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TITLE

ELECTROMAGNETIC SHIELDING PROPERTIES OF COMPOSITE MATERIALS

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ELECTROMAGNETIC SHIELDING PROPERTIES OF COMPOSITE MATERIALS

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1. SUMMARY

In order to ensure that composite structures have adequate electromagnetic (EM) shielding, a knowledge of the EM properties of anisotropic laminated materials is necessary. In this paper, we provide an overview of work we have carried out to measure the intrinsic EM shielding properties of carbon and non-carbon epoxy laminates. These experimental results are compared with numerical results that have been calculated using the Method of Moments. Finally, results showing the effect of repair of carbon/epoxy composites on shielding properties are presented.

KEYWORDS: Electromagnetic Shielding; Composite Materials;Electric/Magnetic;Carbon/Hybrid/Non-carbon; Repair

2. INTRODUCTION

Composite materials are being used increasingly by the designers of military aircraft, ships and land vehicles. As an example, Figure 1 shows the use of carbon/epoxy composites in the CF-18 aircraft that is in service in the Canadian Forces. Traditionally, the use of composites for the construction of aircraft has been driven by the superior specific strength and stiffness of these materials which allows a significant reduction in weight. More recently, other factors such as the ease of shaping composites has led to their use for the minimization of radar cross-section (RCS). Table 1 gives values of RCS for various aircraft taken from the literature. The reduction of RCS is dramatic.

There is also increasing interest in the use of composites for the construction of ship superstructures. Some of the benefits of the use of composites for this application include: improved stability through a reduction in topside weight; reduced maintenance costs; reduced RCS; and superior fire containment. The use of composites for land vehicles offers improved mobility as a result of weight reduction and improved personnel protection from shells.

3. ELECTROMAGNETIC PROPERTIES OF COMPOSITE MATERIALS

In the previous section, some of the advantages of composite materials, that are leading to an increased use of these materials in military vehicles, have been described. In almost all cases, however, successful operation of these vehicles depends on the reliable operation of sophisticated systems for flight control, navigation, self-defence and fire control. Protection of these systems from the severe electromagnetic environment, including high power microwaves (HPM), that can be encountered is a necessity. The increasing susceptibility of modern microelectronic systems to electromagnetic interference (EMI) makes the job of providing adequate electromagnetic (EM) protection all the more difficult.

To ensure adequate EM shielding, a knowledge of the EM properties of composite materials is necessary. Table 2 provides a summary of some of the electromagnetic properties of composite materials. The conductivity of most of the commonly used reinforcements is poor compared to most metals. Even graphite has a conductivity 2 or 3 orders of magnitude lower than commonly used metals as is seen in Table 2. Other reinforcements such as glass and aramid are

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TABLE 1 - AIRCRAFT RADAR SIGNATURES

TARGET	RADAR CROSS SECTION (M^2)
JUMBO JET	100.0
B-52 BOMBER	10.0
LARGE FIGHTERS	5-6
SMALL FIGHTERS	2-3
B-1B BOMBER	1.0
MAN	1.0
F-117A STEALTH FIGHTER	0.1
B-2 STEALTH BOMBER	0.01
SMALL BIRD	0.01
SOURCE: SAMPE Journal, 27, 4 (1991)	

TABLE 2 - EM PROPERTIES OF COMPOSITE MATERIALS

1. EM SHIELDING EFFECTIVENESS IS NOT AS GOOD AS METALS

CONDUCTIVITY	- COPPER	- $5.8 \cdot 10^7$ MHO/M
	- ALUMINUM	- $3.5 \cdot 10^7$
	- STEEL	- $1.0 \cdot 10^7$
	- GRAPHITE	- $7.0 \cdot 10^4$
	- GLASS	- $1.0 \cdot 10^{-12}$

