Evaluation of Lightning Induced Effects in a Graphite Composite Fairing Structure

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***Abstract* —** Defining the electromagnetic environment inside a graphite composite fairing due to near-by lightning strikes is of interest to spacecraft developers. This effort develops a transmission-line-matrix (TLM) model with CST Microstripes to examine induced voltages on interior wire loops in a composite fairing due to a simulated near-by lightning strike. A physical vehicle-like composite fairing test fixture is constructed to anchor a TLM model in the time domain and a FEKO method of moments model in the frequency domain. Results show that a typical graphite composite fairing provides attenuation resulting in a significant reduction in induced voltages on high impedance circuits despite minimal attenuation of peak magnetic fields propagating through space in near-by lightning strike conditions.

***Index Terms* —** Composite, Lightning, Magnetic, Method of Moments, Shielding, Transmission Line Method.

I. INTRODUCTION

A. Background

Direct strike lightning effects have been thoroughly evaluated for composite aircraft structures [1]. In the space industry, launch commit criteria and ground protection systems such as catenary wires shift the focus for launch vehicle protection to indirect effects from a near-by strike. Note that the use of the term indirect effects based on a nearby strike is different than that of the aircraft industry where the effects on internal circuitry from a strike to the airframe is indicated [2]. Aircraft avionics are typically hardened to this environment, but such hardening is not characteristic of typical spacecraft systems that are sensitive by design. Much work in the launch vehicle industry has concentrated on lightning coupling analysis of the large umbilical cable connecting ground support equipment to vehicle/spacecraft power and data circuits as illustrated in Fig. 1. Accordingly, any protection of spacecraft afforded by the composite structure is not well characterized [3].

Minimal shield transfer impedance is required to reduce the common mode coupling to a differential circuit [1]. When design criteria constraints prohibit adequate shielding, voltages induced into sensitive circuitry are primarily driven by the loop area, magnetic field amplitude, and the transient rise time. Thermal constraints can also limit the application of wire twisting, which makes the cancellation of the magnetic field via loop area reduction impractical.

In the event of a near-by lightning strike the spacecraft system must evaluate the retest criteria. This retest criteria is important because only minimal on-pad testing is possible due to limited interface controls. Triggering of this criteria can lead to payload destack and return to processing facilities where mission specific testing can ensue.

Submitted On: August 6, 2011
Accepted On: January 23, 2012

False indications of this trigger based on the assumption of zero shielding in composite fairings is costly from a budget and schedule standpoint. Albeit, the consequences of unneccessary retest are severe, the repercussions of an undetected failure are irreversible. As there is no possibility to retrieve a payload on orbit, a conservative, yet easily implementable prediction of attenuation of indirect lightning effects is desired.

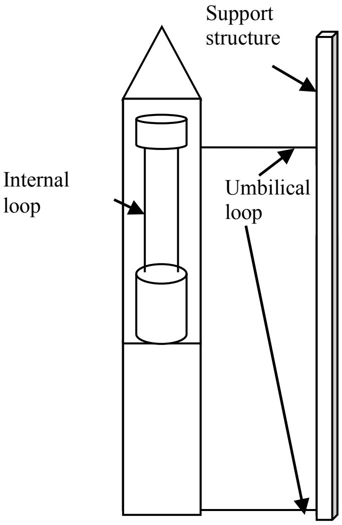

Fig. 1. Launch vehicle and umbilical tower.

B. Lightning Induced Effects

The time varying magnetic and electric fields lead to induced voltages and currents in vehicle and spacecraft circuitry. The governing equation used to approximate the magnetic field from a nearby lighting strike ignoring ohmic losses is given by

$$\begin{aligned}&\oint H \cdot dl = I_i + I_d \\ &= \iint_A J_i \cdot da + \iint_A \frac{\partial}{\partial t}(\varepsilon_0 E)da \\ &\mathit{Where:} \\ &E, H = \mathit{Electric\ and\ magnetic\ fields}, \\ &A, l = \mathit{loop\ area\ and\ length}, \\ &I, J = \mathit{current\ and\ current\ density}, \\ &\varepsilon_0 = \mathit{permittivity\ of\ free\ space, and} \\ &i, d = \mathit{lightning\ source\ and\ displacement}.\end{aligned} \tag{1}$$

