Lightning Induced Electromagnetic Fields into Aerospace Vehicles

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Abstract

Aerospace vehicles such as airplanes and spacecraft are subject to lightning strikes. The control of the vehicles is often dependent upon sensitive electronic equipment such as computers for proper guidance and safety. The currents associated with a lightning strike can be of such magnitude as to render the electronic equipment useless. The result can be catastrophic to the vehicle.

This paper describes the problems associated with a lightning strike, methods that can be used to calculate induced EM fields into the vehicles as a function of the strike, and design means to protect the electronic equipment so housed.

Lightning Hazards

A lightning strike can contain up to 200,000 amperes of current. The current has been known to enter airplanes through navigation lights, fuel filter caps, fuel gauge covers, refueling booms, field vents and antennas, where the current flowing through the aircraft can ignite the fuel as well as destroy electronic components that it comes in contact with.

The aircraft industry is presently manufacturing airplanes that are fly-by-wire. This means that the pilots' controls are tied to a computer and the computer controls the airplane. Additionally, computers are being used more and more by the aircraft industry to perform critical functions. The trend by the aircraft industry to rely on computers and other computer controlled electronics renders aircraft as susceptible to lightning as spacecraft.

Spacecraft are not launched or returned to earth during lightning or thunderstorms. This is due to the susceptibility of the computer controlled guidance systems and other computer controlled functions to the EMI fields which can penetrate the spacecraft through lightning induced currents.

Basically, the electronics in aerospace vehicles are protected from lightning as well as other electromagnetic fields by having a highly conductive skin riveted with closely spaced rivets to the airframe structure. Doors and maintenance covers are held in place with screws or other types of fasteners. EMI gaskets are often used on doors and maintenance covers to assist in obtaining the required EM isolation from detrimental electromagnetic fields such as lightning. The bonding requirement of .0025 ohms is impinged on these joints to insure that the voltage across the joint does not exceed 500 volts. This is sufficient for safety to personnel and the electrical systems on the aerospace vehicle. The .0025 ohms (or a maximum of 500 volts) across the joint cannot be characterized as sufficient to protect computer and computer controlled equipment that is housed in an aerospace vehicle.

Lightning Induced EM Fields

When aerospace vehicles are struck by lightning, the vehicles assist the current in getting to earth (i.e., the current will strike the vehicle at the uppermost point, flow over or through the vehicle as appropriate and exit the vehicle at the lower most point). Lightning protection is achieved by providing highly conductive paths across the vehicle, which minimizes the risk to the vehicle to within acceptable levels. This acceptable level is 500 volts across faying surfaces and is achieved by

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insisting on a maximum resistance of .0025 ohms across each joint of the vehicle skin and structure as required by MIL-B-5087.

The lightning strike is impinged on the aerospace vehicle at a small area and spreads out over the skin of the vehicle. The concentration of the current at the point of entry is extremely high, and becomes less extreme as it flows over the vehicle. Because the exit is at a point, the current concentration again becomes high at that point.

The penetration of a lightning induced wave into the vehicle is a function of the current density in amperes/meter and the impedance of the joint in ohm-meters. The density of the current is the amplitude of the lightning divided by the width of the surface. MIL-B-5087 implies that the maximum density of concern is 200,000 amperes/meter, and that the impedance of the joint is .0025 ohm-meters.

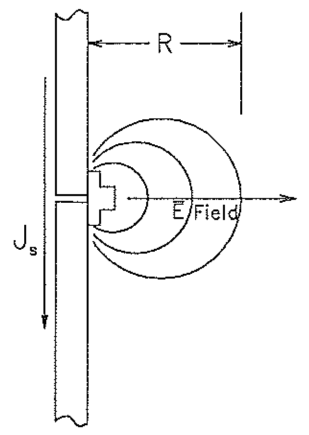

Figure 1.

Figure 1 illustrates the penetration of a lightning induced EM wave into the interior of an aerospace vehicle. As is illustrated in the figure, the current flows over the joint creating a voltage across the joint. This voltage in turn generates an electromagnetic wave that can penetrate into the vehicle. The magnitude of this wave is equal to the voltage differential divided by the length of the wave, i.e.,

> If Js equals 200,000 amperes/meter and the impedance of the joint is .0025 ohm-meters, the voltage across the joint is 500 volts. If the distance "R" of concern is ¼ meter, the field strength at that point will be approximately 500 divided by the length of the wave (i.e., 500/.25π or 636 volts/meter).