2. ELECTRICAL BONDING OF COMPOSITES IS DIFFICULT

   CORROSION PROBLEMS

3. DIFFICULT TO MAINTAIN EM SHIELDING DURING REPAIR

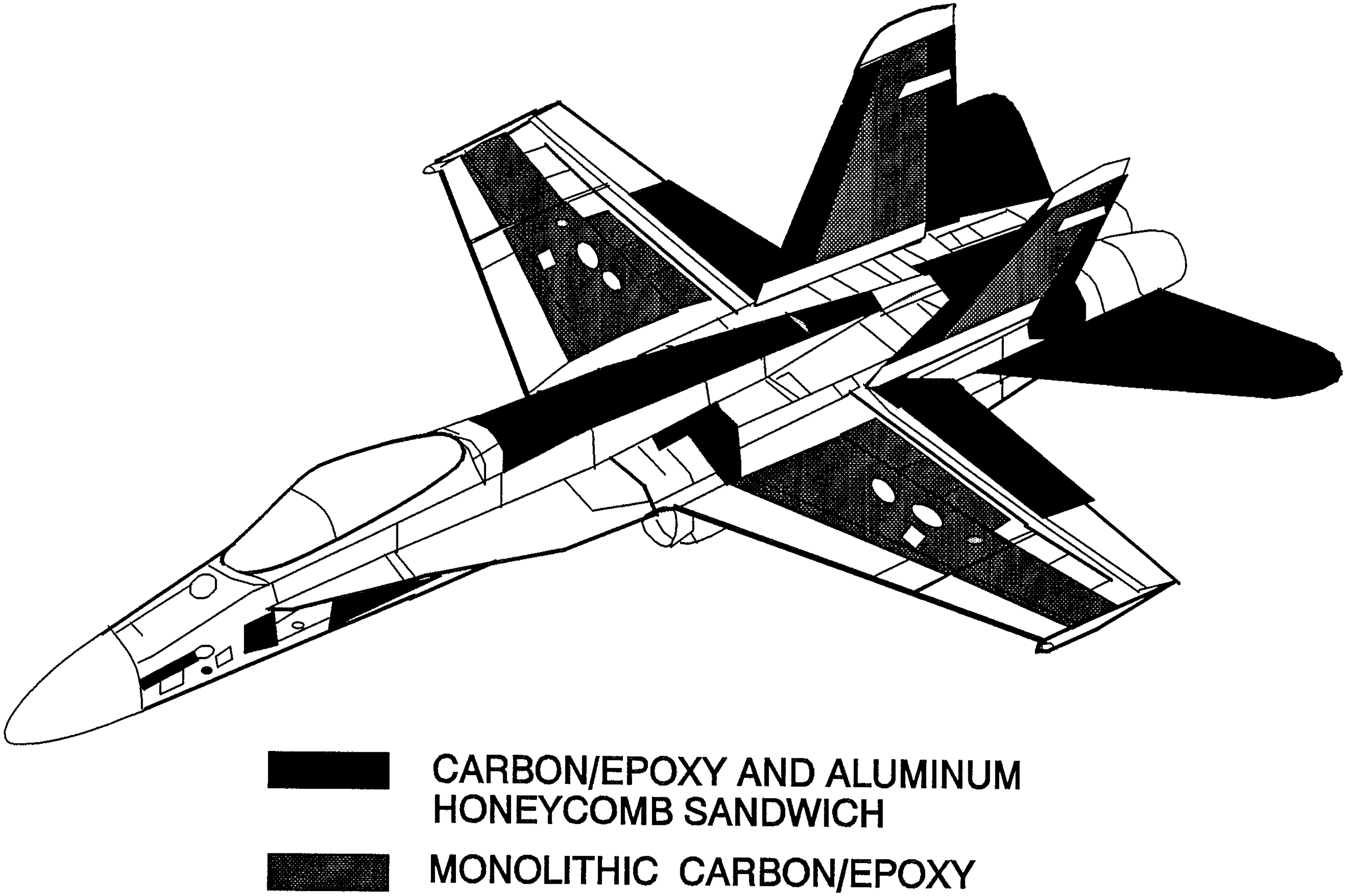

Figure 1 - Use of Composites in the CF-18

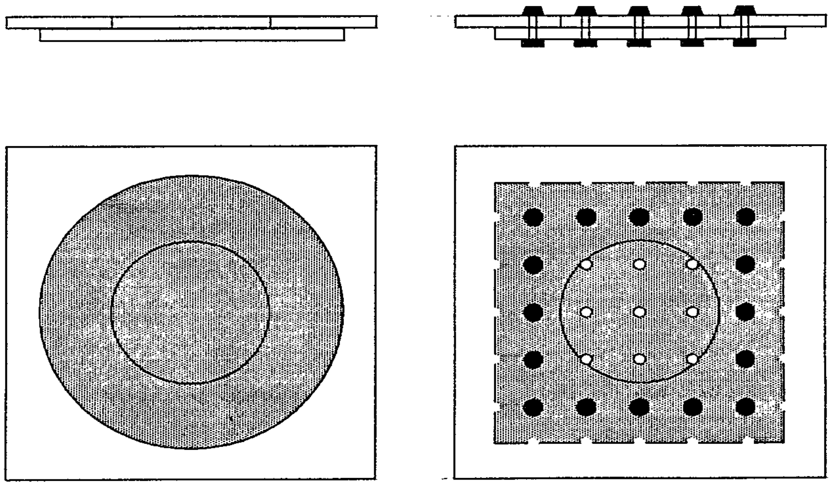

Figure 2 - Methods of Repair. Left-Bonded Epoxy Patch. Right-Bolted Patch

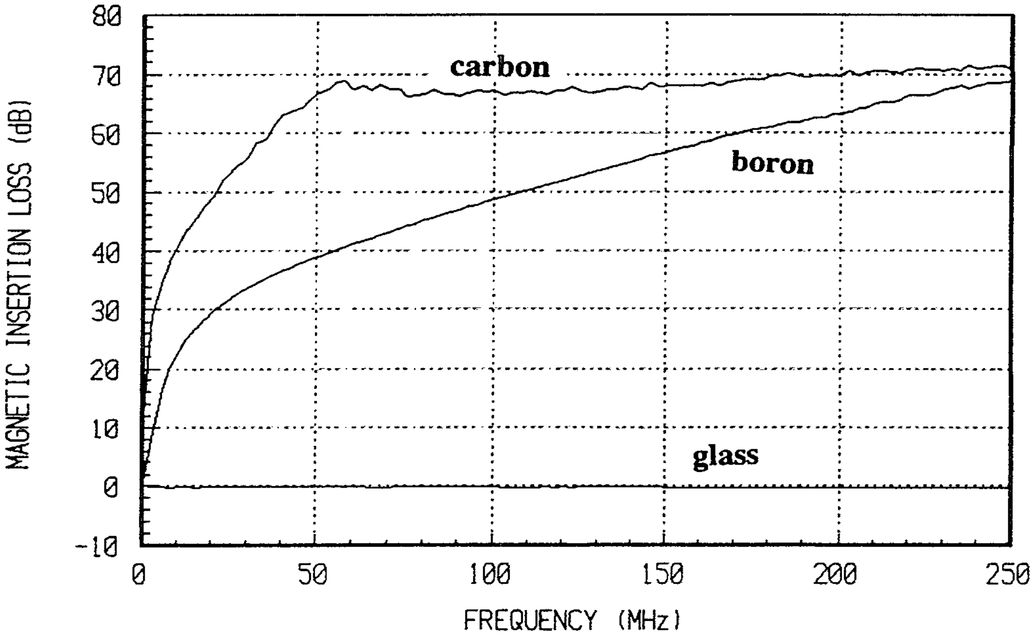

Figure 3 - Effect of Fibre Conductivity on Magnetic Insertion Loss

non-conductive. Because of their limited conductivity, structures made from composite materials generally have poorer EM shielding when compared to metallic structures. For many military applications, it is therefore necessary to either incorporate one or more conductive layers within a laminate or to apply a metal coating to the surface.

EM shielding requirements can also influence the design, construction and life cycle maintenance of composite structures. The need to ensure continuity of conductive pathways wherever composite panels are joined together or connected to adjacent metallic structure can add considerably to the cost and complexity of fabrication. This is especially true where galvanic corrosion concerns would dictate that no electrical contact should exist. Corrosion in fact poses a double threat, reducing the life of the metal components present and slowly degrading the EM shielding by increasing the electrical resistance of the joints. Standard structural repair methods may also have to be modified to ensure electrical continuity between a bonded or bolted patch and the structure itself.

