

On Electromagnetic Shielding in Composite Aircraft: An Applied Electromagnetic Approach

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ABSTRACT

Effectiveness of current electromagnetic shielding techniques in composite aircraft has been called into question several times before and is a subject of interest and research in the aerospace industry. We present an analytical approach to understand the issues in detail. It was found using first order approximations that a panel with Aluminum expanded metallic foil (ExMF) along with carbon fiber plies used on composite aircraft provides fair albeit lower electromagnetic shielding from source frequencies of a few KHz until well into MHz range when compared to an aluminum panel used on metallic aircraft.

This was primarily attributed to relatively large skin depth value at low frequencies which was due to: a) low electrical conductivity of aluminum ExMF when compared to bulk aluminum; b) low electrical conductivity of resin impregnated carbon fiber layers and; c) very thin layer of aluminum ExMF used.

It was also found that as source frequency goes higher (between 800 MHz to 18 GHz range), fields penetrate through the aluminum ExMF and although they may get attenuated by the CFRP plies however, shielding effectiveness at higher frequencies still remains lower for composite aircraft when compared to metallic aircraft.

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INTRODUCTION

This paper explores the issues related to the electromagnetic shielding of composite aircraft at present times.

Topics covering effects of electromagnetic sources at low frequency (3 KHz to 30 MHz) on aircraft as well as high frequency effects (800 MHz to 18 GHz) are presented with mathematical rigor to understand the issues analytically.

This paper details as to how and why the current electromagnetic shielding techniques fall short of an effective solution. Since the first step in developing a solution requires a detailed and clear understanding of the problem, a thorough understanding of the issues related to the electromagnetic shielding of the aircraft's structure and systems is necessary to research into possible solutions that would potentially provide cost effective as well as efficient shielding solution.

It must also be noted that the paper does not consider effects such as coupling through the windows as apertures since the goal of this paper is strictly to analyze the behavior of the E&M fields given the characteristics of the material used for

electromagnetic shielding in modern aircraft. The paper uses wave theory on composite and aluminum panels used in aircraft.

The current issue is divided into two main sections: Low Source Frequency related issues (indirect effects) from 3 KHz to 30 MHz and high source frequency related issues from 800 MHz to 18 GHz.

The paper concludes with a realization of the ineffectiveness of the current situation and a need for better techniques and materials that can provide adequate electromagnetic shielding with lightweight structures needed for fuel efficient and cost effective solutions.

1. LOW SOURCE FREQUENCY EFFECTS

Although lightning is modeled by instantaneous fields (transients), the frequency of these transients falls within the low section of the radio frequency spectrum approximately from 3 KHz to about 30 MHz.

This low source frequency effect experienced by the aircraft is broken down (typically) into **direct and indirect effects**. Direct effects relate to the damage caused at the “direct” lightning attachment points to the aircraft. Indirect effects relate to the “induced” effects which occur “in turn” due to the direct effects of lightning attachment to the aircraft. In this paper we are concerned with indirect effects.

1.1. Indirect Effects

Latest aircraft structures show more and more composite use due to the lightweight characteristic of the composite material when compared to metal which in turn amounts to fuel savings. However these composite structures in general are non-conductive or have low electrical conductivity compared to metal.

Current techniques for aircraft electromagnetic shielding allows for typically a few layers (2-10) of carbon-fiber resin impregnated plies (a.k.a. carbon-fiber reinforced polymer or CFRP) with an aluminum or aluminum mesh above these layers.

Resin is dielectric and carbon fiber is low conductive material when compared to copper or aluminum (more on this later). Latest techniques make use of “expanded metal foil” instead of metallic mesh. Expanded metal foil is a thin metallic foil with holes punched into it. It is more popular since mesh relies on contact between the wires for a better electrical conductivity. Expanded metal foil (ExMF) does not have the same issue. Aluminum ExMF is more popular since it does not have the same galvanic corrosion issues with carbon fiber as aluminum does. It must also be noted that aluminum ExMF is primarily used for protection against direct effects but at low frequencies it still provides for certain level of shielding effectiveness.

Although the technique explained above is the latest technique that is popular for protection against direct and indirect effects, it falls short of being effective since at low frequencies “skin depth” values are quite large.

One skin depth is the depth of penetration of electromagnetic fields at which the fields attenuate to approximately 37% of their original value while propagating in the material [1].

In order to elaborate on this, let us consider [figure 1](#) below.

