ELECTROMAGNETIC TOPOLOGY TECHNIQUE FOR SYSTEM INTERACTION THROUGH A SMALL APERTURE

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Abstract: The paper describes a new technique to analyze the transfer function between an external source and internal circuitry of a semi-shielded system through a small aperture. The simulation and analysis were performed using the state of the art CRIPTE code which is based on electromagnetic topology concept, having cable network as its application domain. The results compare well with experiments. Analysis shows that the effects of the external fields on the cable current depend on the cable length, location, driving voltage and impedances at the terminals.
Key words: electromagnetic topology, system interaction, CRIPTE network simulation

1. Introduction

Modern day electronic systems used in commerce, communications and other sensitive areas are characterized by the use of very sensitive devices. Hence the deliberate use of high power microwaves to jam or burnout the electronic hardware is of immediate concern to the defense and the commercial sector alike. In simulating a system's response to external threats it is possible to divide the problem into independent processes such as external coupling (external interaction), energy penetration (external-internal transfer function), and the excitation of the electrical system (internal interaction) [1]. Such a separation of response is also conducive to simulations based on electromagnetic topology (EMT) where it is assumed that different compartments or volumes are independent of each other and interact only through preferred paths [2-4]. Thus in the topological network, which describes the global system's coupling as the relationships between each volume, one can analyze each volume for a separate response mechanism and then provide the solution to the overall problem. This simulation concept has been incorporated in the state of the art CRIPTE code through the solution of the network equations. The code thus has cable network as its application domain [5].

An important area of study is the determination of the transfer function from the external volume to the interior. In this paper, we introduce a new methodology for simulating the external-internal interactions and transfer function through the use of the CRIPTE code and compare it with previously measured values and simulation methods. The methodology described here is implemented on a simple system or volume which can also be applied to more complex systems incorporating a large number of volumes and cables such as an aircraft or other large electronic systems under external EMP threat. We have shown that this technique for introducing the transfer function in terms of current at interior volumes compares well with measured H and E-fields. The trends in fields then translate to the current and voltages in the interior of the system.

2. System Description

2.1 Volume/Surface Topology

The simplified shielding topology of a system shown in Fig. 1 having the external volume V_0 covering the entire system. Upon penetrating the outer shielded surface $S_{0,1}$, the EMP wave radiates through the internal medium with ε_0 and μ_0 in volume V_1 and couples on the shielded surface $S_{1,2}$, which may represent the shielding enclosures and coaxial outer layer. The volume V_2 contains the housings $V_{3,1}$ and $V_{3,2}$, which are representing electronics flight control units (FCU) connected by the unshielded communication wires. The symbol $T_{0;2}$ represents the EMP transfer function from volume V_0 to volume V_2.

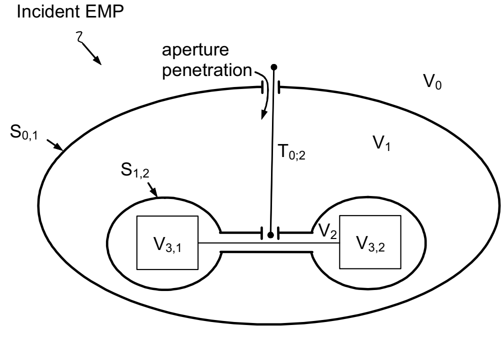

Fig. 1 Shielding volume/surface topology of the simplified aircraft system.

2.2 Frequency-Domain Analysis of Lightning and EMP

Two types of transient external excitation sources such as direct-lightning strike and EMP are discussed. In case of a lightning strike, a charge enters and leaves the aircraft at different points as a part of the lightning current, thus inducing skin currents and external fields on the aircraft surface. On the other hand, the EMP wave couples on to the vehicle exterior, producing skin currents and external fields. The plots shown in Fig. 2 show the Fourier transforms of the lightning and EMP responses within the range of 1 and 500 MHz. The response data are recorded at the external sensors (a B-dot sensor for magnetic fields and a D-dot sensor for electric fields) on an aircraft [6]. The plots of the lightning and EMP spectra show that the field magnitudes of EMP sources dominate those of the lightning sources and both of them decrease as the frequency increases.