MIL-STD-464 gives the change in the electric field contributed by a near lightning strike 10 m away as 6.8 x 10^{11} volts/meter/second (V/m/s) [4]. Assuming a reasonable worst case circuit area, A, of 4 m x 0.05 m = 0.2 m^2, the contributing portion of the magnetic field due to the displacement current (I_d) is 1.2 A/m [1]. This displacement current is relatively insignificant compared to the contribution of the lightning channel, allowing the magnetostatics assumptions to be applied [1], [5,6]. Hence, an approximation of the magnetic field simplifies to $I_i/(2\pi r)$, where r is the distance from the strike and 2πr represents the circumference of the circle with radius, r. For instance, a 50 kA strike at 10 meters would contribute a magnetic field of 795 (amperes/meter) A/m. To determine the induced voltage that arises due to a lightning related magnetic field, the rise time is key as depicted in (2). This rise time varies from 1.4 μs to 50 ns depending on which component of lightning is active (initial severe stroke, return stroke, multiple stroke, or multiple burst). For most launch sites, the range data includes strike magnitude and location (within a 250 to 500m accuracy), but does not include rise time information. MIL-STD-464 [4] reports the change of magnetic field with respect to time for a near lightning strike 10 m away as 2.2 x 10^9 A/m/s and using this, we get

$$\begin{aligned}&\mathit{Max}\, V_{oc} = \frac{d(\mu_0 \mathrm{HA})}{\mathrm{dt}} = \mu(2.2\times10^9)(0.2) = 552.9V \\ &\mathit{Where:} \\ &\mu_0 = \mathit{free\ space\ permeability} = 4\pi\times10^{-7}\ H/m.\end{aligned} \tag{2}$$

The differential circuit voltage will be less than predicted by (2) due to actual circuit impedances and common mode rejection; however, the remaining voltage is undesirable for most spacecraft instrumentation cirucuits. Spacecraft retest criteria of 10 – 50 volts is common; however, lower sensitivities have been reported by design constrained spacecraft payloads.

C. Motivation

Test data and two-dimensional numerical models presented in the literature for a single composite panel in otherwise conductive enclosures, show greater than 40 dB reduction in dB/dt levels with a composite panel as compared to a fiberglass panel when a nearby transient lightning pulse is simulated [7-9]. The diffusion of direct strikes through composite walls is addressed in evaluation of composite aircraft in [1]. Spacecraft developers and launch vehicle providers have questioned the applicability of panel only studies to the launch vehicle fairing structure. In this study the attenuation of a composite graphite fairing-like structure to the induced effects of nearby lighting strikes is addressed. A physical fairing fixture model is built and test validation is performed as a baseline for the model. Both frequency and time domain testing are performed to anchor the model.

II. FAIRING MODEL

A. Test Fixture

The scaled fairing fixture model shown in Fig. 2 and used for all simulations in this work is ½ to $^1/_7$ the size of typical launch vehicles. The 1.8 m by 0.6 m fairing fixture is made of two composite fairing halves with tabs at the edges for clamping the fairing enclosure. Two 1 mm 4 ply layers of carbon composite material sandwich a 6.35 mm Rohacell®WF foam core. Rohacell®WF is a closed-cell rigid foam based on polymethacrylimide chemistry, which does not contain any carbon fiber composites (CFC's) and is often utilized in manufacturing advanced composites for aerospace applications [10]. The surface resistivity was measured as 161 mohms. The composite fairing structure was grounded via a metallic flat plate which interfaced with the bottom edges of the fixture.

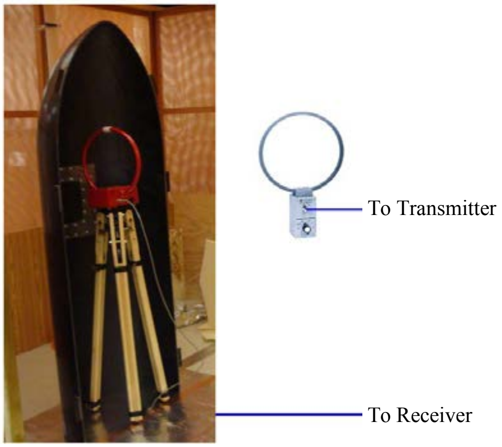

Fig. 2. Test fixture.