In the following section, we give an overview of the work we have done to measure the intrinsic EM shielding properties of epoxy matrix composite laminates as well as experiments to study the effect of repair on EM shielding. Parts of this work have been published earlier [1,2].

4. EXPERIMENTAL

Measurement Technique

Measurements of the shielding properties of composite materials have been made using a dual transverse electromagnetic (TEM) cell, as described by Wilson and Ma [3]. In this method, two TEM cells are coupled by a common aperture. Measurements are made of the penetration of the EM fields from the driven (lower) cell into the receiving (upper) cell. 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.

The theory of the dual TEM cell has been developed by Wilson and Ma [3,4]. 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 backwards direction, to the difference. Expressions [3] 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 below.

$$\mathrm{IL}_{\mathrm{forward}} = 20\log\left|\frac{\alpha_{ey}+\alpha_{mx}}{\tilde{\alpha}_{ey}+\tilde{\alpha}_{mx}}\right| \qquad (1)$$

and

$$\mathrm{IL}_{\mathrm{backwards}} = 20\log\left|\frac{\alpha_{ey}-\alpha_{mx}}{\tilde{\alpha}_{ey}-\tilde{\alpha}_{mx}}\right| \qquad (2)$$

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, [5] 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;

$$\mathrm{IL}_{e} = 20\log\left|\frac{\alpha_{ey}}{\tilde{\alpha}_{ey}}\right| \qquad (3)$$

and

$$\mathrm{IL}_{m} = 20\log\left|\frac{\alpha_{mx}}{\tilde{\alpha}_{mx}}\right| \qquad (4)$$

Measurements of the magnetic and electric insertion 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 numerically combined to give either the sum or difference signals.