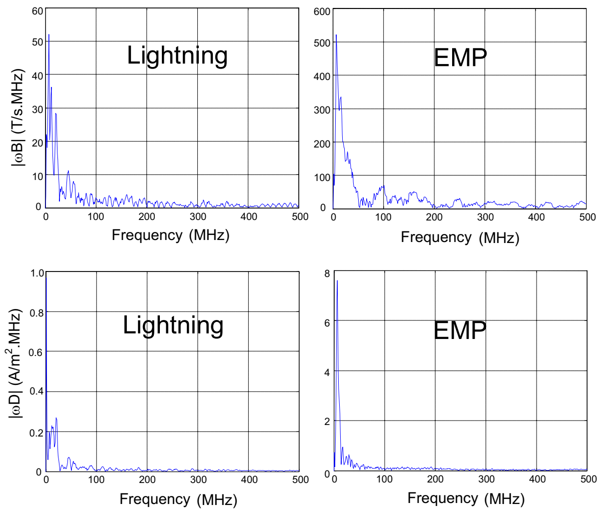

Fig. 2 Lightning and EMP spectra at the aircraft exterior of (a) magnetic fields and (b) electric fields.

2.3 CRIPTE Interaction

Fig. 3 shows the setup for CRIPTE code for simulating the coupling of these fields on the aircraft external surface using the gap as a one dimensional aperture illumination source [7]. The aperture acts as an illumination source for the internal circuitry of the system. For an electrically small aperture, the coupling magnetic field H_{sc} and electric field E_{sc} associated with Fig. 2 can be created with an assumption of a short imaginary transmission line, having a characteristic impedance of air (Z_0), over the small aperture [8], as also shown in Fig. 3. The values of terminal impedances adjust the field angles. The parameter a represents the aperture illumination of the external fields and can be linearly approximated as $a = l/p$, where p is the length of the aperture and l the length of the imaginary transmission line. This short transmission line can be considered as a short radiating dipole [9] producing the radiated waves through the aperture, and represents the external-internal transfer function. It should be noted that, previously, such a transfer function was determined with a different approach. The transfer function was determined through experiment and simulations were carried out using measured transfer function [10].

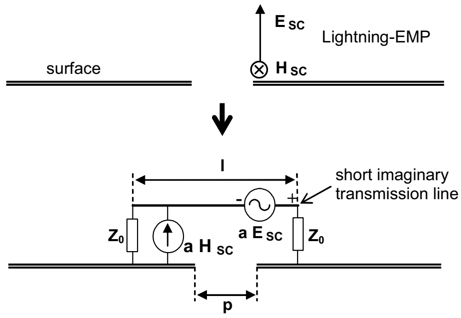

Fig. 3 Imaginary transmission line representing the field external couplings on the aircraft surface

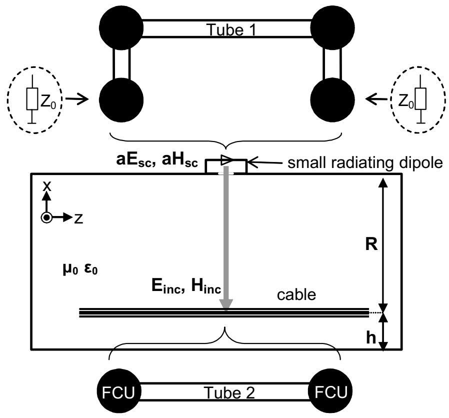

Fig. 4 CRIPTE network representation of the entire system processes (external-internal interactions and transfer function.

