANSMITTER

RECEIVER

NETWORK ANALYZER

gain, g
phase, \( \phi \)

Xn: IMAGINARY COMPONENT OF NORMALIZED IMPEDANCE = \( \frac{g_m}{g_0} \cos \phi \)
Rn: REAL COMPONENT OF NORMALIZED IMPEDANCE = \( \frac{g_m}{g_0} \sin \phi \)

Fig. 3. Frequency generation and transfer impedance measurement circuit.

The diagram of the circuit used to measure the normalized transfer impedance is shown in Figure 3.

MATERIAL RESPONSE

The material responses of the three coil combinations were compared in terms of the normalized impedance diagram. Data points for a given coil system/material combination were generated over a range of frequencies by measuring the gain and phase lag between the two coils in the absence of the test material \( g_0 \) and with the test material inserted between the driver and receiver \( g_m \). The various coil combinations were tested on 3 cylinders. The cylinder materials, dimensions and resistivities, along with the applicable coil combinations, are listed in Table 1, which also identifies the symbols used in impedance diagram in Figure 4.

Table 1

<table>
<thead>
<tr>
<th>Cylinder Material</th>
<th>Wall Thickness (in)</th>
<th>Outside Diameter (in)</th>
<th>Resistivity ( \mu \Omega \text{cm} )</th>
<th>Symbol</th>
<th>Coil# Comb.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>0.055</td>
<td>5.25</td>
<td>3.99</td>
<td>o</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>o</td>
<td>C</td>
</tr>
<tr>
<td>Carbon/Carbon</td>
<td>0.20</td>
<td>8.38</td>
<td>942.0*</td>
<td>x</td>
<td>C</td>
</tr>
<tr>
<td>Graphite Epoxy</td>
<td>0.72</td>
<td>8.25</td>
<td>?</td>
<td>x</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>v</td>
<td>C</td>
</tr>
</tbody>
</table>

# A - Opposed surface probes.
B - Opposed circumferential coils
C - Circumferential driver and horseshoe receiver

*Estimated to within +10% using single-sided eddy current method.1
Several observations can be made regarding the normalized transfer impedance diagram shown in Figure 4. First, unlike the typical single-sided normalized impedance diagram, both the real and imaginary components can have negative values. The through-transmission system can be compared with a series of coupled transformers where it is possible for the phase of the output voltage to lag the phase of the input voltage by as much as 360°, resulting in negative values of the components.

Second, when the phase lag is less than one radian (the phase lag associated with one skin depth) all the data appear to fall on a circle whose center is located at Xn=0.3, Rn=0. For phase lags greater than one radian, the data begin to spiral towards the origin of the impedance diagram (0,0), with the aluminum data apparently approaching the center at a faster rate than that of the higher resistivity materials. The theoretical basis for the circle if, indeed, it is real, has yet to be established.

Finally, location on the impedance diagram appears to depend on a reference number given by $Tr/\delta^2$ where $T$ is the thickness of the material and $\delta$ is the skin depth. When the driver is an encircling coil, $r$ appears to be the inside radius of the cylinder. For the case of opposed surface probes of the same size, $r$ appears to be half the outside diameter of the probe. When circumferential transmitter coil phase lag values for the aluminum and carbon/carbon cylinders were plotted against the reference number $(Tr/\delta^2)$, the data fell on a straight line for phase lag values less than one radian. Applying this relationship to the graphite epoxy data, its resistivity was estimated to be approximately 7000 $\mu$S.cm.
Several preliminary conclusions were drawn with respect to the effects of coil design on material response. Since all the data fell on a single curve for phase lags less than one radian, both the magnitude of the material response \( \frac{E_m}{E_0} \) and the phase lag depend only on the reference number \( (T/r^2) \) for phase lags less than a radian. Coil design affects the impedance in that the quantity \( r \) in the reference number refers to the radius of the probes for the opposed surface probe combination and to the inside radius of the cylinder when the transmitter is an encircling coil. For phase lags greater than one radian, transfer impedance is determined not only by resistivity as a factor in the skin depth, and consequently in the reference number, but also as it affects rate at which the normalized transfer impedance approaches zero.

**SCALE UP POTENTIAL AND RESOLUTION**

Opposed surface probes provide good axial and circumferential resolution, but this combination has two drawbacks with respect to its application to large filament-wound cylinders. The combination is highly sensitive to the relative positions of the probes and it requires some conductivity in the axial direction so current can flow in a circular path in the material beneath the probes. Accurate positioning can readily be assured for smaller components by mechanical means. For very large cylinders accurate positioning could be achieved by moving the receiver until the received signal was maximized. The requirement for this approach simply introduces a complicating factor. Of greater significance is the requirement for axial conductivity; there is no guarantee that all filament-wound cylinders will have sufficient conductivity in the axial direction.

The opposed surface probe combination might well be the most effective combination for materials having a less anisotropic conductivity, such as some carbon/carbons. However, given the potential for minimum axial direction conductivity in filament-wound graphite epoxy cylinders, this combination was eliminated, for the time being, from further consideration.

Opposed circumferential coils require no conductivity in the axial direction. Positioning is not a problem as the field associated with the transmitter was found to be uniform along the center third of its length. While axial resolution is good, there is no circumferential resolution. Furthermore, the effect of a flaw would be averaged over the circumference, resulting in lowered sensitivity.