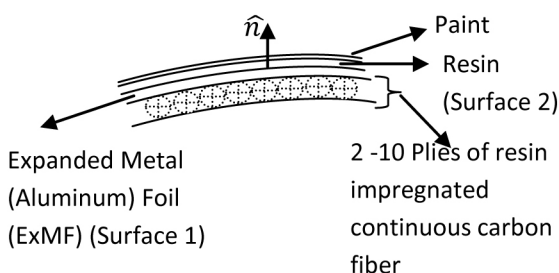


Figure 1. (Composite Panel Layup)

In [figure 1](#) above, the top surface is the paint, then resin, then ExMF and then 2 - 10 plies of CFRP. The honeycomb is ignored for simplicity that comes after the CFRP plies. In typical commercial aircraft, average thickness of ExMF (expanded metallic foil) ranges from 0.051mm to 0.381mm and each carbon fiber ply thickness typically range from 0.201mm to 0.421mm. We will use the average which is 0.3 mm for our calculations. These values will be used later on during analysis in this paper and are typical values in practice.

It has been reported [2] that electrical D.C. (direct current) surface resistance of a typical aluminum mesh (area weight of approximately 0.040 lb/ft²) is 0.6(mΩ/square).

Using the formula:

$$\sigma_{d.c.(elect.)} = (R_s \times t)^{-1} \text{ (Siemens/meter)} \quad (1)$$

In the equation above, $\sigma_{d.c.(elect.)}$ is the D.C. electrical conductivity in Siemens/meter, R_s is the electrical D.C. surface resistance in Ohms/square and t is the thickness of expanded metal foil (ExMF) in meters, one can calculate D.C. electrical conductivity given surface resistance and thickness of the conductive sheet. It must be noted that surface resistance value noted above assumes that the thickness of the material is such that this thickness should not exceed approximately half of value of the linear spacing between the adjacent two pins of the four point probe used to measure this surface resistance.

This is because the four point probe assumes that the thickness is “small enough” that a uniform current (D.C.) flows along the thickness of the material in the conductor. Expanded metal foils (ExMF) will have different characteristics (including electrical D.C. conductivity) due to their physical difference when compared to metallic mesh but for a first order approximation we shall assume that the electrical D.C. conductivity is the same for both of them.

Assuming the thickness of aluminum (ExMF) to be 0.0035” (0.089mm) thick, R_s to be 0.6 mΩ/square; we have from [equation \(1\)](#), $\sigma_{d.c.(elect.)}$ to be approximately 1.8×10^7 (Siemens/meter) which is relatively good when compared with the electrical conductivity of aluminum bulk material which is approximately 4×10^7 (S/m). However, this D.C. electrical conductivity depends on several factors in a mesh or expanded foil including metal mesh open area, overall thickness, mesh per inch (MPI: that is number of meshes along the so called “Short Way of Diamond” (SWD, refer to [figure 4](#)) direction) etc.

In fact surface resistance values of 0.3 mΩ/square (minimum) (corresponding to 0.381mm thickness) to 13 mΩ/square (maximum) (corresponding to 0.051mm thickness) are realistic values typically required of ExMF manufacturers and are used. These when used in [equation \(1\)](#) give values ranging from 0.15×10^7 (Siemens/meter) to 0.87×10^7 (Siemens/meter).

Therefore the reported value [2] of surface resistance of 0.6 mΩ/square requires very high MPI which is achievable but increases the overall weight of the aircraft and is not practically used.

For the purposes of our discussion, we will assume lowest value to be 0.15×10^7 (S/m) and highest value to be 0.87×10^7 (S/m).

Before using "skin depth" concept introduced before, it must be determined whether a material will behave as a good conductor or a good dielectric to the E&M fields at a certain frequency. Skin depth is different when a material behaves as a good conductor to when the material behaves as a good dielectric.

Since this behavior (conductor versus dielectric) is frequency dependent, it is important to discuss the concept of *Electric Loss Tangent* (ratio of magnitude of conduction current density to the displacement current density within a material) which specifies a material to be a good conductor or a good dielectric at a specific frequency and is given as:

$$l_e = \frac{(\sigma_e + \omega\epsilon'')}{\omega\epsilon'} \quad (2)$$

Where l_e is the electric loss tangent (no units), σ_e is the electrical D.C. conductivity (S/m), ω is the angular frequency, ϵ'' is the imaginary part of the complex permittivity (Farads/m), ϵ' is the real part of the complex permittivity (Farads/m). Here $\sigma_e + \omega\epsilon''$ in the numerator is known as conductivity loss in the medium, $\omega\epsilon'$ represents the part related to displacement current density in the material and comes from one of the well known point form of Maxwell's equations (Ampere's law, as follows) in time harmonic regime:

$$\nabla \times \vec{h} = \vec{j} + j\omega(\epsilon' - j\epsilon'')\vec{e} \quad (3)$$

