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Measurement of the Shielding Properties of Composite Materials: Comparison of the Dual TEM and Noncontact Probe Methods

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Measurement of the Shielding Properties of Composite Materials: Comparison of the Dual TEM and Noncontact Probe Methods

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***Abstract*—A comparative study has been made of the use of a noncontact probe method and the dual TEM cell method for the measurement of the surface impedance of composite materials. The results show that the values of surface impedance obtained by the two methods are in substantial agreement when the samples are pseudo-isotropic. Very different results are obtained by the two methods, however, when the samples are anisotropic because the two techniques induce a different flow of current (circular in the case of the noncontact probe method and laminar in the case of the dual TEM method). Comparison of the results from the two methods has shed light on the structure of carbon composite materials.**

***Index Terms*—Graphite, materials testing, resistance measurement, shielding.**

I. INTRODUCTION

TRADITIONALLY, electronic equipment has been shielded through the use of metallic enclosures. In recent years, new materials such as conductive plastics and composites have been increasingly used by designers of consumer electronics and aircraft because of factors such as low-cost superior specific strength and ease of manufacture. The introduction of these new materials has brought with it new electromagnetic (EM) challenges since, in general, they have electrical conductivities several orders of magnitude lower than most metals and electrical bonding of the plastic or composite sections can be difficult. This can severely hamper the EM shielding effectiveness offered by the structure. New semiconductor components are also becoming increasingly susceptible to EM interference. If not properly protected, equipment can be upset or damaged as a result of induced currents.

Because of the difficulty in predicting the EM shielding properties of these complex materials, there has been considerable interest in the development of techniques for the measurement of their shielding effectiveness (SE). A number of methods have been proposed and compared in the literature (see, for example, [1]–[5]). The results of standard test methods used for the characterization of shielded enclosures such as MIL-STD-285 [6] and NSA 65-2 [7] depend, to some extent, on geometry and antenna placement and do not directly measure the material properties of the shield. For the characterization of the intrinsic EM shielding properties of materials, the measurement of the surface impedance of the material is often chosen.

One of the more widely used and effective methods that has been developed for the measurement of the shielding effectiveness and surface impedance of materials is the dual TEM cell technique that has been developed by Wilson and Ma [8]. The need to achieve a good electrical contact between the sample being measured and the body of the TEM cell can sometimes make the use of this technique difficult. In a recent development, Gobin *et al.* [9], [10] have developed a noncontact probe technique that has the advantage that the problems associated with making good electrical contact with the materials that are encountered with some measurement methods can be eliminated. In addition, the noncontact probe method only requires access to one side of the material. This has obvious advantages for making measurements on complex structures where access to both sides may be difficult.

In this paper, a comparative study is made of the use of the noncontact probe method and the dual TEM cell technique to measure shielding properties of composite materials. Conclusions regarding the structure of these materials are drawn from the results obtained.

II. DESCRIPTION OF THE EXPERIMENTAL TECHNIQUES

A. Noncontact Probe Technique

1) Theory of the Noncontact Probe Method: The theory behind the noncontact magnetic probe technique has been discussed by Gobin [9]. Related discussion has also been given by Wilson [11] and Criel *et al.* [12]. The technique consists of measuring the component of the magnetic field normal to the surface of the sample at the same location in the presence (H_z) and in the absence ($Hz0$) of the sample. The magnetic shielding effectiveness SE_m of the sample is then defined as $SE_m = 20 \log |S|$ where $S = H_z/H_{z0}$. The probe consists of two loops: one acts as an emission antenna that generates an axial magnetic field and the second loop measures the strength of the received signal. In this analysis, the sample is assumed to be infinitely large.

For an arrangement such as the one shown in Fig. 1, where the measurement loop is placed at a distance z from the transmission loop, Gobin [9] has shown that the ratio S

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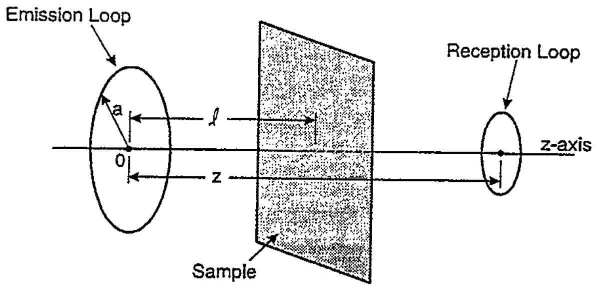

Fig. 1. Measurement loop on the opposite side of the sample.