Sample Preparation

The composite materials used in these studies were made from unidirectional pre-preg of carbon, glass, aramid and boron fibres in an epoxy matrix. The 18 cm square samples were prepared [1] by laminating six 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 (eg 0°,±45°,90°). Thoughout this paper, fibre orientations are designated with respect to the direction of propagation of the EM waves in the TEM cell.

The degradation in the EM shielding properties of carbon/epoxy components caused by typical structural repairs was investigated to the extent that the geometric constraints imposed by the TEM cell would allow. Thus while it was not possible to study honeycomb sandwich panels typical of the avionics doors on the CF-18, for example, the same repair materials and procedures normally used for these components were applied to the test samples. Eight ply quasi-isotropic laminates of AS4/3501-6 carbon/epoxy containing a 75 mm diameter hole in the centre were repaired using two different methods. In two of the repairs, 152 mm circular patches of either 6 ply (0°,±60°) carbon/epoxy or titanium (Ti-6Al-4V) were adhesively bonded over the hole on one side of the sample using FM-300 epoxy film adhesive from American Cyanamid. The third repair involved a rapid repair technique in which sixteen 7mm diameter blind fasteners were used to attach a thick aluminum patch, drilled with a square array of 7 mm holes equally spaced at 25 mm, to one side of the laminate. These two methods of repair are illustrated in Figure 2.

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.

Experimental Measurements

While measurements were made of both the magnetic and electric insertion losses for all of the samples examined, in the discussion that follows we only discuss the magnetic shielding properties. The reason for this is that the provision of adequate magnetic shielding at low frequencies is normally of most concern.

Effect of Fibre Type on Magnetic Insertion Loss

The effect of fibre type on the magnetic shielding properties of a number of different materials is shown in Figure 3. The carbon/epoxy laminates provide high levels (>60 dB) of shielding for frequencies above 50 MHz. As anticipated, the glass/epoxy laminate provides essentially no shielding as it is non-conducting. The boron/epoxy laminate on the other hand provides an intermediate degree of shielding.

The dependence of the magnetic insertion loss on frequency and fibre conductivity (Figure 3) is in accordance with theory developed by Casey [6] and Latham and Lee [7].

Effect of Fibre Orientation on Insertion Loss

Fibre orientation has a major influence on magnetic shielding, as seen in Figure 4, which shows the magnetic insertion loss of AS-4 carbon/epoxy laminate having fibres oriented unidirectionally at 0°, 30°, 45°, 60° and 90° to the direction of propagation of the EM wave. Above 60 MHz, the insertion loss measurements for the 0° sample are influenced by the limited dynamic range of the network analyzer which results in a flattening of the 0° curve above this frequency.

Qualitatively these results relate directly to the anisotropic conductivity of the composite laminate. The conductivity is greatest along the fibres and, hence, when they are oriented at 0°, there is very little interruption of the current flow along the body of the cell and shielding is high. By comparison, the conductivity transverse to the fibres is lowest leading to poor shielding when the fibres are oriented at 90°.

Effect of Repair on Magnetic Insertion Loss

Figure 5 shows the magnetic insertion loss of a carbon/epoxy laminate with a 75 mm diameter hole that has been repaired with a bonded carbon/epoxy patch. Also included in this figure are the results for a complete carbon/epoxy laminate and the same laminate with an unfilled 75 mm dia. hole. From these results it is seen that the repaired laminate offers considerably poorer shielding than the undamaged laminate, especially at high frequencies where the difference can be as high as 40 dB. In the application of the bonded patch, no effort is made to electrically connect the graphite fibres in the patch to those in the bulk material. It is interesting therefore that the patch still provides 10 to 20 dB additional shielding over almost all of the frequency range (0.3 - 500 MHz). There is sufficient capacitive coupling apparently between the carbon/epoxy laminate and the patch to allow some current to flow through the patch. This suggestion is supported by the observation that the amount of shielding that the patch provides depends (Figure 6) on the orientation of the patch in the aperture of the dual TEM cell. The shielding provided by the patch is better when the fibres in the upper layer of the carbon/epoxy laminate next to the patch are oriented so that current can flow through this layer (i.e. parallel to the direction of propagation in the TEM cell).

