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A Contribution to Shielding Effectiveness Analysis of Shielded Tents

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Abstract. An analysis of shielding effectiveness (*SE*) of the shielded tents made of the metallised fabrics is given. First, two electromagnetic characteristic fundamental for coupling through electrically thin shield, the skin depth break frequency and the surface resistance or transfer impedance, is defined and analyzed. Then, the transfer function and the *SE* are analyzed regarding to the frequency range of interest to the Electromagnetic Compatibility (EMC) Community.

Keywords: Tents, Shielding, Metalized fabric, Skin depth break frequency, Shielding effectiveness, Shielded cavity, Cavity resonance.

1 Introduction

In the last ten years, the metalized fabrics and composite materials have been used for a portable light weight easily erectable shielded test facilities for testing large systems in the field. Other uses for a shielded tent like enclosure with adequate electromagnetic *SE* are a secure communications facility and workspace protected against the effects of adverse electromagnetic environment, [1]. Besides, these materials have been partially used for space craft and aircraft. Despite these benefits such as their light weight, high strength and ease of fabrication, composite materials are not as electrically conductive as traditional metal structure.

Some other new products for the same purposes, advanced composite materials (ACM), are generally constituted by a binding resin reinforced by high-strength fibers such as kevlar, glass, graphite or boron. Among these, only graphite offers some degree of electrical conductivity and thus exploiting a certain level of shielding. However, the conductivity of most metals is roughly 1000 times greater than that of graphite fiber reinforced composites (GFRC).

The electromagnetic shielding characteristic of novel materials, like metallized fabric, thin foils, or metallic sprays are often questioned, and the problem has been partially solved from the theoretical and practical point of view by Blanchard, et. al., [2]. Analysis of *SE* characteristic related to structures having finite dimensions and being made of thin multilayered composite material such as ACM and/or GFRC is only possible by the use of numerical techniques e.g. the finite-difference time-domain (FD-TD) method, [3].

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2 Electromagnetic characteristics of electrically thin metallized fabrics

Fundamental characteristics for electromagnetic coupling through electrically thin metallized fabrics are: the skin depth, the skin depth break frequency and the surface resistance or transfer impedance. First one is given by

$$\delta = \frac{1}{\sqrt{\pi \cdot \mu_0 \cdot \mu_r \cdot \sigma \cdot f}}\,, \tag{1}$$

where μ_0 is the permeability of free space, μ_r is the relative permeability of the shield, σ is conductivity of the shield and f is frequency of the incidental field. Second one are defined as the frequency where the skin depth equals the effective thickness of the shield and is given by

$$f_\delta = \frac{1}{\pi \cdot \mu_0 \cdot \mu_r \cdot \sigma \cdot D^2}\,, \tag{2}$$

where D is the effective thickness of the shield. Finally, third characteristic the surface resistivity is given by

$$R_S = \frac{1}{\sigma \cdot D}\,. \tag{3}$$

From equations (1) to (3) it is evident that the important electromagnetic characteristics of metallized fabric are the material properties of the metal in the walls, i.e. conductivity, relative permeability and the effective geometric characteristic, primarily the effective thickness. Therefore, the electromagnetic characteristic of the walls are very important at audio frequencies since the walls become electrically thin. Above the skin depth break frequency the *SE* depends on the physical size of the tent and of imperfections on the walls (joints, holes, apertures etc.). For high frequencies where the tent becomes electrically large, it reacts like the cavity, or more precisely, it becomes reverberant chamber and the *SE* is primary determined by the Q-factor of the cavity. From electromagnetic point-of-view, the weave of fabric is not critical and they may be only important for mechanical reasons.

3 Shielding effectiveness of the tents made of electrically thin metallized fabrics

Related to previous statements, analysis of the *SE* in a quantitative manner may be divided into the following three frequency ranges:

- Low-Frequency Range: Shielded tent is electrically small, wall is electrically thin and no standing waves or resonance occur in it;
- Mid-Frequency Range: Shielded tent is no longer electrically small, wall is electrically thin. Shielding effectiveness is only limited by surface resistance and direct radiation from fields at the surface of the wall and

- High-Frequency Range: Shielded tent is electrically large. Internal (transmitted) field is determined by absorption inside of the tent and shielding effectiveness is determined by the Q-factor of the cavity.