If a computer system (or signal control or power lines going to or from a computer) is situated ¼ meter behind a joint possessing a transfer impedance of .0025 ohm-meters, it can be subjected to a field strength of 636 volts/meter as a result of a 200,000 ampere lightning strike. This field strength is significantly higher than computer equipment is designed to withstand. As such, the computer will be expected to be subject to failure. This failure could be catastrophic if the failure consists of destroying components or computer memory. Table 1 illustrates the predicted field strength penetrating a joint as a function of the transfer impedance of the joint and distance R from the face of the joint assuming a lightning current of 200,000 amperes (the transfer impedances of .00001 and .000002 are illustrated because they are achievable, and in some cases required for the safety of the vehicle).

R	Transfer Impedance of Joint (ohm-meters)				
Meters	.0025	.001	.0001	.00001	.000002
0.25	636	254	25.4	2.5	.5
0.50	318	127	12.7	1.3	.25
1.00	159	64	6.4	6	.13

Table 1

Predicted Amplitude of $\overline{E}$ Field Induced into Aerospace Vehicle

Transfer Impedance

Transfer impedance of a joint in a shielded barrier is used extensively by the academic community to predict the field strengths emanating from a joint as a function of an EM source being shielded by a shielded barrier.

A source of EM radiated fields as emanating from a pair of wires is best characterized by a set of plates opposite each other with a voltage source tied between them as illustrated in Figure 2. The current that flows through the wire comes from the top plate and is stored in the bottom plate. The over presence of the electrons on the bottom plate

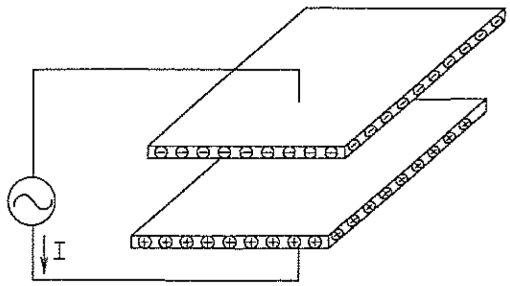

Figure 2.

is illustrated by ⊕ and the absence of electrons on the top plate is illustrated by⊖. This creates an electromagnetic field which is illustrated in Figure 3. As is illustrated, a field exists between the plates. The magnitude of the $\overline{E}$ field is equal to the voltage differential between the plates divided by the distance between the plates in meters. The resultant $\overline{E}$ field is in volts/meter (e.g., we use a set of parallel plates for performing $\overline{E}$ field susceptibility testing to MIL-STD-461/462).

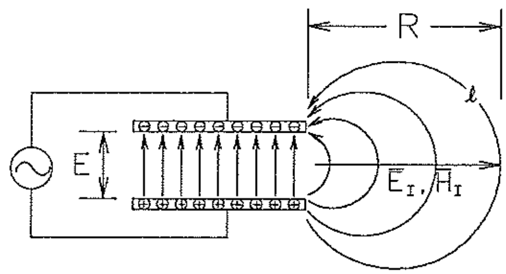

Figure 3.

As is illustrated in Figure 3, the lines of flux in the center of the plates are straight and flow from the bottom to the top plate. At the edges they bow out, where the fields or lines of flux repel each other, forcing the bowing. The field that bows out is an EM field where the $\overline{E}$ vector quantity is equal to the voltage divided by the length of the force line in meters (i.e., if the point of concern is one meter from the set of plates, the $\overline{E}$ field would be the voltage across the set of plates divided by the circumference of the circle or approximately $\overline{E}/3.1$). The magnetic or $\overline{H}$ field is approximated by the following equation:

$$\overline{H} = 2\pi R\overline{E}/377\lambda$$

Where R = Distance from dipole antenna to barrier (m)
λ = Wave length = c/f
c = 3×10^8 m/sec
f = Frequency (Hz)

When we place a shielded barrier in the path of the EM field, the force of the field causes current to flow in the barrier. As is illustrated in Figure 4, the excess electrons in the bottom plate create a

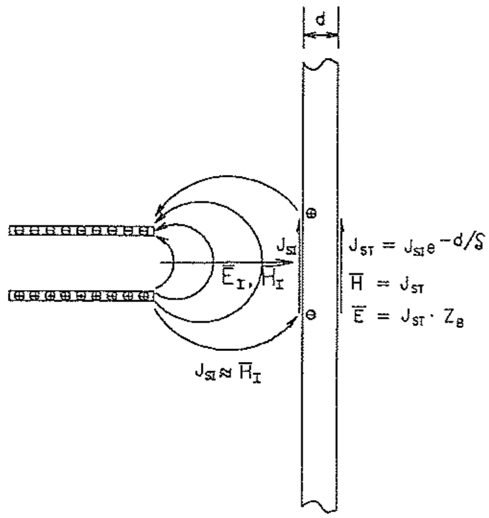

Figure 4.

