EDDY CURRENT INSPECTION OF GRAPHITE-EPOXY SOLID ROCKET MOTOR CANISTERS

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INTRODUCTION

Filament wound graphite/epoxy cylinders are used in a number of applications because of their favorable strength-to-weight ratio. Eddy current techniques are receiving more attention for composite inspection because eddy currents detect broken fibers but not delaminations. Therefore, eddy current inspection of this material would be desirable in its own right and as an adjunct to ultrasonic inspection which detects delaminations, but not broken fibers. However, filament wound graphite/epoxy is difficult to inspect because of its large and anisotropic electrical resistivity. This paper presents a technique for eddy current NDI of filament wound graphite/epoxy which uses currents flowing in the low-resistivity circumferential direction. This method eliminates several objections to conventional eddy current inspection of this material.

First it is shown why ordinary eddy current inspection is ineffective in filament wound graphite/epoxy. This is followed by a discussion of circumferential eddy current inspection. Results of inspections of 14 mm thick sections of composite cylinders are presented. Finally, conclusions are given concerning the results presented in this paper.

CONVENTIONAL EDDY CURRENT INSPECTION OF FILAMENT WOUND GRAPHITE/EPOXY

Eddy current inspection is often carried out with a pancake coil whose axis is perpendicular to the surface under inspection. For best resolution of small defects the windings are placed on a shielded ferrite core called a cup core [1]. For best results, the outer diameter of the ferrite cup should be about equal to the sample thickness. The response of such a coil to a defect in an isotropic conductor is shown in Fig. 1. These data were taken by scanning a cup coil over a sample and recording the non lift-off component of the coil impedance at regularly spaced points.
The response in Fig. 1 has a characteristic volcano shape which is common for isotropic materials. To understand the effect of anisotropic resistivity on the eddy current response, it is assumed that the anisotropic resistivity is given by:

\[ \rho(\theta) = \rho_p + \rho_t \cos^2(\theta) \]  

(1)

where \( \theta \) is the angle of integration with respect to the low resistivity direction, \( \rho_p \) is the low resistivity in that direction and \( \rho_t \) is the resistivity in the high resistivity direction [2]. This model displays the important features of an anisotropic material without necessarily duplicating the behavior of any particular material. A cup coil responds to the average of the resistivity over an eddy current loop parallel to the exciting coil, as shown in Fig. 2. If this current loop is roughly circular, then the average resistivity is given by:

\[ \rho_{avg} = \frac{1}{2\pi} \int_0^{2\pi} \rho(\theta) d\theta = \rho_p + \frac{1}{2} \rho_t \]  

(2)

In a typical filament wound graphite/epoxy composite the transverse resistivity \( \rho_t \) is about 100,000 micro-ohm cm and is much larger than the parallel resistivity \( \rho_p \) of about 500 micro-ohm cm. Therefore, the cup coil response is primarily determined by the transverse resistivity. Since the transverse resistivity is also large compared to that of good conductors at 1-10 micro-ohm cm, the cup coil sensitivity to defects in filament wound graphite/epoxy is low.
The cup coil response for an anisotropic conductor is quite different than the response shown in Fig. 1. In an anisotropic conductor a defect at point A in Fig. 2 will interrupt current in the low resistivity direction and change $\rho_p$ but not $\rho_t$ in equation 2. Similarly, a defect at location B will influence $\rho_t$ but not $\rho_p$. Alternately, the response of a moving coil to a fixed defect will depend on the azimuth of the defect with respect to the high resistivity direction, being low when the defect lies in the high resistivity direction and vice versa. Consequently the cup coil response to a small defect is not the volcano shown in Fig. 1, but consists of two isolated responses about a coil diameter apart and centered over the defect.