B. Composite Structure Model

Modeling the layers of the composite fairing individually requires the mesh to be small with respect to the thickness of each layer and is computationally prohibitive with respect to the entire model size. However, although CFC structures are inhomogeneous and tensor formation of permittivity and permeability are needed for accurate representation of electromagnetic shielding, the frequency range of lightning is generally below the interlayer resonance of composite structures, allowing an effective one layer representation of the composite fairing [11,12]. Literature supports modeling composite materials as a single layer if the period of the structure is small with respect to wavelength [11]. This criterion is clearly met with a thin structure and lightning frequency content below 30 MHz [1]. Several composite builds can effectively be modeled as one layer into the GHz frequency range [11]. Each composite 4 ply build was represented as an electromagnetically penetrable thin film with conductivity parameters developed from surface resistivity measurements [13].

In addition, composite material is not uniform in all directions; hence, the volume conductivity cannot entirely be determined from the surface conductivity and thickness. However, if there are several layers of composite materials, then multiple orientations of the fibers will exist allowing the standard volume resistivity calculated from surface resistance to approximate the actual conductivity of the structure [14]. The conductivity for the graphite composite layer was modeled with the uniform material assumption and calculated using (3) shown below

$$\sigma = \frac{1}{\rho}, \quad \rho = R_s t,$$

$$\sigma = \frac{1}{(161 mohm)(1 mm)} = 6211\, s/m \tag{3}$$

Where:

$\sigma = \text{conductivity in } s/m,$

$\rho = \text{volume resistivity},$

$R_s = \text{surface resistivity, and}$

$t = \text{thickness.}$

III. MODEL CHARACTERIZATION

Before examining the induced voltages with precise industry lightning models, a characterization of the composite structure was performed with a lab implementable test set-up. The thin layer approach to model the composite fairing was anchored with test data in both the frequency and time domain.

A. Frequency domain

Initially, an industry standard magnetic shielding test was performed [15]. The test set-up was then simulated in the frequency domain using the method of moments (MoM) solver in the electromagnetic simulation software, EM Software & System's FEKO [16], and an imported Pro-E fairing model. Although time domain computational methods dominate lightning related literature, use of the MoM with post-processing has been shown effective [17]. The equivalent layer model was implemented with an infinitely thin impedance sheet based on the direct surface impedance measurement. The impedance sheet represents the relationship between the tangential electric field on the surface and the electric surface current [18].

For both the modeling and test, a sensor is placed 1 meter high in the center of the fairing (see Fig. 2). The baseline case is obtained from measurements with no fairing in place. A small loop was used to provide external excitation and internal sensing at specific frequencies.

Both test and simulation results, shown in Table 1, indicate an increase in magnetic field shielding effectiveness with increasing frequency upto 10 MHz.

Table 1: Frequency domain shielding comparisons

Frequency	Shielding Effectiveness (Test Data) dB	Shielding Effectiveness (Model Data) dB	Difference dB
150 kHz	2	0.9	1.1
300 kHz	5	0.8	4.2
2 MHz	11	10	1
5MHz	17	19.5	2.5
10 MHz	21	21.9	0.9

B. Time Domain

Given the limited frequency content in lightning transient pulses, the TLM tool in CST Microstripes is optimally applied for this electrically small structure. Adaptations can be made to the TLM process to account for edge effects, especially for higher frequency applications [19]. TLM divides the physical space into circuits that can be solved for voltages and currents that are related to fields through analogies to Maxwell's equations [20]. The current source is proximally placed with respect to the composite fairing structure to represent a low impedance magnetic field associated with near field conditions and thus worst case (minimal) shielding of the composite fairing structure. The distal leg of current loop is selected as far as possible away from the fairing in order to limit field cancellation effects as shown in Fig. 3 [13].

The transient source was implemented with a 2 m square PVC structure supporting a 16 gauge wire. An Electrometrics, EM 3410, spike generator was placed at the base of the structure to drive a 10 µsec pulse into the loop. The closest side of the loop was placed 0.5 meters from the fairing, as depicted in the model shown in Fig. 3. This transient current loop was selected rather than a high voltage source for feasibility of implementation in the laboratory setting.