The radiating short dipole and the transmission cable are assumed to be located on the same *x-z* plane. The projection of a point of entry on the internal transmission cable is at the middle. The calculation of the internal propagation shows how the radiated or incident electric field E_{inc} and magnetic field H_{inc} excite the voltage and current on the transmission cable. Many coupling formulations of the incident fields on the cable have been proposed including the popular Taylor and Agrawal formulations [11-12], which has been incorporated in the CRIPTE code. The field coupling on the transmission cable can be represented by the local voltage and current sources causing the current propagation on the cable. Here, the sources for all conductors can be determined by Taylor formulations

$$\boldsymbol{V}_s = -j\omega\mu_0 \int_0^h H_y^{inc}\, dz \qquad (1)$$

and

$$\boldsymbol{I}_s = -j\omega\boldsymbol{C} \int_0^h E_x^{inc}\, dz\,. \qquad (2)$$

Fig. 4 shows the CRIPTE network system representation consisting of two main tubes and two junctions for each tube. The tube 1 represents the short imaginary transmission line on the external aircraft surface. Its junctions represent the terminals with the matching impedances Z_0. Similarly, the tube 2 represents the internal sensitive communication cable connecting the flight control unit.

2.4 Multiconductor Transmission Line Realization

To realize an internal communication cable as a multiconductor transmission line (MTL), the MTL cable was constructed by CRIPTE code and compared the distortion of the input signal at various frequencies with the ISO/IEC 11801 standard attenuation shown in Table I. The MTL in this study is a straight-through UTP-CAT5 cable consisting of four pairs of 24-AWG conductors. Fig. 5 shows the cross section of the UTP-CAT5 cable used in the simulations. During a communication between FCUs, only one of four pairs will be used, i.e., a pair of conductors 1 and 2 is used to transmit while a pair of conductors 3 and 6 is used to receive the data. The conductor radius is R_1 = 0.2625 mm. The radius of the dielectric coating is R_2 = 0.465 mm. The outer jacket radius is R_4 = 2.5 mm. The cable height above the ground plane is h = 10 mm.

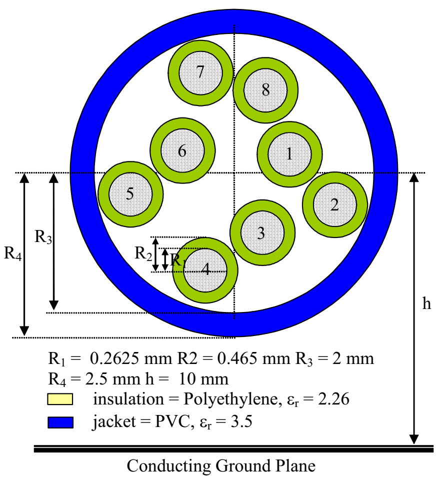

Fig. 5 Cross section of the straight-through UTP-CAT5 used in the CRIPTE network studies.

Table I standard attenuation (dB) – 100 m	
1 MHz – 2.1	20 MHz – 9.2
4 MHz – 4.3	31.25 MHz – 11.8
10 MHz – 6.6	62.5 MHz – 17.1
16 MHz – 8.2	100 MHz – 22.0

Fig. 6 shows the cable attenuation characteristics (100 m) of a differential-mode voltage, which is similar to recommended data. Since there is a match in attenuation, ones can say that the simulation structure is similar to a practical structure and guaranteed in using to model tube 2 in Fig. 4.

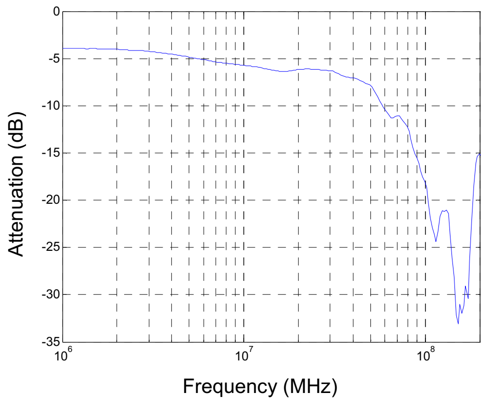

Fig. 6 Attenuation characteristics of the 100-m UTP-CAT5

3. EMP response for Aircraft

In this section, the CRIPTE calculations investigate the aircraft system interaction responses caused by the EMP. The parameters of dimensions associated with Figs. 3 and 4 are shown in Table II. Fig. 7 shows the plots of the H-fields induced by the EMP from the radiating dipole located at the aircraft's surface (aH_{sc}) and the incident H-fields exciting on the computer cable (H_{inc}) as functions of the distance R from the aircraft's surface to the cable. The plots show that the aircraft system interior behaves as a high pass filter for the fields. Also, the influences of the fields at high frequency relative to those at low frequency increase as the distance R becomes larger.