3.1 Low-Frequency Shielding Effectiveness

According to the low frequency model, incidental magnetic field causes a current to flow on the exterior surface of the tent's wall. This current couples through the wall producing a tangential electric field on the inside surface wall of the tent. In the low frequency range shielded tent is electrically small and transmitted field is everywhere in phase. Therefore, transmitted field acts like a voltage source, driving a current around the interior surface of the tent. Magnitude of this current is determined by the impedance of the interior surface of the shielding material and the intensity of the tangential electric field on same surface. At low frequencies (below 10 kHz), the surface resistance is dominant in the impedance of interior surface, however it is rather small and the *SE* tend to zero, [4]. As frequency of the incidental magnetic field increases, the inductance of the interior surface increases too and slowly predominates into the impedance. On the other hand, inductance of the interior surface is roughly proportional to frequency and the *SE* increases in same manner. Since the inductance of the interior surface is proportional to the dimension of the tent a large tent provides better shielding effectiveness. In this frequency range the *SE* of a tent is determined by, [5] and for two layers material is given by

$$SE = 20 \log \left| \frac{1}{T(\omega)} \right| = 20 \log \left| \frac{H_t(\omega)}{H_i(\omega)} \right| , \tag{4}$$

where $T(\omega)$ is transfer function of the tent, $H_t(\omega)$ intensity of transmitted magnetic field and $H_i(\omega)$ intensity of incidental field. In canonical form equation (4) is given by

$$SE = \{1 - \omega^2 D_1 D_2 \cdot \left[1 + (a_1 / a_2)^3\right]\} + j\{\omega \cdot (D_1 + D_2)\} , \tag{5}$$

where D_1 and D_2 are thickness of the layers (subscripts are used to denote each layer), a_1 and a_2 are radii of the sphere whose volume is the same as the shielded tent and $\omega = 2 \cdot \pi \cdot f$, where f is the frequency of the incidental field.

3.2 Mid-Frequency Shielding Effectiveness

In the mid-frequency range, the walls are electrically thin but the tent is not electrically small. This range starts where the low frequency shielding effectiveness equals to the limiting value and it continues until the first internal resonance of the tent occrs. According to the mid frequency-model, the external field (incidental field) is in phase almost everywhere on the outside surface of the tent. The surface current diffuses through the metalized fabric resulting tangential electric field on the inside surface is everywhere in phase. The manner in which the shielded tent transmits electromagnetic waves has been shown to be analogoue to manner in which a conventional two-wire transmission line transmits electrical current and voltage, [6]. With reference to Fig. 1, the *SE* is explained by the transmission of the incidental wave. The reflected part of the incidental wave either travels back to infinity or suffers sufficiently high penetration loss in the metalized fabric of thickness *D*.

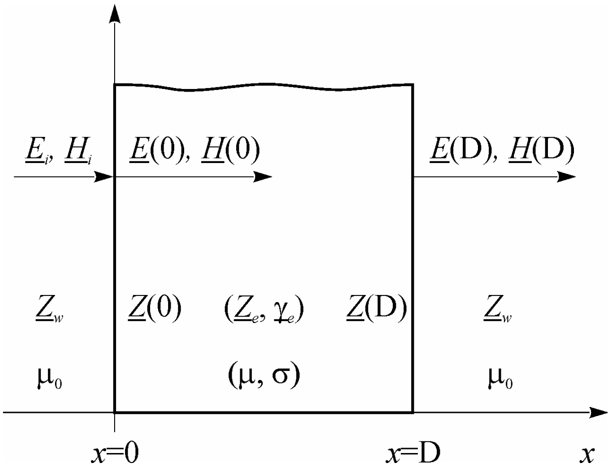

Fig. 1.

In this case, the transmission coefficients across the metalised fabric are:

$$\underline{T}_H = \frac{\underline{H}(D)}{\underline{H}_i} = \frac{\underline{H}(0)}{\underline{H}_i} \cdot \frac{\underline{H}(D)}{\underline{H}(0)} \tag{6.1}$$

and

$$\underline{T}_E = \frac{\underline{E}(D)}{\underline{E}_i} = \frac{\underline{E}(0)}{\underline{E}_i} \cdot \frac{\underline{E}(D)}{\underline{E}(0)} \tag{6.2}$$

where *$\underline{E}(0)$, $\underline{H}(0)$, $\underline{E}(D)$* and *$\underline{H}(D)$* are actual values of electric and magnetic fields at interface 0 and D, respectively. At the interface 0 (left side of the shield) from the work of Schulc [7]

$$\frac{\underline{H}(0)}{\underline{H}_i} = \frac{2\underline{Z}_w}{\underline{Z}_w + \underline{Z}(0)} \tag{7.1}$$

and

$$\frac{\underline{E}(0)}{\underline{E}_i} = \frac{2\underline{Z}(0)}{\underline{Z}_w + \underline{Z}(0)}, \tag{7.2}$$