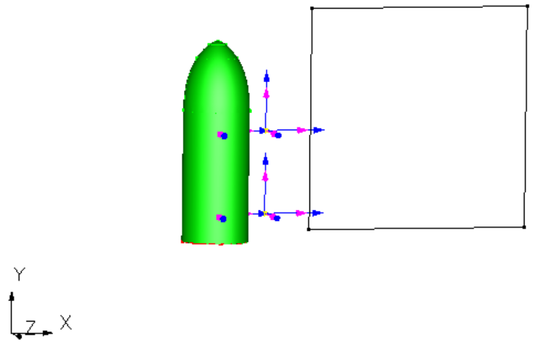

Fig. 3. Laboratory and simulation set-up.

A B-dot sensor (ELGAL MDM-0) was employed in conjunction with a digital oscilloscope, to measure the change in magnetic field with respect to time in the test case. For simulation, this change was determined by examining the time response of the magnetic field data. The baseline comparison case is obtained from measurements with no fairing in place.

The current source in the model was designed to closely characterize the transient generator pulse that could be implemented with a spike generator into an inductive loop. The laboratory loop was modeled with a 10 ohm load impedance to partially account for the inductance created by the loop. A 100 volt transient pulse source was applied to a loop with a wire conductivity of 5.87×10^7 s/m and a radius of 0.15 cm.

The difference in the change in magnetic field with respect to time with and without the fairing was 8.06 dB in simulation and 7.4 dB in test, revealing model and test case agreement.

IV. INDUCED EFFECTS MODEL

First, to represent a nearby lighting strike, a 1MV/1Mohm source at the top of a 30 foot long simulated lightning channel was substituted for the loop in the model characterization phase as shown in Fig. 4 [21]. To reduce electric field contributions, the source was shielded with a graphite epoxy box as in [21].

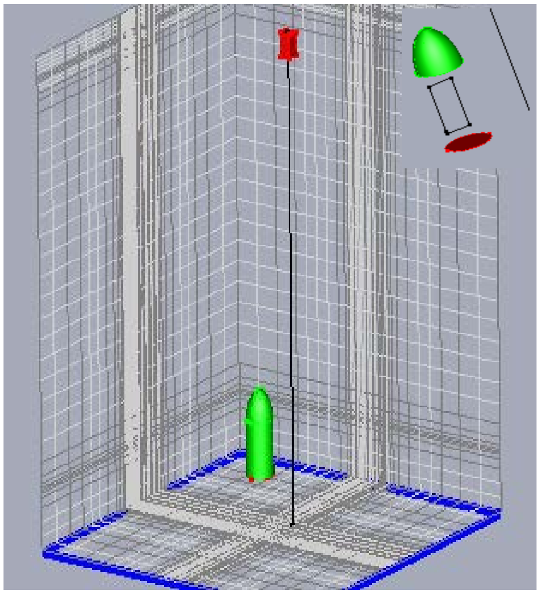

Fig. 4. Composite vehicle with a simulated lightning strike.

The source was driven by the double exponential source characteristics given in (4) which are based on MIL-STD-464 [4].

$$i(t) = I_0(e^{-\alpha t} - e^{-\beta t}) \tag{4}$$

Where: $I_0 = 218{,}810$ A, $\alpha = 11{,}354\ s^{-1}$, and $\beta = 647{,}265\ s^{-1}$.

The TLM model frequency span is set to 20 MHz for broad band evaluations, and the structure mesh size is driven by this frequency. The run time duration is extended beyond the default settings to account for the total waveform time.

In addition, a loop was added in the simulated vehicle to examine currents and voltages on low and high impedance circuitry with respect to magnetic field peak reduction. The emphasis of this paper is the composite fairing attenuation of induced lightning effects. More detailed studies of the lightning induced effects related to loop ground and termination impedances, loop height above ground, and structure surge impedance modeling can be found in recent studies [22-23].

V. RESULTS

Figure 5 depicts the low resistance circuit response excited by a simulated nearby (1 m away) lightning strike with and without a composite fairing surrounding the loop.