Table II CRIPTE simulation parameters	
Dipole length l	40 mm
Aperture width p	10 mm
Distance R	2 ~ 16 m
Distance h	10 mm
Cable length	20 m

Basically, the low-frequency domination of the external fields (see Fig. 2) vanishes as the fields penetrate to the internal transmission cable through

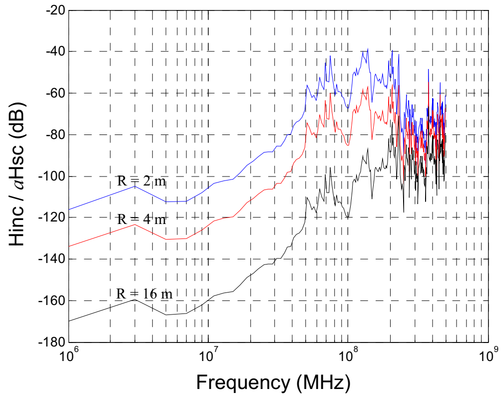

Fig. 7 H_{inc}/aH_{sc} as functions of distance *R*.

the medium. The magnitudes of the fields at high frequencies become comparable to those at low frequencies. These results thus compare well with the experimental results reported by Nanevicz et al. [6]. Therefore, the high-frequency shielding is extremely desired under the EMP influences.

As the EMP couples on the internal cable, the field excitation creates the current propagating on the cable. The plot of the cable total current responses under the EMP influence (see Fig. 8*b*) relative to the current during a normal condition (see Fig. 8*a*) when the UTP-CAT5 is terminated with matched loads is shown in Fig. 9. Due to the low radiation field strength with *R* = 2 m, the driving voltage V_{cc} was appropriately chosen to allow the EMP effect on the current observable. As a result, the cable total current has a tendency of being magnified as the frequency increases until 500 MHz. In addition, simulations show that the high-frequency resonances on the cable voltage and current depend on the line length and termination impedances of the internal circuitry where those results, however, are not shown here.

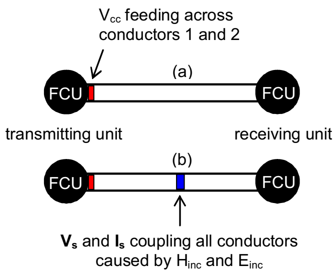

Fig. 8 CRIPTE network (a) without and (b) with the field coupling on the transmission cable.

4. Conclusion

In summary, we have shown that the response of electronic systems to external EMP threat can be simulating using Electromagnetic Topology (EMT) techniques. The results agree quite well with the previous experimental measurements. CRIPTE code is shown to be able to construct the MTL. CRIPTE analysis also shows that the response of a system to external high frequency pulse depend to a large extent on the location, the length and the termination impedance of the internal circuitry. Thus the use of a transmission line domain code with volume decomposition technique is a viable option for EMP effect studies.

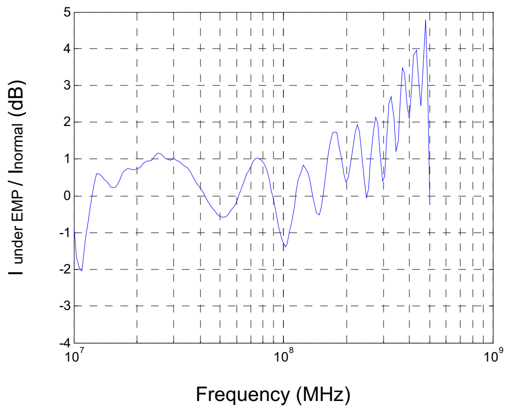

Fig. 9 $I_{\text{under EMP (Fig. 8}b\text{)}} / I_{\text{normal (Fig. 8}a\text{)}}$ in dB.

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