

Lightning Effects on Hydraulic Transport Elements in Composite Aircraft

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ABSTRACT

In this study, lightning effects on hydraulic transport elements in composite aircraft have been considered for the first time. Based on recent test results and analysis, several forms of possible structural damage and system component failures are presented. A unique approach in analysis has been taken to account that hydraulic transport elements, as a part of several aircraft systems, have a common interface with electrical wiring, and become complex electric networks. When an aircraft is exposed to a direct lightning strike, a metal skin on the wings and fuselage will conduct lightning currents in a way that only a small amount of induced electromagnetic energy will be present on hydraulic transport elements. So, in the past, hydraulic tubes, actuators, manifolds, and all other hydro-mechanical devices, as parts of various aircraft systems, have never been considered as lightning sensitive components. A new trend in the aerospace industry is the use of composite materials in the construction of aircraft wings and fuselages. This has brought about new technologies, with a reduction in weight being a major advantage. At the same time, lightning safety has become a new challenge, not only for aircraft system integrators but for component and subassembly designers as well. Due to the low conductivity of the composite structures, in the case of direct lightning strike, high currents will flow through the conductive structural elements. As a result of electromagnetic effects, a significant amount of energy will be present on all aircraft metallic assemblies, including electrical harnesses, cables and hydraulic transport elements. Considering that all hydro-mechanical components are connected with hydraulic tubes, they become part of conductive paths where induced currents and pulse voltages can cause serious damage. The intention of this article is to bring awareness to the Aerospace industry, and to outline safety boundaries concerning future projects with composite structures.

Key words

Lightning secondary effects, composite aircraft, hydraulic transport elements, models, electromagnetic field, coupling, induced voltages

INTRODUCTION

For many years lightning phenomenon in the earth's atmosphere has been the subject of physical studies and considerations, especially in the aerospace industry and in civil aviation. It is estimated that each commercial aircraft will be affected by a lightning strike every 3000 flight hours, or one time per year. For the aircraft made of aluminum and titanium, when lightning strikes occur, the aircraft's structure and metallic skin become a part of the stationary lightning discharge channel. Entering through the aircraft's conductive structure, a lightning charge rapidly spreads and current density is quickly reduced to harmless levels. As the aircraft moves, the lightning channel sweeps across the aircraft surface. An aircraft exits the lightning channel after it has flown a distance approximately equal to its own length. The time length of the stroke and continuing currents are long enough that it would appear to an observer on the ground that lightning is exiting from the aircraft through the tail, as shown in [Figure 1](#).

Table 1. Standard lightning current components applicable to aircraft lightning protection design and certification.

Lightning Current	Standard Component	I_{PK} (KA) (Peak current)	Q (As) (Injected current over time period)	Action Integral ($A^2 s$)	Pulse Peak Time Duration
First Stroke	A	200	18.9	$2 * 10^6$	500 μs
Intermediate Current	B	4	9.4	$2.6 * 10^4$	5 ms
Continuing Current	C	0.4	200	$8 * 10^4$	0.5 s
Subsequent Stroke	D	100	4.7	$2.5 * 10^5$	250 μs

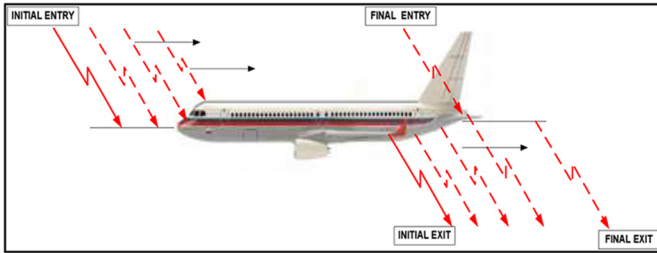
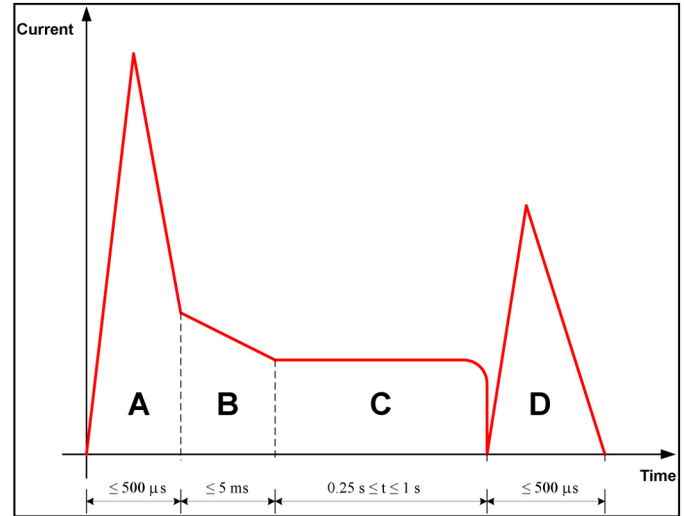