Filament wound composites display highly anisotropic resistivity. A typical layup is shown in Fig. 3. Layers of filaments in a Trident rocket motor canister, for example, are alternately at 22, 0, and -22 degrees from the circumferential direction. Current flowing circumferentially passes alternately along +22, 0, and -22 degrees fibers, with occasional transitions from one layer to another as required. Such transitions are infrequent because all fibers lie close to the circumferential direction. However, no fiber lies close to the axial direction so that conduction in that direction relies heavily on contacts between fibers. These contacts are few because all fibers are immersed in non-conducting epoxy.
Figure 4 shows a contour plot of the cup coil response to two flat bottom holes (FBH's) drilled in the outer surface of an 200 mm diameter filament wound graphite/epoxy cylinder. The FBHs are responsible for the pairs of closed contours labeled '2.9' and appear between them as shown. The signal-to-noise ratio in this figure is about 12 dB.

Figure 5 shows circumferential eddy currents in a filament wound cylinder. The exciting coils encircle the cylinder and are not shown. In the absence of a defect, the currents are images of the exciting coils and travel around the entire cylinder. When a defect interrupts the eddy current flow, a small current in the axial direction is developed and the circumferential current is reduced as well.

In a reflection-mode eddy current inspection system these disturbances are detected by means of a small separate pickup coil, also not shown. The pickup coil and the driving coils may be outside the cylinder which allows inspection of canisters which are loaded with fuel. The pickup coil geometry is optimized to detect changes in the circumferential component of the current, as this component displays greater signal-to-noise ratio than the axial component. The pickup coil is scanned over the surface of the cylinder, thereby allowing defects to be resolved in the circumferential direction as well as the axial direction.

Figure 6 shows a contour plot of the encircling coil eddy current response to the FBHs responsible for the image of Fig. 4. The scan extends 90 degrees away from the defects in each direction. The deeper FBH is represented by the label '4.5' at 90 degrees and x=25 mm. The other FBH is at 90 degrees and x=55 mm. The contours surrounding these indications are contributed by the FBHs. The contours centered at 90 degrees and x=15 mm, 40 mm and 80 mm are due to the passage of the exciting coils over the defects. These contours are lower in amplitude than those in the region far from the FBHs (not shown), and combine to form a wide negative-going contour at x=40
mm. The noise in Fig. 6 contributes irregularities to the contours but is not responsible for any closed contours. Therefore the signal-to-noise ratio in Fig. 6 is immeasurably higher than that for the cup coils shown in Fig. 4. These figures suggest that encircling coil eddy current inspection provides defect detection at much higher signal-to-noise ratios, and therefore at lower detection threshold, than does inspection using conventional cup coils. The results further suggest that the encircling coil images are easier to interpret than the cup coil images.

Fig. 5. Eddy Currents in Filament Wound Cylinder

Fig. 5 shows the encircling coil response to a small notch on the inner surface of the same 19 mm thick cylinder. The eddy current frequency was 200 kHz and the skin depth was greater than the sample thickness. The notch was 9 mm deep and 19 mm long and oriented along the axis of the cylinder. In this position the notch broke as many fibers as possible. The notch was not intended to simulate an actual defect but to show that the technique is sensitive to a small number of broken fibers on the distant side of a filament wound graphite/epoxy cylinder. The notch response is centered at 90 degrees and x=10 mm and is clearly detected in Fig. 6. This notch was undetected with conventional eddy current cup coils.

Finally, Fig. 8 shows the encircling coil response to a notch 3 mm deep by 9 mm long on the inner surface of the cylinder. This notch broke about 2000 fibers. Some image processing was required to bring this response out of the noise since the notch probably lies at the detection threshold of the system. Optimization of the operating frequency, coil geometry and coil spacing would probably improve this preliminary detection threshold.

CONCLUSION

An eddy current inspection technique is described which has improved sensitivity to graphite/epoxy composite cylinders over conventional cup coil techniques. This new technique yields higher signal-to-noise ratios and yields results which are easier to interpret than conventional cup coil techniques. This eddy current inspection system may be used to discriminate between delaminations and broken fibers if used in conjunction with ultrasonic techniques.
Fig. 6. Encircling Coil Eddy Current Image of FBHs

Fig. 7. Eddy Current Image of Large Notch in Gr/Ep Canister
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