A comparison of the magnetic insertion loss of the three patch types is given in Figure 7. The shielding provided by the bonded carbon and titanium patches is very similar. The bolted patch, on the other hand, provides

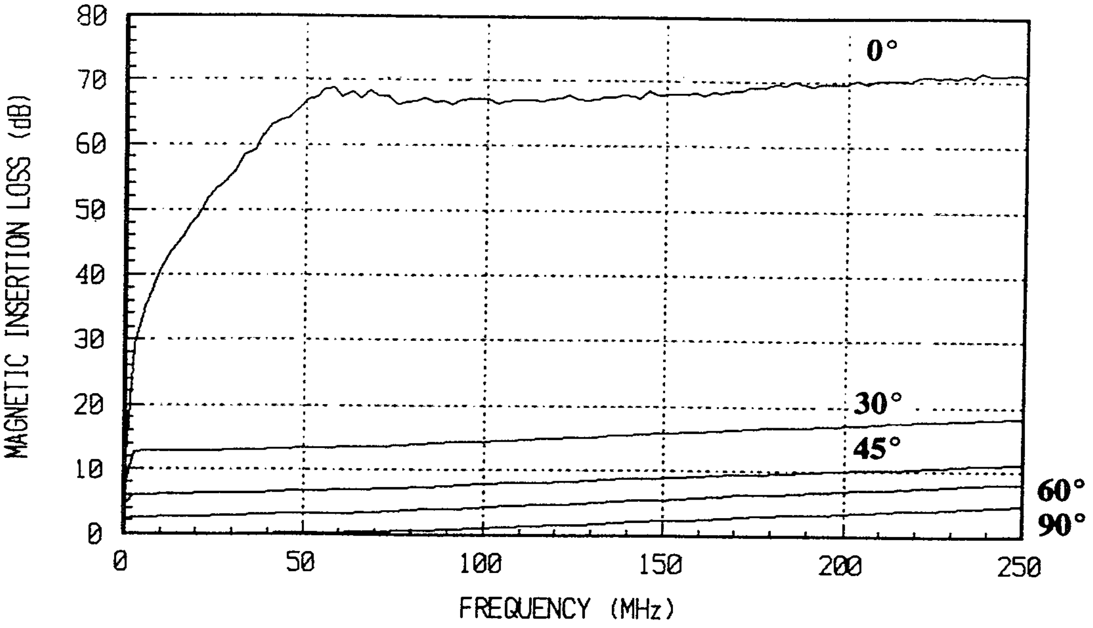

Figure 4 - Effect of Fibre Orientation on Magnetic Insertion Loss

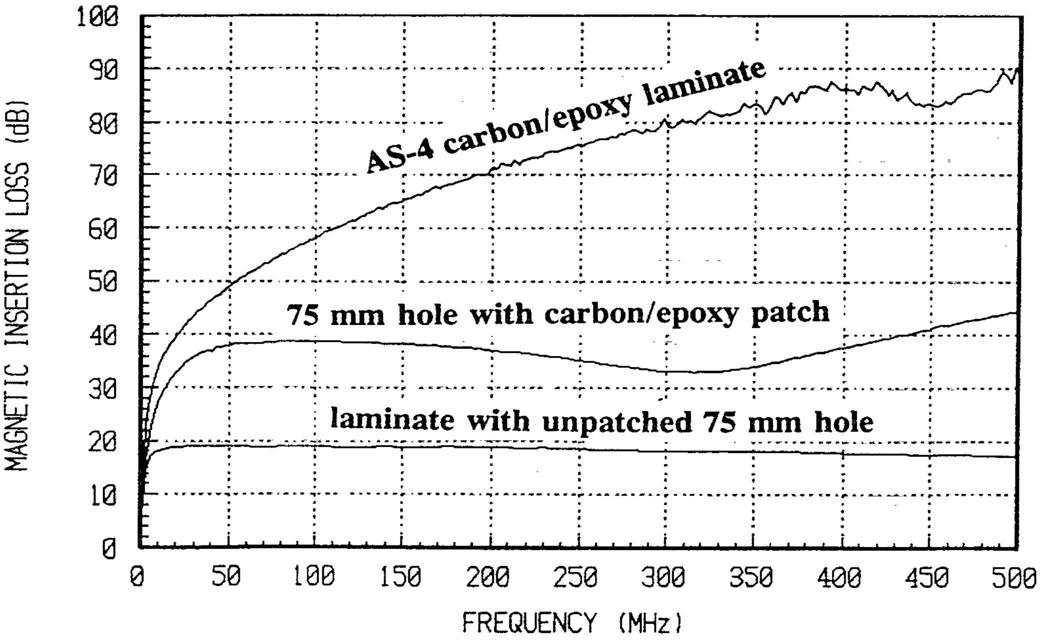

Figure 5 - Effect of Repair on Magnetic Shielding: Carbon/Epoxy Patch

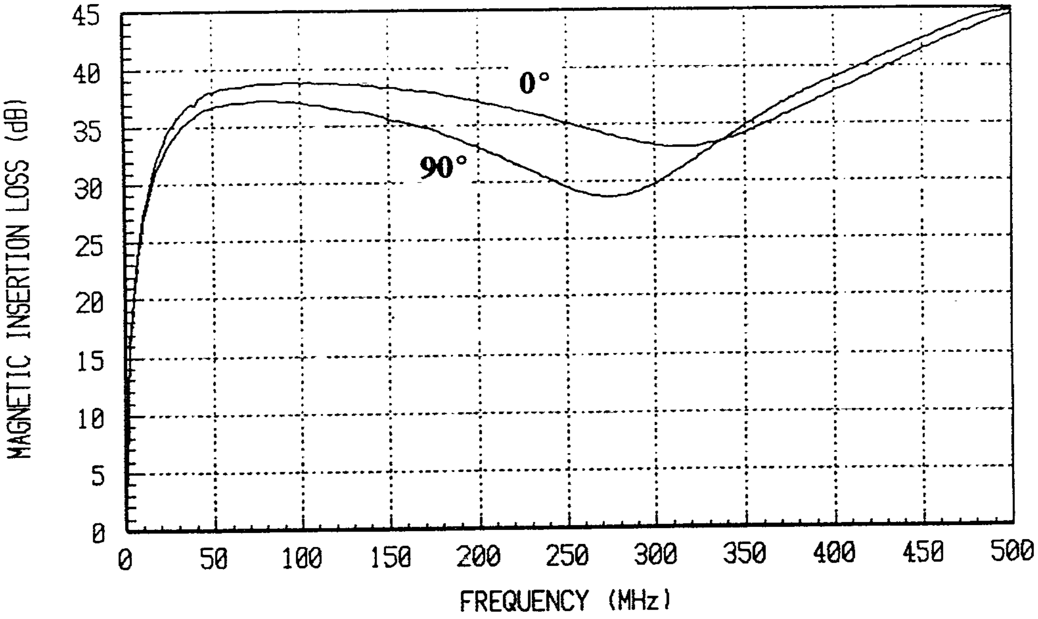