Figure 1. Typical path of sweep flash attachment points.

Two types of lightning effects are known:

- Direct effects or physical damage to the structure, due to high voltage and high current flow. Damage may be extensive if lightning energy dispersion is prevented, or if there is limited current-carrying capacity in the path taken by the lightning channel. Although direct lightning strikes to aircraft have not recently been a major cause of aircraft accidents, certain aircraft components and systems are of special concern regarding potential lightning effects. Currents flowing through the aircraft structure can also result in isolated arcing or sparking and heating. If this occurs in a fuel tank or in flammable leakage areas, explosion, fire, and catastrophic structural damage can result.
- Indirect effects are caused by lightning induced electromagnetic fields that couple high voltages and currents into an aircraft's internal environment and can cause temporary or permanent damage to aircraft system components.

The external lightning environment, representing cloud to earth positive lightning flash currents, can be simplified in four waveform components A, B, C, & D as it is shown in [Figure 2](#). Each lightning component is characterized with a different time duration and energy level (as shown in [Table 1](#)). These interact with an aircraft's structure to induce voltage and current transients on the internal cabling and equipment.



NOTE: Not to scale.

Figure 2. Lightning waveform components.

Component (A) represents the first stroke of a lightning event with amplitudes up to several hundred kiloAmpere, and this component carries the highest energy level. Component (B) is an intermediate current of some tens of kiloAmpere reducing to component (C) which represents continuing current flowing in the lightning channel. This can last for several hundred milliseconds with currents in the hundreds of Amperes range. Subsequent stroke represented with component (D) corresponds to restrikes on the airframe with peak amplitudes up to one hundred kiloAmpere range. For indirect lightning effect evaluation, a lightning restrike with component (D) can be replaced with multiple strokes or with multiple bursts.

The multiple strokes consist of a component (D) current pulse, followed by 13 randomly spaced subsequent strokes, with a peak amplitude equivalent to 50% of the component D amplitude, and all spaced randomly over period of 1.5 (s). The multiple burst is comprised of 3 bursts of 20 current pulses characterized with high rate of rise whose amplitude and time duration are much less than those of a return stroke.

More details about primary lightning waveforms definition, timing, and intensity can be found in ARP5412.

Regardless of the aircraft structure, electromagnetic waves can penetrate and transients will be induced in the internal systems. The major induced transients in aircraft systems are results of high current amplitudes and rates of change of the lightning components A and D. The single largest event is the initial stroke (component A), this can be coupled as a magnetic field, penetrating the structure and inducing currents with the Waveform 1 shape (6.4/69 μ s), shown in [Figure 3](#).