between H_z and H_{z0} at the same location is given by

$$S(f,z) = \frac{H_z}{H_{z0}} = [1 + (z/a)^2]^{3/2} \cdot \int_0^\infty \frac{u^2}{u + j\,\dfrac{f}{f_{c0}}} J_1(u) e^{-(uz/a)}\, du \qquad (1)$$

where J_1 is the first-order Bessel function. The cutoff frequency f_{c0} is defined by

$$f_{c0} = Z_s/\pi\mu_0 a \qquad (2)$$

where the surface impedance Z_s is related to the tangential electric field and the current density in the sample by the relationship $\vec{E} = Z_s\vec{J}$. For a sample of thickness d and electrical conductivity σ, the surface impedance Z_s is given by the expression $Z_s = 1/\sigma d$, assuming that the sample is isotropic.

Note from (1) that S does not depend on the distance l between the emission loop and the material; it only depends on z—the distance between the two loops. Thus, the material can be put anywhere between the two loops. As noted by Gobin [9], since the normal component of the magnetic flux is continuous across an interface, putting the receiving loop immediately to the left or on the right of the sample will not affect the results. Hence, it is possible to measure the shielding effectiveness of a material by putting both loops on the same side of the material. To further illustrate this point, (3) is the equation of $S(f,z)$ for a receiving loop put at a point (which is a distance z from the transmission loop) on the same side as the emission loop [9] (as shown in Fig. 2)

$$S'(f,z) = 1 - \frac{(1+(z/a)^2)^{3/2}}{\left(1 + \left(\dfrac{2l - z}{a}\right)^2\right)^{3/2}} + (1 + (z/a)^2)^{3/2} \cdot \int_0^\infty \frac{u^2}{u + j\,\dfrac{f}{f_{c0}}} J_1(u) e^{-u(2l - z/a)}\, du. \qquad (3)$$

$$<S_1> \quad <S_2>$$

$S'(f,z)$can then be considered as the sum of two terms—S_1 and S_2. The first term S_1, which is the sum of the first two terms on the right-hand side of (3), depends on the geometry of the arrangement and the second term S_2, which is an integral similar to (1) that depends both on frequency and geometry. If the sample is put immediately to the right of the receiving loop so that $h = 0$ and $z = l$, then the first term in (3) vanishes leaving us with the same $S(f,z)$ expression as in (1).

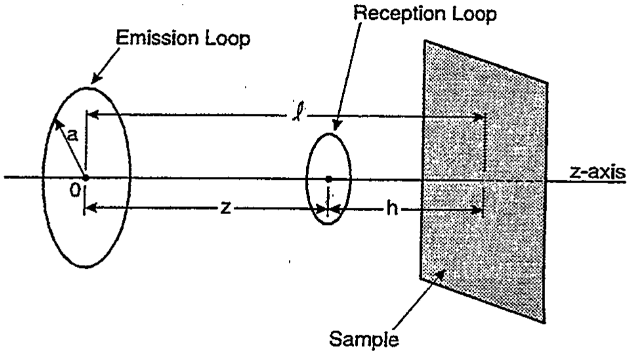

Fig. 2. Measurement loop on the same side of the sample.

By evaluating the integrals numerically, Gobin [9] has shown that if the distance between both loops is equal to the radius of the emission loop ($z = a, z/a = 1$), then, to a good approximation, S' can be expressed as

$$S'(f) = \frac{1}{1 + j\left(\dfrac{f}{f_c}\right)} \qquad (4)$$

where $f_c = 1.4 f_{c0}$.

The shape of a graph of $SE_m = 20 \log|S|$ versus frequency is similar to that of a first-order low-pass filter. The main characteristics of such a curve are a −20 dB/decade slope at high frequencies and a cutoff frequency proportional to the surface impedance Z_s of the sample. In practice, because it is impossible to make $h = 0$ and the sample has finite thickness, the slope flattens at high frequencies and reaches the constant value of $20 \log(S_1)$ [see (3)] as the S_2 term goes to zero. Gobin [9] has presented numerical results showing the effect of h on the shape of the measured curves. When $l \gg z$ (i.e., the receiving loop is far from the sample) $S_1 \to 1$ and $SE_m \to 0$.