Figure 6 - Effect of Sample Orientation on Magnetic Shielding

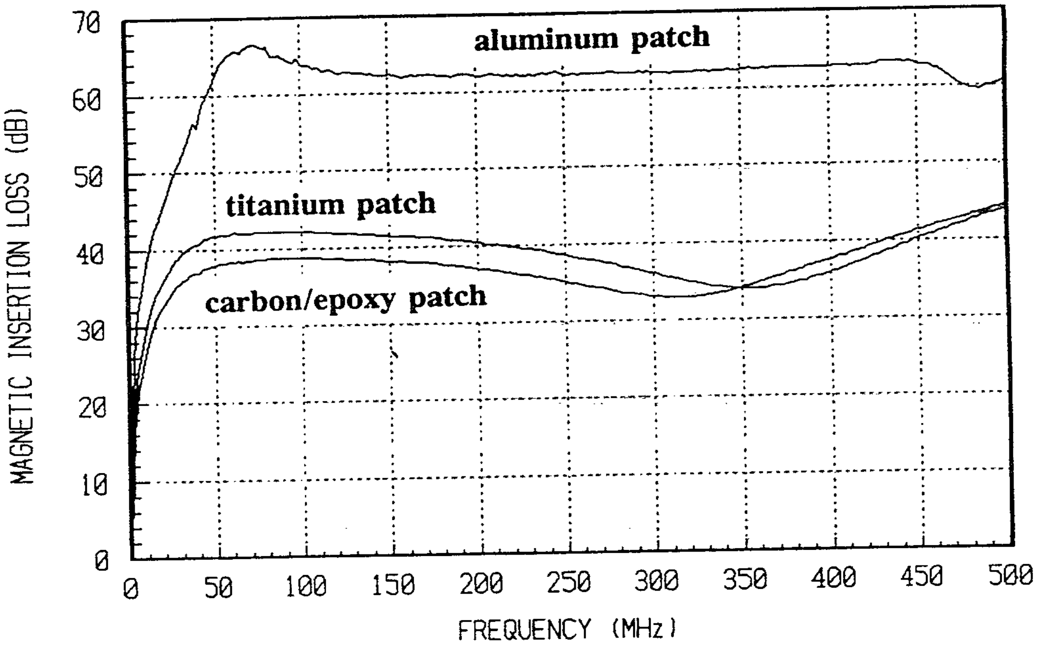

Figure 7 - Effect of Patch Type on Magnetic Shielding

considerably greater shielding. With the bolted patch, electrical contact between the carbon fibres in the carbon/epoxy laminate and the aluminum patch is provided by the bolts. Presumably the shielding would be even higher if the aluminum patch did not contain the 7 mm bolt holes.