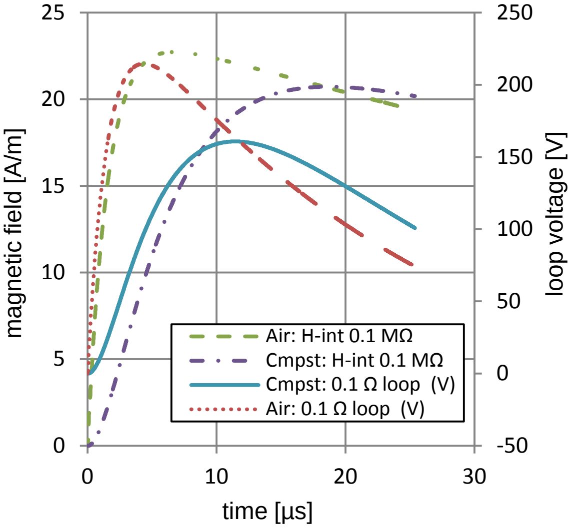

Fig. 5. Composite fairing to air comparison with low impedance loop coupling.

Figure 6 indicates the high impedance circuit response for the same case. Although peak magnetic field coupling is similar with and without the fairing in place, the rise time is longer with the fairing in place leading to lower induced voltages in interior circuits. As evident in (2), Fig. 6 reveals a much sharper peak in induced voltage for the air (no-fairing) case due to the derivative relationship between this voltage and the magnetic field rise time. When the coupled voltage is dominant, as in high impedance circuits, the variation in induced effects is influenced by the diffusion process which slows the rise of the magnetic field [24]. The effect is much less dominant in the low impedance circuit.

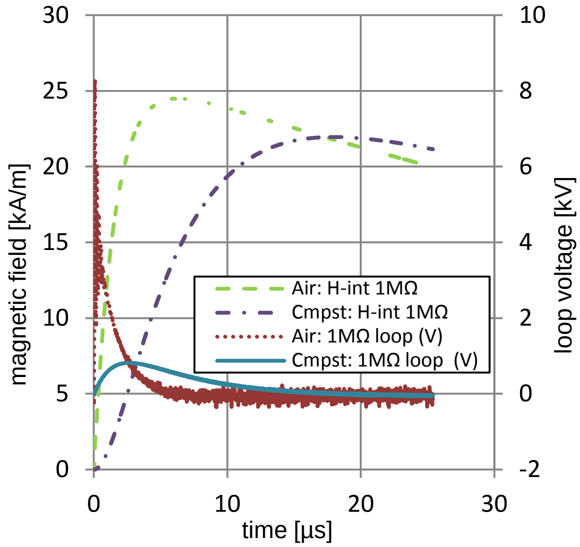

Fig. 6. Composite fairing to air comparison with high impedance loop coupling.

Table 2 provides the composite fairing attenuation effects on magnetic field and coupled loop voltage. It also includes the effects of source distance on the internal magnetic field and the coupled voltages.

Table 2: Comparison of fairing attenuation of induced effects for varying internal loop impedance and distance from source

Loop Impedance Ohms	0.1	1M			
Distance (m)	1	1	3	10	Plane Wave
Induced Voltage Attenuation (dB)	1.5	20.1	20	18.22	31
Magnetic Field Attenuation (dB)	0.8	1.04	.93	1.06	0.87

The plane wave case provides the greatest attenuation due to the higher source impedance of the field with respect to the composite structures. Nevertheless, significant attenuation of induced voltage in the high impedance loop is achieved at close distances where the source impedance is lower than a plane wave.

VI. CONCLUSION

The results presented show that the TLM thin film modeling of the composite structure is effective for the evaluation of attenuation from frequency based and transient based magnetic fields.

The model was modified to align with the industry approach for lightning induced electromagnetic effects. Results shown indicate a typical graphite composite fairing provides significant reduction in induced voltages on high impedance circuits despite minimal attenuation of peak magnetic fields. The energy in the pulse is spread by the diffusion process through the composite material. This spreading slows the incident pulse rise time which in turn reduces the coupling to the circuit.

This study provides a good insight into the differences between literature that specifies attenuation of lightning induced effects and account for any lightning related attenuation for composite structures. The data from this effort is useful for evaluating spacecraft/launch vehicle destack criteria.

ACKNOWLEDGMENT

The ingenuity of Dr. Ellen Lackey and Dr. Elliott Hutchcraft from University of Mississippi who developed this low cost composite fairing was essential in this task.

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