and at the interface D (right side of the shield),

$$\frac{\underline{H}(D)}{\underline{H}(0)} = \frac{\underline{Z}_e}{\underline{Z}_e \cdot ch\left(\underline{\gamma}_e D\right) + \underline{Z}(D) \cdot sh\left(\underline{\gamma}_e D\right)} \tag{8.1}$$

and

$$\frac{\underline{E}(D)}{\underline{E}(0)}=\frac{\underline{Z}(D)}{\underline{Z}(D)\cdot ch\left(\underline{\gamma}_e D\right)+\underline{Z}_e\cdot sh\left(\underline{\gamma}_e D\right)},\tag{8.2}$$

where $\underline{Z}_w$ is impedance of the incident wave in the air (120 π), $\underline{Z}_e$ the intrinsic impedance of the tent and $\underline{\gamma}_e$ the propagation constant in the tent's walls. When equations (7) and (8) are substituted in (6), the following expressions are obtained for the transmission coefficients across the tent

$$\underline{T}_H=\frac{2\underline{Z}_w}{\underline{Z}_w+\underline{Z}(0)}\cdot\frac{\underline{Z}_e}{\underline{Z}_e\cdot ch\left(\underline{\gamma}_e D\right)+\underline{Z}(D)\cdot sh\left(\underline{\gamma}_e D\right)}\tag{9.1}$$

and

$$\underline{T}_E=\frac{2\underline{Z}(0)}{\underline{Z}_w+\underline{Z}(0)}\cdot\frac{\underline{Z}(D)}{\underline{Z}(D)\cdot ch\left(\underline{\gamma}_e D\right)+\underline{Z}_e\cdot sh\left(\underline{\gamma}_e D\right)}.\tag{9.2}$$

Introducing the following notation for reflection and transmission coefficients of the magnetic and electric fields respectively

$$\underline{q}_H=\frac{\left(\underline{Z}_w-\underline{Z}_e\right)\cdot\left[\underline{Z}(D)-\underline{Z}_e\right]}{\left(\underline{Z}_w+\underline{Z}_e\right)\cdot\left[\underline{Z}(D)+\underline{Z}_e\right]}\tag{10.1}$$

and

$$\underline{p}_H=\frac{4\underline{Z}_w}{\left(\underline{Z}_w+\underline{Z}_e\right)\cdot\left[\underline{Z}(D)+\underline{Z}_e\right]},\tag{10.2}$$

and when $\underline{Z}$(D)= $\underline{Z}_w$ (because the shielded tent is usually erected in the air), the following formula is obtained

$$\underline{T}_H=\underline{T}_E=\underline{T}=\frac{\underline{p}}{1-\underline{q}\cdot e^{-2\underline{\gamma}_e D}}\cdot e^{-\underline{\gamma}_e D}.\tag{11}$$

Where

$$\underline{p}=\frac{4\underline{k}}{\left(\underline{k}+1\right)^2},\tag{12.1}$$

$$\underline{q}=\frac{\left(\underline{k}-1\right)^2}{\left(\underline{k}+1\right)^2},\tag{12.2}$$

and

$$\underline{k}=\frac{\underline{Z}_w}{\underline{Z}_e}.\tag{13}$$

By definition, the total shielding effectiveness is

$$SE = 20\log\left|\frac{1}{\underline{T}}\right| \tag{14}$$

and

$$SE = 20\log\left|\underline{p}\right| + 20\log\left|e^{+\underline{\gamma}_e D}\right| + 20\log\left|1-\underline{q}\cdot e^{-2\underline{\gamma}_e D}\right|. \tag{15}$$

Since the wall of metallized fabric is electrically thin in the mid-range frequencies, attenuation of waves passing trough the shield (second term in (15)) and attenuation of internal multiple re-reflections in the wall (third term in (15)) can be neglected, thus the previous equation may be written as follows:

$$SE = 20\ \log|\ \underline{p}\ |. \tag{16}$$

From equations (16) and (13) it is evident that the *SE* in the mid-range frequencies depends on the size of the tent ($\underline{Z}_e$) or more exactly, on the surface resistivity (R_s). On the other hand, the *SE* in this frequency range is frequency independent. These two facts are crucial and were experimentally verified and reported first time by Blanchard [2] in 1988. and many times after.