From (4), note that samples with a lower cutoff frequency will shift the SE curve to the left and those with higher cutoff frequencies will shift it to the right. Thus, at the same frequency, a material with lower surface impedance offers equal or better EM shielding. For this reason, surface impedance is often chosen to be the main parameter to characterize the quality of shield. Z_s can be obtained from the cutoff frequency of a graph of shielding effectiveness versus frequency according to the following relation[1]:

$$Z_s = \frac{\pi\mu_0 a f_c}{1.4}. \qquad (5)$$

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[1] The comparison of the measurement of shielding effectiveness using coupled dipoles and the dual TEM method has been made by Wilson [11]. In this paper, Wilson derived an approximate analytical expression [11, eq. (29)] for the magnetic shielding effectiveness using the coupling between coaxial dipoles. For thin samples, this expression reduces to an equation of the same form as (4), however, the cutoff frequency that is derived is about a factor of two larger. This discrepancy is thought to result from the simplifying assumptions made by Wilson in deriving his equations. Examination of [11, eq. (29)] indicates that this expression implicitly assumes that the loop radius is small compared to the separation between the two dipoles. This is clearly not the case in the experimental setup proposed by Gobin and used in the measurements described in this paper. Gobin, on the other hand, has used a more general expression that is valid when the loops are in close proximity.

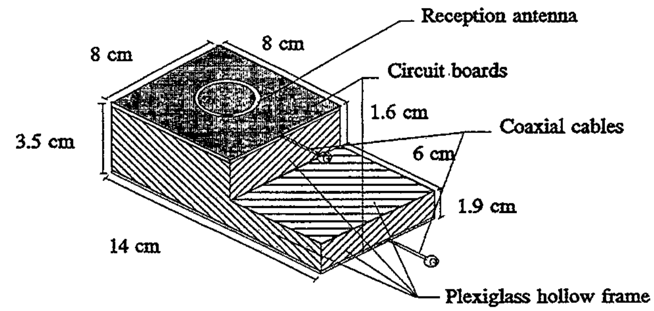

Fig. 3. Design of the noncontact probe.

The noncontact probe method is then a very effective and easy way of measuring the surface impedance of a material. The technique is nondestructive, offers great mobility and practically requires no sample preparation time. Moreover, since there is no electric contact between the circuit and the sample, it eliminates problems that are encountered in contact methods. Measurements of surface impedance can be made even if the material is coated with a dielectric material such as paint.

The expressions derived above assume isotropic conductivity and are valid for frequencies where the sample thickness is small compared to the skin depth. These limitations need to be kept in mind when using these results. The expressions have also been derived assuming that the sample is infinitely large. In practice, provided the sample is large compared to the size of the sensor, the results are expected to be valid. This was the case in the measurements reported in this paper.

2) Probe Design and Experimental Equipment: The design of the probe used for the measurements is shown in Fig. 3. The probe consists of a hollow plexiglass box with a 3.5-cm radius emission loop and a 1.5-cm radius reception loop etched onto the surface of a printed circuit board. All faces were assembled using epoxy glue. This design allows the probe to be as close as physically possible to the sample and minimizes the S_1 term of (3). Care was taken to ensure that both loops had their centres aligned and that the distance between them was equal to the radius of the emission loop such that $z/a = 1$.

The shielding effectiveness of the composite samples was measured over the frequency range from 1 kHz to 200 MHz using a Hewlett-Packard HP 4195 Network Analyzer. To make the measurements, the magnetic field intensity H_{z0}, as recorded by the reception loop in the absence of the composite sample, was measured and stored in memory. The sample was the brought in contact with the sample, the field H_z measured over the same range of frequency, and then the shielding effectiveness $SE_m = 20\ log|S|$ computed.

It was found that the experimental setup worked well over the frequency range from 50 Hz to 50 MHz. The upper frequency is limited by resonances in the cables and loops and the lower frequency is limited by a low signal-to-noise ratio. This frequency range allows samples having Z_s in the range of a few $\mu\Omega$/square to a few Ω/square to be measured.