The combination of a long circumferential transmitter and a horseshoe receiver appeared to be the best of the three combinations for the inspection of filament-wound graphite epoxy cylinders. No axial conductivity is required and scale-up potential could be limited only by the effects of horseshoe receiver dimensions and by the effects of transmitter turns density on material response, resolution, and defect sensitivity. For example, if defect detection required that any of the illustrated horseshoe dimensions (Figure 5) be on the order of the wall thickness*, application to a wall thickness of 10 inches could be impractical.

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*In single-sided inspection the mean coil radius should be at least equal to a skin depth. If the entire thickness is to be inspected, the probe size is related to the thickness of the component. When surface defects are to be detected only very small skin depths are required with the consequence that very small probes can be used. In through-transmission work, the through-thickness location of the defect is not a factor and so will not affect coil size.
It is important to operate at frequencies below the resonant frequencies of both the transmitter and the receiver. Limiting the number of turns, and hence the resonant frequency, of the horseshoe receiver is not a problem. Both the length and the potentially large radius of the transmitter could result in a prohibitively low resonant frequency. The effect of a large coil radius on resonant frequency can be offset somewhat by increasing the separation between the turns. It was necessary to determine the effect of turns density on the defect response, since increasing the radius of the transmitter to 50 inches might require a large separation between the windings.

The effects of transmitter turns density and horseshoe size on defect response were evaluated on the basis of 0.5 inch-OD, 0.15 inch-deep flat bottom hole in the graphite epoxy cylinder described in Table 1. The center of the flat bottom hole was located 3.75 inches from one end of the 8 inch-long cylinder.

To determine the effects of receiver dimensions on resolution and sensitivity, two horseshoes were tested. The smallest horseshoe had an axial length (dimension A in Figure 5) that was approximately 0.5 the wall thickness while the axial length of the largest horseshoe was 1.5 times the wall thickness. Transmitters with two different turns-densities were investigated. The turns-density of one was 2 turns/inch (for a separation equal to 1.4 times the wall thickness) while the turns-density of the other was 7 turns/inch for an inter-turn separation equal to 1/4 the wall thickness.

It was assumed that the field associated with the low turns-density transmitter would be weaker than that associated with the higher density transmitter. It was also assumed that the smaller of the horseshoes might not couple to the material as well as the larger one and so would be less sensitive. Thus the combination of the low turns-density transmitter and the smaller horseshoe might be less sensitive to changes in transfer impedance (smaller defect response magnitude) than would the combination of the high density transmitter and the large horseshoe.

Data were collected at frequencies from 6.25 to 200 kHz as the receiver was rotated around the inner circumference of the cylinder. Data for both transmitter/receiver combinations are shown in Figure 6. It appears that turns-density and horseshoe size, over the range of their variation, did not have a significant affect on the defect response.
The effects of transmitter turns-density and horseshoe size on both circumferential and axial resolution were also determined. The changes in impedance magnitude and in phase lag were measured as the receiver was rotated around the inner circumference. The change in phase lag is plotted against circumferential location in Figure 7 for each of the two combinations. The magnitude versus circumferential location curves were similar. The differences between the curves for the two combinations appear to be insignificant. In both cases, the defect response (change in phase lag) extends well beyond the region of the defect. If there were no conductivity in the axial direction, the effect of the broken fibers would extend around the entire circumference. If the resistivity of the material were isotropic, the spatial extent of the defect response would be expected to be more closely related to the dimensions of the receiver. It was concluded that the effects of material structure on circumferential resolution far outweighed the effects of turns-density and horseshoe size.

Axial resolution was determined by measuring, in 1/4 in increments along the center 4 inches of the length of the cylinder, the difference in phase lag at the circumferential location of the defect and at 180° from the defect. (This subtraction removes effects of possible variations in the transmitter field along its length.) The difference in phase lag for the two combinations is plotted against axial position in Figure 8. Again, the effects of turns-density and horseshoe size, for the combinations considered, appear to be insignificant.

Fig. 7. Change in phase lag versus circumferential location.

Fig. 8. Change in phase lag versus axial position.
APPLICATION TO "LARGE" CYLINDERS

Data were also collected from a smaller, filament-wound graphite epoxy cylinder to provide a basis for extrapolating defect detectability to the hypothetical large, 100 inch-OD, cylinder. The smaller cylinder had a 0.3 inch-wall and a 6.81 inch OD. It contained a 0.2 inch-OD, 0.15 inch-deep flat bottom hole. The transfer impedance curve, with defect responses, was very similar to that shown in Figure 6. In both cases the strongest defect response was obtained at the point on the curve where the phase lag was about 180° (see Figure 6). For the larger cylinder the frequency at this point was 200 kHz and for the smaller, 1000 kHz. The resistivities of both cylinders were estimated to be about 7000 cm, giving a reference number of 18 for the large cylinder at 200 kHz and for the small one at 1000 kHz.

On the basis of these admittedly sparse results, it was tentatively concluded that a relatively strong defect response will be occur when the reference number is 18. In both cases the skin depth associated with this reference number is about half the wall thickness. For the 100 inch-OD cylinder, a reference number of 18 obtains when the frequency is 55 kHz, a reasonable inspection frequency.

Yet to be addressed is the very important question of the relationship between the size of the smallest detectable defect and the wall thickness.

CONCLUSIONS

It was concluded that a circumferential transmitter coil in combination with a horseshoe receiver was the most effective transmitter/receiver combination for the through transmission eddy current inspection of large filament wound graphite epoxy cylinders. Over the range of their variation, neither the turns-density of the transmitter nor the dimensions of the horseshoe had a significant effect on defect sensitivity or on axial and circumferential resolution. Initial results indicate it should be possible to inspect a 10 inch-wall filament-wound graphite epoxy cylinder.

REFERENCES