5. NUMERICAL CALCULATIONS

In this section, results of numerical studies to calculate the shielding properties of conductive materials are presented and the results compared with experiment. The calculation of the extent of EM penetration through the TEM cell aperture when it is loaded with a composite sample can be best accomplished [8,9] through the calculation of the equivalent magnetic surface currents, $\vec{M}_s$, that exist over the surface of the aperture. For small apertures, it can be shown that the equivalent magnetic and electric dipole moments (and polarizabilities) are related to the irrotational and solenoidal components of $\vec{M}_s$ respectively.

Isotropic Resistive Material

For an isotropic, resistive material, the integral equations that need to be solved for the irrotational and solenoidal components of $\vec{M}_s$ are the following.

$$\frac{j\omega}{k^2}[\nabla_s \nabla_s \cdot \vec{F}_I + k^2 \vec{F}_I] + \frac{\sigma_s}{2}\vec{M}_{s,I} = \vec{H}^i_{t,I} \qquad (5)$$

and

$$j\omega \vec{F}_R + \frac{\sigma_s}{2}\vec{M}_{s,R} = \vec{H}^i_{t,R} \qquad (6)$$

where $\vec{F}_I$ and $\vec{F}_R$ are the irrotational and solenoidal components of the electric vector potential defined by

$$\vec{F}_{I,R} = \frac{\epsilon}{4\pi}\iint_A \frac{\vec{M}_{I,R}\, e^{-jk|\vec{r}-\vec{r}'|}}{|\vec{r} - \vec{r}'|} \qquad (7)$$

and $\vec{H}^i_{t,I}$ and $\vec{H}^i_{t,R}$ are the irrotational and solenoidal components of the tangential component of the incident magnetic field.

These equations have been solved using the Method of Moments to determine $\vec{M}_s$ for both the open ($\sigma_s = 0$) and loaded apertures. Once $\vec{M}_s$ is known, the electric and magnetic dipole moments of the open and loaded apertures can be determined from the relationships [10].

$$\vec{p}_e = -\frac{\epsilon}{2}\iint_A \vec{r}' \times \vec{M}_s(\vec{r}')ds' \qquad (8)$$

and

$$\vec{p}_m = -\frac{1}{\omega\mu}\iint_A \vec{M}_s(r')ds' \qquad (9)$$

Figure 8 shows numerical results for the magnetic insertion loss of conductive films having a range of conductivities (in mho) as a function of frequency. These numerical results are in general agreement with the experimental measurements presented earlier (Figure 3) that show that the highly conductive reinforcements provide the highest magnetic shielding.

Anisotropic Resistive Materials

Modification of equation (5) for the case that the aperture is loaded with an anisotropic resistive material is straightforward. In this case the surface conductivity must be expressed in the form of a dyadic, $\bar{\bar{\sigma}}_s$. For composite materials having unidirectionally oriented fibres (eg. fibres oriented along the x-axis), the conductivity can also be considered to be unidirectional to a good approximation and the only non-zero component of the conductivity dyad is σ_{xx}.

Numerical results for the magnetic insertion loss of a unidirectional composite as a function of orientation is shown in Figure 9. These numerical results are in good agreement with the experimental results shown in Figure 4 that show that the magnetic shielding is greatest when the carbon fibres are oriented at 0° and that the shielding degrades rapidly when the fibres are turned from this orientation. Qualitatively, the shielding behaviour can be understood by noting that the unidirectional composite only shields the component of the magnetic field that is orthogonal to the fibre direction. A simple model for predicting the shielding of unidirectional and multi-directional composite materials was given in [1].

6. CONCLUSIONS

The dual TEM cell technique has been shown to be a valuable method to measure the magnetic and electric insertion loss of conductive materials. Fibre conductivity and fibre orientation were found to control the intrinsic EM shielding characteristics. While carbon fibres have resistivities approximately 3 orders of magnitude higher than good metallic conductors (Al, Cu and Ni), they do possess adequate conductivity to provide substantial