B. Dual TEM Cell Technique

1) Theory of the Dual TEM Cell Method: The dual TEM cell technique has been developed and the theory has been described by Wilson and Ma [2], [8]. In this method, two TEM cells are coupled by a common aperture. Measurements of the penetration of the EM fields from the driven (lower) cell into the receiving (upper) cell are made. Insertion loss measurements are made by comparing the results when the aperture is loaded with a composite sample with results for the open (unloaded) aperture. Provided the aperture dimension is small compared to the wavelength used, small aperture theory can be used and the penetration of the EM fields into the upper cell treated in terms of the equivalent electric and magnetic polarizabilities of the aperture. The output of the cell in the forward direction is related to the sum of the electric and magnetic polarizabilities and in the backward direction, to the difference. Expressions [8] for the forward and backward insertion losses (defined as the ratio of the transmitted power with the material in place to that of an open aperture) are given as follows:

$$IL_{\text{forward}} = 20\ \log \left| \frac{\alpha_{ey} + \alpha_{mx}}{\tilde{\alpha}_{ey} + \tilde{\alpha}_{mx}} \right| \tag{6}$$

and

$$IL_{\text{backward}} = 20\ \log \left| \frac{\alpha_{ey} - \alpha_{mx}}{\tilde{\alpha}_{ey} - \tilde{\alpha}_{mx}} \right| \tag{7}$$

where α_{ey} and α_{mx} are the electric and magnetic polarizabilities of the open aperture and $\tilde{\alpha}_{ey}$ and $\tilde{\alpha}_{mx}$ are the electric and magnetic polarizabilities of the loaded aperture.

Experimentally [13], it is possible to separate the electric and magnetic properties of the material by adding or subtracting the two outputs of the receiving cell which gives

$$IL_e = 20\ \log \left| \frac{\alpha_{ey}}{\tilde{\alpha}_{ey}} \right| \tag{8}$$

and

$$IL_m = 20\ \log \left| \frac{\alpha_{mx}}{\tilde{\alpha}_{mx}} \right|. \tag{9}$$

The polarizability for a circular aperture loaded with a conductive sheet has been derived by Casey [14]. For a loaded circular aperture of radius a, Casey has shown that the magnetic insertion is given by

$$IL_m = 20\ log \left| 1 + j\ \frac{f}{f_c} \right| \tag{10}$$

where

$$f_c = \frac{3Z_s}{8\mu_0 a}\left(1 + \frac{R_c}{aZ_s}\right) \cong \frac{3Z_s}{8\mu_0 a} \quad \text{for } R_c \text{ small.} \tag{11}$$

In (11), R_c is the contact resistance between the sample and the body of the TEM cell. As discussed in Section II-C, steps were taken to ensure that was small when making measurements.

Equation (11) was used to estimate the surface impedance of the composite samples by choosing the radius a so that the area of the circular aperture was equivalent to the square aperture of

TABLE I
f_c AND Z_s VALUES OBTAINED BY THE NONCONTACT PROBE METHOD

Sample	f_c (MHz)	Z_s (mΩ/square)
AS4/8/ ±45°	0.50	49.4
AS4/8/0, ±45, 90°	0.56	55.3
AS4/4/0, 90, 90, 0°	1.15	113.5
AS4/8/0°	-	-

the TEM cell. This approximation is not expected to introduce a large error as the polarizability is not very sensitive to shape. For example, the work of Wilson and Ma [8] has shown that the polarizability of a square aperture only differs by about 7% from a circular aperture with the same area.

2) Experimental Setup: Measurements of the magnetic insertion of the composite samples have been made using a dual TEM cell having a square 15.5-cm aperture. Measurements of the magnetic loss of the materials were made over the frequency range from 0.3 to 500 MHz using a Hewlett Packard HP8753B Network Analyzer. Output data from both ends of the receiving TEM cell were collected using a computer and subtracted numerically to obtain the magnetic shielding effectiveness. The magnetic insertion loss was obtained by dividing the shielding effectiveness data for the open aperture by the corresponding results for the aperture loaded with the composite sample [see (9)].

C. Sample Preparation

The composite materials used in these studies were made from unidirectional prepreg of carbon (AS-4) and boron fibers in an epoxy matrix. The 18-cm-square samples were prepared [15] by laminating four or eight plies together using standard composites autoclaving procedures. In some cases, the unidirectional plies were aligned, while in others they were arranged at different orientations in various stacking sequences (e.g., 0°, ±45°, 90°). The thickness of the samples varied from 7.6 × 10^{-2} cm to 1.5 × 10^{-1} cm. To ensure that the sample thickness is small compared to the skin depth of the sample so that the theory developed in Section II-A can be used, it is necessary [9] that $a \gg 1.4d$. This is clearly the case with the TEM cell and samples that have been used.

In order to obtain a proper measurement of the shielding properties of these composite samples, good electrical contact must exist between the sample and the body of the TEM cell used to make the measurements. To achieve this, the edges of all of the samples were copper plated. The use of finger stock and application of pressure to top of the upper cell ensured good electrical contact between the two cells.