force on the electrons in the barrier. This force causes the electrons to flow away from the point of contact. In a similar manner, the lack of electrons on the upper plate will create an excess of electrons on the barrier at the upper point of contact. This current flow is classified as the "surface current density" (J_S) in amperes/meter, and is approximately equal to $2\overline{H}$ of the field incident to the barrier. The current flowing in the barrier is attenuated by the skin depth where the current on the transmitted side is equal to $J_s\, e^{-d/\delta}$. The field emanating from the barrier is equal to the following:

$$\overline{H}_T = J_s\, e^{-d/\delta}$$

$$\overline{E}_T = \overline{H}_T Z_B$$

Where $\overline{E}_T$ = Transmitted $\overline{E}$ field (v/m)
$\overline{H}_T$ = Transmitted $\overline{H}$ field (A/m)
Z_B = Impedance of barrier (Ω)
d = Thickness of barrier (m)
δ = Skin depth (m)

Figure 5 illustrates the same barrier containing a gasketed joint in the middle of the barrier. The current on the barrier (J_s) will be similar to that on the barrier of Figure 4. The current J_S will flow aross the gasket. This current flow will create a voltage drop which in turn will generate another force field identical to the one created by an electric

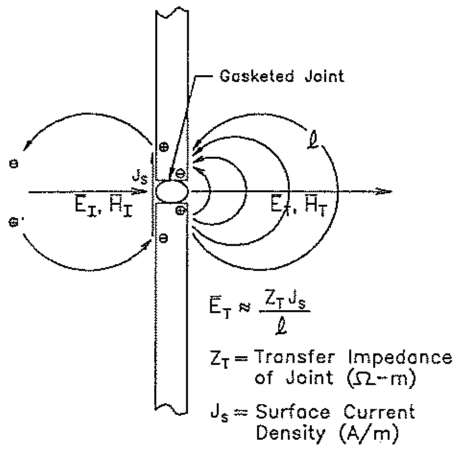

Figure 5.

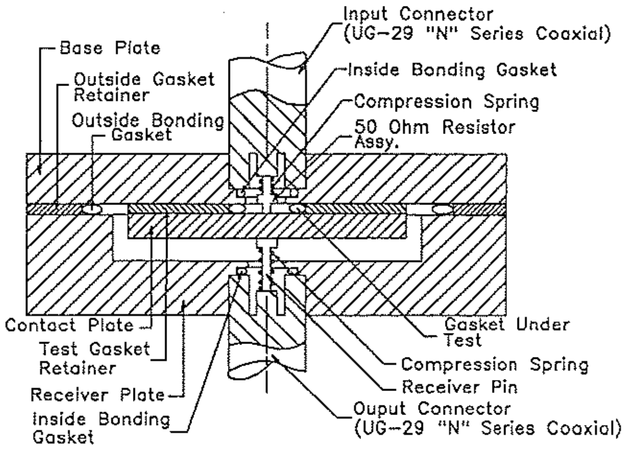

Figure 6.

dipole antenna as illustrated by the parallel plates. The voltage across the joint is equal to the current J_s times the transfer impedance of the joint (Z_T) in ohm-meters, i.e.,

$$E = J_s Z_T$$

The field generated by the gasketed joint can be calculated in a manner similar to the method used to calculate the field generated by the set of parallel plates, i.e.,

$$\overline{E}_T \cong E/\ell = J_S Z_T/\ell$$

$$\overline{H}_T \cong \overline{E}_T \, 2\pi R/377\lambda$$

Transfer impedance of a gasketed joint uses a controlled, calibrated current in amperes/meter flowing across the gasketed joint. The voltage across the gasket under test is measured. The transfer impedance (Z_T) of the gasketed joint is the measured voltage across the gasket divided by the amperes/meter, and is given in ohm-meters, i.e.,

$$Z_T = \frac{E \text{ (Volts)}}{I \text{ (Amps/meter)}} = \text{Ohm-meters}$$

Figure 6 illustrates a transfer impedance test fixture designed and developed by members of the IEEE standards committee. The calibrated current enters the fixture through the input connector. This current flows through a 50 ohm resistor onto the contact plate, through the gasket, to the base plate and back through the connector. The amperes/meter is the calibrated current delivered to the input connector divided by the circumference of the gasket in meters. The voltage generated by the current flowing across the gasketed joint is measured by a receiver (tunable volt meter) attached to the output connector.