3.3 High-Frequency Shielding Effectiveness

The mid-frequency range continues until the first internal resonance of the tent occures and above this frequency the high-frequency range begins. In this frequency range the tent is electrically large and the wall is no longer thin, therefore an electromagnetic analysis is much more complex, [8]. The most obvious complexity is the presence of standing waves inside the tent and these will be particularly evident if the walls are parallel and flat. Fortunately, a tent-like structure made of metalised fabric, will not have flat walls and the walls are not likely to be parallel. Therefore, the tent acts like a cavity and resonates at the specific frequencies determined by dimensions of the tent. If the cavity resonates, transmitted (internal) field will be amplified on those frequencies. The level of the internal field amplification depends on Q-factor of the cavity i.e. dependent on the surface resistivity of material inside of the tent. Therefore a practical conclusion related to this frequency range is that the addition of absorbing material reduces Q-factor of the cavity, but increases the *SE*, [9].

An analysis of the shielding effectiveness in this frequency range, can be performed only by using analogy with acoustic reverberation chamber because the field vectors inside the cavity tend to be randomly oriented and diffuse trough the walls, [10]. The electromagnetic power density inside the cavity will increase if the electromagnetic power flows in. But, if the amount of electromagnetic flow-in power increases, the amounts of dissipated power and power flows through the walls will increase too.

Since both electromagnetic energy flows (in and out) are proportional to the external field strength, equilibrium between energy flows is reached when the power being dissipated in the absorbing material is equal to the power flowing into the cavity. This fact implies that distribution of the transmitted field is different for each resonant mode of the cavity and the *SE* itself is changeable too. Therefore, *SE* of the shielded tent is only possible to define on the base of spatial average of the transmitted field in the rms sense, [9]. Thus, the *SE* in this frequency range is given as follows:

$$SE_E = 20\log_{10}\frac{E_i}{E_{rms}} \tag{17}$$

and

$$SE_H = 20\log_{10}\frac{H_i}{H_{rms}}, \tag{18}$$

where

$$E_{rms} = \sqrt{\frac{3}{4\pi \cdot a^2} \cdot \int_0^a \int_0^{2\pi} \int_0^{\pi} E_0^2 \cdot R^2 \cdot \sin\theta \cdot d\theta \cdot d\varphi \cdot dR}, \tag{19}$$

$$H_{rms} = \sqrt{\frac{3}{4\pi \cdot a^2} \cdot \int_0^a \int_0^{2\pi} \int_0^{\pi} H_0^2 \cdot R^2 \cdot \sin\theta \cdot d\theta \cdot d\varphi \cdot dR}, \tag{20}$$

and a is radius of the sphere whose volume is the same as the shielded tent.

Degradation of *SE* due to the cavity resonance (fundamental resonance and higher resonant frequencies above fundamental) has similar characteristic for the electric field SE_E and the magnetic field SE_H. Within this frequency range, there are many specific frequencies at which SE_E and SE_H sharply drop. This phenomenon is interpreted as follows: The incident power partially penetrates into the cavity through the metallised fabric - shield and this electromagnetic power excites resonant modes of the cavity at specific frequencies. When the cavity is resonating, amplitude of the field in the cavity (the transmitted field) sharply increases resulting into sharp degradation of *SE* (*SE* sharply decreases).

4 Summary

In this paper the author gives a contribution to shielding effectiveness analysis of shielded tents for the frequency range which is of interest to the EMC Community (10 kHz - 10 GHz). This contribution is simplified from the mathematical point of view but with strong physical and experimental background. This analysis shows that in the low-frequency range shielded tent is electrically small and the wall is electrically thin. Dominant factor in the impedance of the interior surface is the small surface resistance, therefore the *SE* of the tent tends to zero. As frequency of the incidental field increases, the inductance in the impedance of interior surface increases too and slowly predominates.

Therefore, increasing of the *SE* becomes proportional to frequency of the incidental field and since the surface impedance is proportional to the dimension of the tent, a large tent provides better *SE* at low frequencies.

In the mid-frequency range, the walls are electrically thin but the tent is not electrically small. The mid-frequency range starts where the low frequency shielding effectiveness equals to the limiting value and continues until the first internal resonance of the tent occurs. From equations (16) and (13) it is evident that the shielding effectiveness in the mid-frequency range depends on the size of the tent ($\underline{Z}_e$) or more exactly, on the surface resistivity (R_s). On the other hand, the shielding effectiveness in this frequency range has a constant value i.e. it is frequency independent.

In high-frequency range the tent is electrically large and the wall is no longer thin. The standing wave inside the shielded tent becomes apparent and it acts as a cavity. The cavity resonates at the specific frequencies which depends on dimensions of the tent and amplifies the internal electromagnetic field (the transmitted field). The level of amplification depends on the Q- factor of the cavity i.e. on the surface resistivity of absorbing materials inside the tent. Therefore, a practical conclusion related to analysis of this frequency range is that the addition of absorbing material reduces the Q-factor of the cavity, but increases the shielding effectiveness.

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