III. RESULTS AND DISCUSSION

A. Surface Impedance Measurements Using the Noncontact Probe Method

Experimental results for the shielding effectiveness of an eight-ply AS-4 composite sample having a ±45° (pseudo-isotropic) layup are included in Fig. 4. Note that the curve flattens at high frequencies to a value between −20 and −25 dB. This flattening, which is a result of the S_1 term in (3), results from the fact that the distance h between the reception antenna and the sample cannot be made equal to zero because of the dielectric coating that is used to insulate the antenna and the finite thickness of the composite sample. Note also that the maximum slope of the curve is greater than −20 dB/decade. To determine the cutoff frequency f_c from the experimental curves, a straight line having −20 dB slope was extended from the mid point of the curve to determine the frequency at the 0 dB intercept. The validity of this approach is confirmed by results presented by Gobin [9] who made a detailed study of the effect of the distance of the reception loop from the surface of the sample on the shape of the shielding effectiveness curves. Gobin's results show that the procedure used to determine f_c should give accurate results.

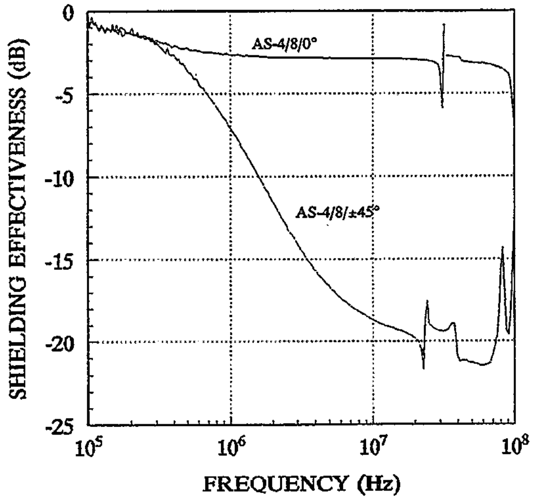

Fig. 4. Noncontact probe shielding effectiveness curves: eight-ply AS-4 samples.

By extrapolating back to 0 dB as described, a value for f_c of 5.2 × 10^5 Hz is obtained which, from (5), corresponds to a surface impedance of 49 mΩ/square. Using the same procedure, the surface impedance of an eight-ply AS-4 composite sample having a zero ±45, 90° lay up and a four-ply AS-4 composite sample having a 0, 90, 90, 0° lay up was measured. The results of these measurements are included in Table I.

An attempt was also made to measure the surface impedance of an eight-ply unidirectional AS-4 composite sample. The SE results obtained are included in Fig. 4. In this case, the sample offers only minimal (less that −3 dB) shielding over the entire frequency range examined. This poor shielding is the result of the unidirectional nature of the conductivity of this sample. Apparently, the fibers or fiber bundles are insulated from each other by the epoxy matrix so that the conductivity normal to the fiber direction is very low. Because the shielding

TABLE II
f_c AND Z_s VALUES OBTAINED BY THE DUAL TEM CELL METHOD

Sample	f_c (MHz)	Z_s (mΩ/square) measured	Z_s (mΩ/square) calculated
AS4/8/0°	0.10	29.3	-
AS4/8/ ±45°	0.19	55.7	58.6
AS4, Glass/2, 6/0°	0.35	102.	117.2
AS4/4/0, 90, 90, 0°	0.40	117.	117.2
Boron/8/0°	1.20	351.	-

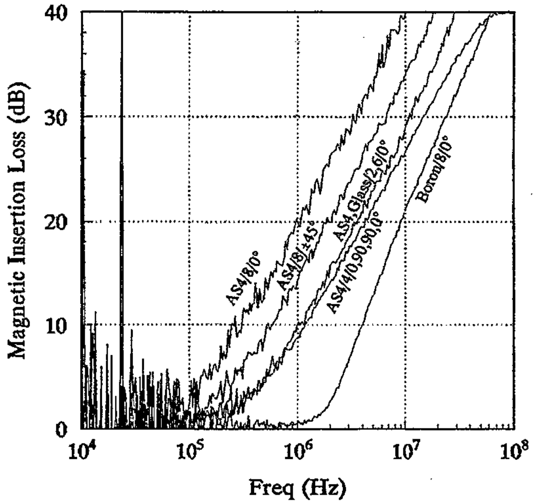

Fig. 5. TEM cell insertion loss measurements: AS-4 samples.

of the normal component of the magnetic field depends on a circular flow of current in the sample, the shielding provided by the unidirectional samples is poor and it is not possible to determine the surface impedance of these materials using the noncontact probe method.