Here $\vec{h}$ is the magnetic field intensity vector (Amperes/meter), $\vec{j}$ is the impressed and induced volume current density (A/m²), $\epsilon' - j\epsilon''$ is the complex permittivity as described in (2) and $\vec{e}$ is the electric field intensity vector (Volts/meter). $\vec{j}$ is a combination of impressed volume current density or the source current density represented by $\vec{j}_i$ and induced current density represented by $\vec{j}_c = \sigma_e \vec{e}$. Using these in (3) and rearranging we have:

$$\nabla \times \vec{h} = \vec{j}_i + j\omega\epsilon'(1 + \frac{(\sigma_e + \omega\epsilon'')}{j\omega\epsilon'})\vec{e} \quad (4)$$

The form of electric loss tangent in (2) can be clearly seen in (4). Therefore electric loss tangent is a direct consequence of the Ampere's law and since it is a ratio of magnitude of conduction current density to the displacement current density

within a material, the higher the value of conduction current density versus displacement current density, the better conductor a material is. Therefore, it follows obviously that for $l_e \gg 1$, a material is a good conductor and for $l_e \ll 1$, a material is a good dielectric. Returning back to equation (2), two things must be noted:

- In nature there is no complex permittivity, however when dealing with time harmonic fields, it is customary to represent the "time delay" between the polarization of a material and the external field by "phase delay" as $e^{j\phi}$ thereby introducing the complex permittivity.
- The real and imaginary part of complex permittivity themselves are functions of frequency and are related to each other by Kramers-Kronig relations [4] which is beyond the scope of this paper. However since we are dealing primarily with conductors, we will assume the imaginary part of complex permittivity is negligible compared to the D.C. losses, i.e.: $\sigma_e \gg \omega\epsilon''$, therefore, $\sigma_e + \omega\epsilon'' \approx \sigma_e$.

From equation (2), we then have:

$$l_e \approx \frac{\sigma_e}{\omega\epsilon'} \quad (5)$$

Using σ_e to be 0.15×10^7 (S/m) in one case and to be 0.87×10^7 (S/m) in another case with frequency of 3 KHz and 30 MHz in (5), and assuming $\epsilon' = \epsilon_0 = 8.854 \times 10^{-12}$ (F/m) which is the permittivity of free space, we have:

$$\begin{aligned} l_{e(3 \text{ KHz}, \sigma=0.15 \times 10^7)} &\approx 8.98 \times 10^{12} \gg 1 \\ l_{e(30 \text{ MHz}, \sigma=0.15 \times 10^7)} &\approx 8.98 \times 10^8 \gg 1 \\ l_{e(3 \text{ KHz}, \sigma=0.87 \times 10^7)} &\approx 52.08 \times 10^{12} \gg 1 \\ l_{e(30 \text{ MHz}, \sigma=0.87 \times 10^7)} &\approx 52.08 \times 10^8 \gg 1 \end{aligned}$$

It suffices to say directly from (5) that if electric loss tangent at a higher frequency was much greater than unity, than at lower frequency it would naturally be greater than unity and the results above for different values of l_e clearly indicate that for frequencies from 3 KHz to 30MHz the ExMF will behave as a good conductor.

Skin depth for good conductors is given by the relation below:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma_e}} \text{ (m)} \quad (6)$$

In the equation above, δ is the skin depth (meters), f is the frequency (Hz), and μ is the permeability. Since aluminum is diamagnetic, we assume $\mu = \mu_0$ (permeability of free space) and is equal to $4\pi \times 10^{-7}$ (Henries/m), σ_e is the well known electrical D.C. conductivity.

Since ExMF behaves from 3 KHz to 30 MHz as a good conductor with finite conductivity, the boundary conditions below (7), (8), (9) and (10) require continuity of tangential and normal component of electric and magnetic fields across the boundary between resin and ExMF in figure 1.