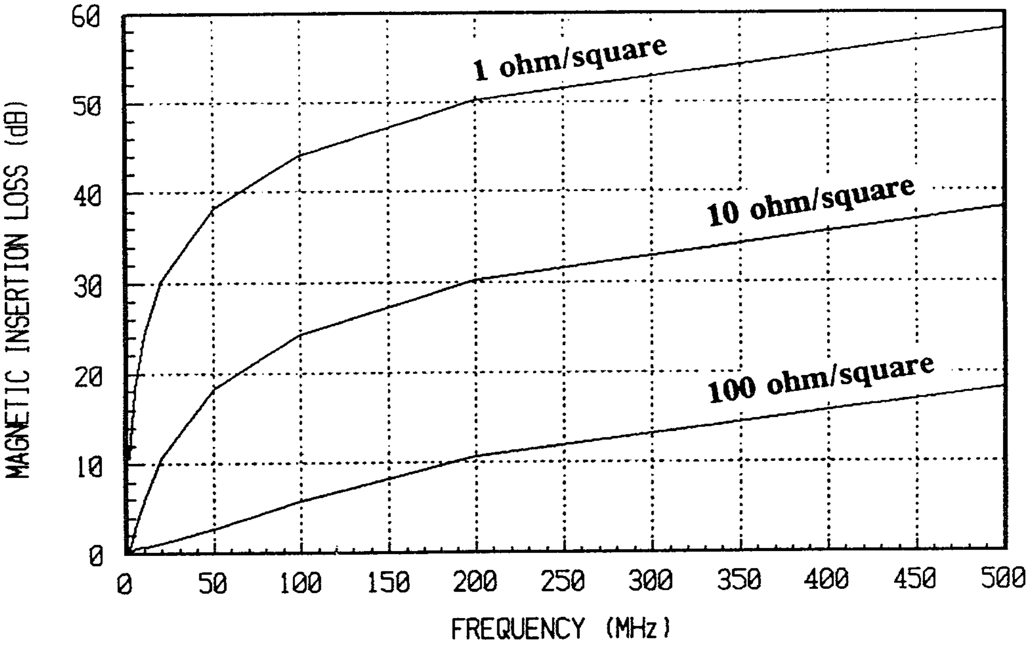

Figure 8 - Effect of Resistivity on Magnetic Insertion Loss

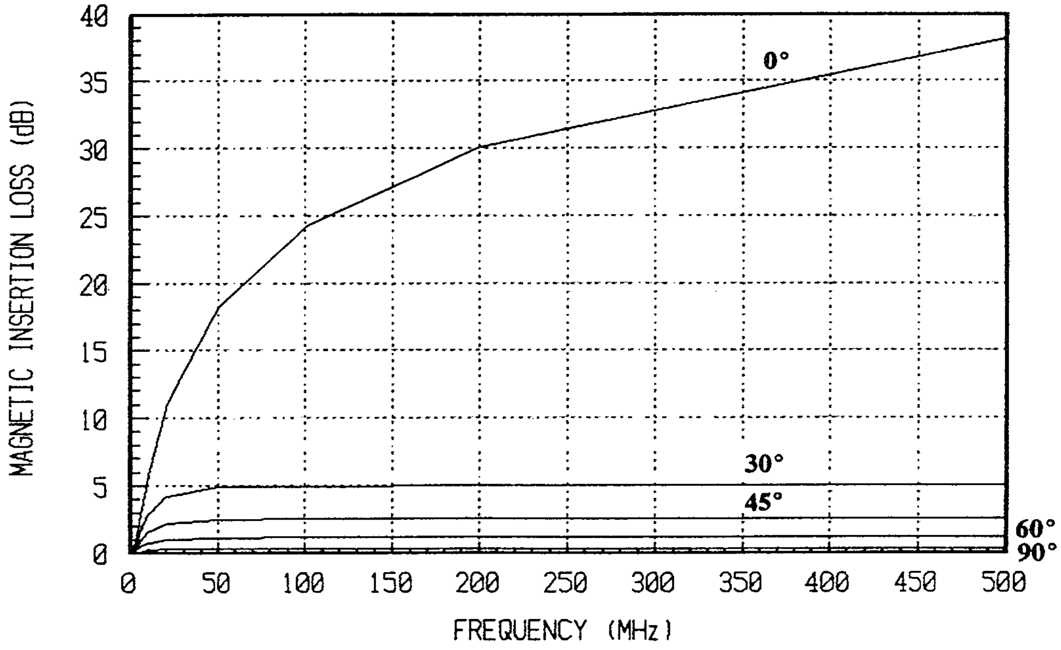

Figure 9 - Effect of Orientation on Magnetic Insertion Loss

shielding to structures made from carbon/epoxy composite materials. However, other common reinforcements such as aramid and glass fibres are incapable of providing adequate shielding unless mixed (hybridised) with carbon fibres.

Repair of composite structures using prescribed techniques for applying bonded patches can result in a substantial degradation of EM shielding. This results because electrical contact is lost between the conductive fibres in the bulk material and those in the patch.

Shielding properties calculated numerically using the Method of Moments are in general agreement with the experimental results presented.

7. ACKNOWLEDGEMENTS

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DISCUSSION

LABAUNE

In your work you consider that the magnetic polarizability of the aperture between the two TEM cell is a function of the conductivity of the sample under test. In fact the contact resistance between the sample and the cells is an important parameter. Have you taken it into account ?

AUTHOR'S REPLY

In carrying out our experiments, we have spent considerable effort to minimise the contact resistance to ensure that it did not influence the measured results. We have copper plated the edges of all of the samples to ensure a low resistance contact between the sample and the cell.