B. Surface Impedance Measurements Using the Dual TEM Cell Method

The experimental results for the magnetic insertion loss of five composite samples are shown in Fig. 5. To obtain the cutoff frequency f_c from the experimental curves a straight line having a 20-dB slope was extended back from the curve to obtain the frequency at the 0 dB intercept. The results from this extrapolation are given in Table II. The surface impedance values, also included in Table II, were obtained from the measured cutoff frequencies using (11).

The experimental results can be compared with those obtained from a simple electrical model [16] of the composite materials that assumes:

1) that the individual plies are electrically connected in parallel;
2) that for a ply oriented at an angle θ to the direction of propagation (and current flow) in the TEM cell, the impedance of the single ply is given by $Z_s^1(\theta) = \cos^2\theta \times Z_s^1(0)$; the $\cos^2(\theta)$ term arises because the decrease in fiber number needs to be considered as well as decomposition of the current flow into parallel and perpendicular components.

The results from the simple electrical model outlined above (as applied to the AS-4 samples) are included in Table II. To obtain these results a single-ply AS-4 surface impedance of 234.4 mΩ has been used. This value was obtained from the experimental of the eight-ply unidirectional AS-4 sample assuming the plies to be connected in parallel. The agreement between the measured results and the model is good. This indicates that the contact impedance between the TEM cell and the sample is small compared to the surface impedance of the sample.

It is interesting to compare the results for the unidirectional eight-ply AS4 sample when the fibers are oriented parallel and perpendicular to the direction of current flow in the cell. The results show that the impedance is very high (~44Ω/square) for the perpendicular orientation. As noted earlier, this indicates that the fibers or fiber bundles are insulated from each other by the epoxy matrix so that the conductivity normal to the fiber direction is very low. The surface impedance is only 29 mΩ/square when the fibers are oriented parallel to the direction of current flow.

C. Comparison of the Noncontact Probe and TEM Cell Results

In comparing the surface impedance results obtained using the noncontact probe method and the dual TEM cell method, it is important to understand that different processes are involved in the two measurements. As outlined earlier, the noncontact probe measurement relies on the measurement of the normal component of the magnetic field in the absence and presence of the sample. Shielding is provided by the sample as a result of the circular flow of current induced in the sample as a result of the normal component of the magnetic field. By contrast, the dual TEM cell method relies on the comparison of the attenuation of the tangential component of the magnetic field with and without the sample present. The tangential field in the cell induces a laminar flow of current in the sample.

The fact that good shielding of the normal component of the magnetic field is obtained in pseudo-isotropic but not in unidirectional samples provides some insight into the structure of these materials. It is apparent that in the pseudo-isotropic samples, manufacture of the samples presses the plies together so that adjacent plies are in good electrical contact so that a circular flow of current is possible. In unidirectional samples, adjacent fibers are apparently insulated by a layer of epoxy, thus preventing a circular flow of current.

Comparison of the surface impedances obtained by the two methods is interesting. If the eight-ply sample having a ±45° lay up is considered, then in order to obtain a circular flow of current, the current must alternately flow between plies in order to complete a circular (or square) loop. On this basis, one can estimate that the surface impedance of a pseudo-isotropic eight-ply sample should be about the same as that measured on a four-ply unidirectional sample in the dual TEM cell. Using the single ply value of 234.4 mΩ obtained from the TEM cell measurements, then the surface impedance measured using the noncontact probe method on eight- and four-ply pseudo-isotropic samples is estimated to be 58.6 and 117.2 mΩ/square, respectively. These values are in good agreement with values presented in Table I.

IV. CONCLUSIONS

The work presented in this paper shows that the results obtained for the surface impedance using the dual TEM and noncontact probe techniques are in substantial agreement if the composite samples are pseudo-isotropic. Because the two techniques induce a different flow of current (circular in the case of the noncontact probe method and laminar in the case of the dual TEM method), very different results are obtained for anisotropic (unidirectional) samples.

Comparison of the results from the two methods has shed light on the structure of these composite materials. In particular, in a unidirectional sample, the epoxy matrix is apparently extruded between the fibers or fiber bundles so that the conductivity normal to the fiber direction is poor. In a multidirectional laminate, on the other hand, the fibers in adjacent plies are pressed together so that they are in good electrical contact allowing a circular flow of current and, hence, shielding of a magnetic field normal to the surface to occur.

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