$$\hat{n} \times (\vec{h}_2 - \vec{h}_1)|_s = \vec{J}_s = \vec{0} \quad (7)$$

$$\hat{n} \times (\vec{e}_2 - \vec{e}_1)|_s = -\vec{m}_s = \vec{0} \quad (8)$$

$$\hat{n} \cdot (\vec{b}_2 - \vec{b}_1)|_s = \rho_{ms} = 0 \quad (9)$$

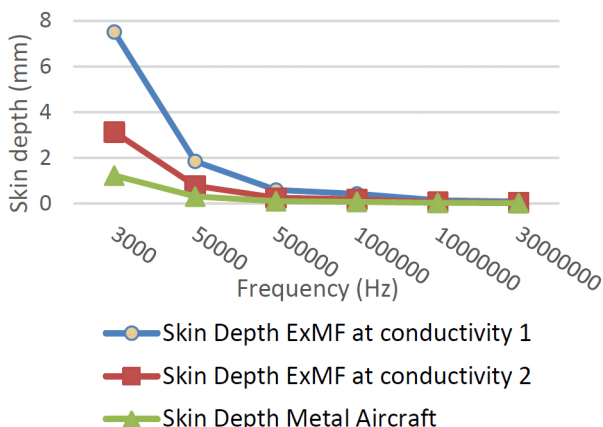
$$\hat{n} \cdot (\vec{d}_2 - \vec{d}_1)|_s = \rho_{es} = 0 \quad (10)$$

In equations (7), (8), (9), (10) above, $\hat{n}$ is the unit normal vector and points from Surface 1 (ExMF) to Surface 2 (Resin) as shown in figure 1. The subscript 1 and 2 in equations (7), (8), (9), (10) represent the fields associated with surface 1 and 2 respectively.

Additionally, $\vec{b}$ and $\vec{d}$ represent magnetic flux density (Webers/m²) and electric flux density (Coulombs/ m²) and ρ_{ms} and ρ_{es} is magnetic surface charge density (Webers/m²) and electric surface charge density (Coulombs/ m²) respectively.

Returning back to figure 1 and equation (6) for skin depth, we calculate skin depth for Aluminum ExMF with conductivity 0.15×10^7 (S/m) in one case and to be 0.87×10^7 (S/m) in another case and frequency ranging from 3 KHz to 30 MHz in each case.

The graph (1) below shows the skin depth at each of the two conductivity values from 3 KHz to 30 MHz and represent the depth of the ExMF required in attenuating 63% of the original signal (field) amplitude (therefore only 37% of the original signal amplitude remains after one skin depth penetration).



Graph 1. (Skin Depth versus freq. for ExMF and metal skin)

Table 1. (Skin Depth (mm) versus freq. for ExMF and metal skin)

Frequency	Skin Depth for ExMF ($\sigma=1.5$ MS/m)	Skin Depth for ExMF ($\sigma=8.7$ MS/m)	Skin Depth for Aluminum Metal ($\sigma = 57.7$ MS/m)
3 KHz	7.5	3.122	1.2178
50 KHz	1.839	0.765	0.298
500 KHz	0.5817	0.242	0.094
1 MHz	0.4113	0.1712	0.067
10 MHz	0.13	0.054	0.021
30 MHz	0.075	0.0312	0.012

In the graph 1 above in the legends, "conductivity" 1 for ExMF refers to 0.15×10^7 (S/m) and "conductivity" 2 for ExMF refers to 0.87×10^7 (S/m). From the graph 1 and table 1 above, it is clear that when aluminum ExMF was 0.381mm thick which corresponds to conductivity 0.15×10^7 (S/m) (the curve with legend, skin depth ExMF at Conductivity 1) one skin depth is reached only after 1 MHz and before 10 MHz.

Comparing to metal aircraft, skin depth (assuming a practical value of 2.0 mm thickness of the metallic skin) is just 1.218mm at 3 KHz and beyond this frequency the skin depth is practically zero. This shows that aluminum ExMF is not comparable with regards to electromagnetic shielding with metallic skin.

Moreover for aluminum ExMF 0.051 mm thick corresponding to conductivity 0.87×10^7 (S/m), one skin depth is reached well after 10 MHz, which means before tens of MHz frequency, more than 37% of the transmitted signal into aluminum ExMF is un-attenuated. This also means that below these MHz of frequencies for one skin depth, majority of the field amplitude passes through the aluminum ExMF. Therefore for indirect effects aluminum ExMF thickness is one of the major factors contributing to the shielding ineffectiveness.

As in figure 1 there are 2-10 plies of continuous carbon fabric which are resin impregnated and are stacked below this aluminum ExMF. The number of plies depends on the criticality of the systems within a specific area of aircraft.

To find out how much field amplitude makes it through the aluminum ExMF and through the plies finally ending up inside the aircraft, we must also know the conductivity of CFRP in addition to aluminum ExMF. According to one manufacturer of Carbon Fiber Fabric [3] for aerospace applications, the electrical resistivity of one of their more popular products (Continuous Carbon Fiber Fabric) is approximately 1.6×10^{-3} (Ω -cm). Since electrical resistivity is the reciprocal of electrical conductivity, we get for electrical conductivity, $\sigma_{d.c.(elect.)}$ CFRP = 6.25×10^4 (S/m).