EM Joint Considerations

EMI gaskets are used in aerospace vehicles to provide a lower EM bond and higher reliability to a faying surface than can be achieved without the gasket. The joint (or faying) surfaces are also plated to protect the base metal from corrosion. Both of these can create problems in obtaining the EM bond or protection from lightning that must be achieved to protect modern aerospace vehicles from the induced EM fields generated by the current in a lightning strike. As is illustrated in Table 1, the field strength induced into an airframe structure as a function of a 200,000 ampere lightning strike can vary by more than three orders of magnitude. This variation is due to the impedance of the joint surface, as well as the gasket which is selected. A gasket is required for impedances of .0001 ohm-meters and less, and to reduce the number of fasteners required to hold the door or maintenance cover in place, where less fasteners facilitate maintainability requirements.

The contents of Table 2 illustrate work that was accomplished by Earl Groshart. In obtaining the data, aluminum, steel and copper bars were coated with various types of plating. The resistance was obtained by applying a force on a set of bars pre-

Resistance Measurements of Selected Materials

Material	Finish	Resistance (mΩ)		
		Initial	At 400 hr 95% RH	At 1,000 hr 95% RH
Alum				
2024	Clad/Clad	1.3	1.1	2
2024	Clean Only/Clean Only	0.11	5	30
6061	Clean Only/Clean Only	0.02	7	13
2024	Light Chromate Conversion/Same	0.40	14	51
6061	Light Chromate Conversion/Same	0.55	11.5	12
2024	Heavy Chromate Conversion/Same	1.9	82	100
6061	Heavy Chromate Conversion/Same	0.42	3.2	5.8
Steel				
1010	Cadmium/Cadmium	1.8	2.8	3
1010	Cadmium-Chromate/Same	0.7	1.2	2.5
1010	Silver/Silver	0.05	1.2	1.2
1010	Tin/Tin	0.01	0.01	0.01
Copper	Clean Only/Clean Only	0.05	1.9	8.1
Copper	Cadmium/Cadmium	1.4	3.1	2.7
Copper	Cadmium-Chromate/Same	0.02	0.4	2
Copper	Silver/Silver	0.01	0.8	1.3
Copper	Tin/Tin	0.01	0.01	0.01

Table 2.

pared as described. The bars were then subjected to a moisture soak of 95% relative humidity for 400 hours and then an additional 600 hours. A resistance test was performed at the conclusion of each of the moisture soaks.

What this table illustrates is that the EM bond can vary as a function of aging, (i.e., the lightning protection will degrade with time) and the variation in the joint resistance can be as much as four orders of magnitude as a function of the surface preparation and aging. This means that the protection from lightning induced EM waves can vary by as much as 80 dB as a function of the selection of the plating as well as the selected EMI gasket.

MIL-STD-810 contains environmental conditions and subsequent test procedures which various DoD systems and components can be subjected to. Table 3 contains a list of Transportation/Storage environments that have been known to degrade the conductivity of some of the EMI gaskets on the market. Table 4 lists Mission/Sortie environments which have been known to degrade the conductivity of joints (both gasketed and un-gasketed). Degradation of the conductivity of the joints due to the listed environments can present a significant lightning induced risk to an aerospace vehicle.

Transportation/Storage Environments

Environmental Stress Condition	Test Method/Procedure (MIL-STD-810D)
High Temperature (Dry/Humid)	Method 501.2
Low Temperature (Rain/Hail/Freezing)	Method 502.2
Thermal Shock	Method 503.2
Solar Radiation	Method 505.2
Fungus Growth	Method 508.3
Rain	Method 506.2
Humidity	Method 507.2
Salt Fog	Method 509.2

Table 3.

Mission/Sortie Environments

Environmental Stress Condition	Test Method/Procedure (MIL-STD-810D)
High Temperature	Method 501.2
Salt Fog	Method 509.2
Explosive Atmosphere	Method 511.2
Rain	Method 506.2
Emersion	Method 512.2
EMP/Lightning	MIL-STD-461 Req CS12

Table 4.

Summary

The computers and computer peripherals in spacecraft and modern aircraft are subject to high risk of failure due to lightning induced EM waves. When these computers, computer-peripherals, or the signal control and/or power lines leading to or from the computers are behind surface mounted maintenance panels, the computers are subject to failure when the equipment is being protected by the .0025 ohm bonding requirements of MIL-B-5087.

Bonding levels as low as .000002 ohm-meters are achievable and can eliminate the problem. However, the proper EMI gasket as well as the joint surfaces the gasket will interface with must be selected with extreme care. In evaluating the gasket and joint surface, transfer impedance test methods should be employed to properly assess the risk.

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