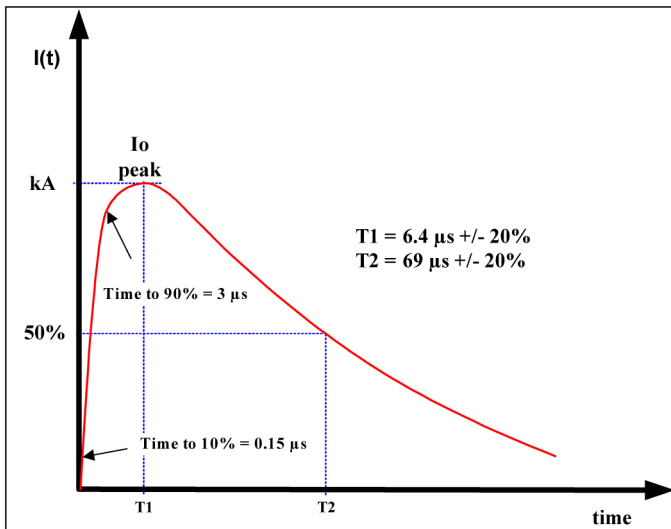


Figure 3. Double Exponential Current Waveform 1 per ARP5412.

A Waveform 1 signal can be synthesized as a double exponential curve defined in the [Equation \(1\)](#).

$$I(t) = I_o (e^{-\alpha t} + e^{-\beta t}) \quad (\text{Eq. 1})$$

Where:

$$\alpha = 11,354 \text{ (s}^{-1}\text{)}$$

$$\beta = 647,265 \text{ (s}^{-1}\text{)}$$

t = Time (s)

and

I_o is peak pulse current (A).

The idealized transient waveforms used for the magnetic field penetration analysis, indirect tests, and simulation are Waveforms 1, 5B, and D, as defined in ARP5412.

Based on numerous lightning events during extensive flight test program, a NASA report "Aircraft Jolts From Lightning Bolts" indicates that electromagnetic coupling includes both

external and internal aspects. External coupling refers to the generation of surface currents and charges on the aircraft metallic skin, while internal coupling refers to the generation of electromagnetic fields, currents, and voltages on the inside of the aircraft. There are several mechanisms over which the external lightning event is coupled into an aircraft's systems. In reality, most transients are induced as complex waves through several coupling paths. For practical purposes, these can be narrowed down to three basic mechanisms: aperture coupling, along exposed conductors, and diffusion.

Apertures include hatches, doors, areas covered by composite panels, engine exhaust ports, windows, and wheel wells. Exposed conductors include antennas, airspeed probes, and some electrical or control cables which may be struck directly by lightning or energized by fields induced by nearby lightning channels. Diffusion describes the induction by surface currents of tangential electric field inside aircraft, by means of surface transfer impedance that relates the internal electric field to the surface current. The transfer impedance is a function of the surface material, its thickness, and frequencies of the lightning waveform. At low frequencies, the internal tangential field is simply the resistive voltage drop along the surface.

This mechanism produces voltages in loops existing between internal conductive elements and the aircraft structure. If the structure is highly conductive, the voltages may have the wave shape associated with the external environment

1. AIRCRAFT FLUID TRANSPORT ELEMENTS ACTING AS A LIGHTNING PATH

Recently, the aerospace industry has introduced a full carbon fiber composite structure civil aircraft. Performance - enhancing composite materials are relatively poor electrical conductors resulting in new challenges to ensure that required lightning protections are met. Advanced techniques, such as metallization of exterior surfaces and fine metal wires implemented into carbon fiber composite skins, are used to provide adequate conductivity for lightning currents. Despite those protections on composite aircraft, shielding and attenuation from composite skin are not sufficient to protect from high magnetic field frequencies that are associated with lightning. As result of that, it is expected that in the case of direct lightning strike, a significant amount of electromagnetic energy will be transferred in a form of high voltages and currents present on all electrically conductive elements. In that category, we can consider electrical harnesses, cables, wiring and fluid transport elements. Fluid transport elements include all tubing, fittings, mechanical components, and equipment containing electric/electronics elements. As such, they are a major part of an aircraft's hydraulic, fuel, nitrogen generation, cooling equipment, and

fire extinguishing systems. In the past, none of those systems have been considered from a lightning effects point of view. With fully composite aircraft, lightning effects on fluid transport elements have brought about new safety concerns, particularly in the area of hydraulic system and hydro-mechanical components.

Hydraulic transport elements are part of the flight control and landing gear systems. Hydraulic tubing and hydro-mechanical components are located from the nose gear bay to the vertical stabilizer, and across the entire wing span, as shown in [Figure 4](#).

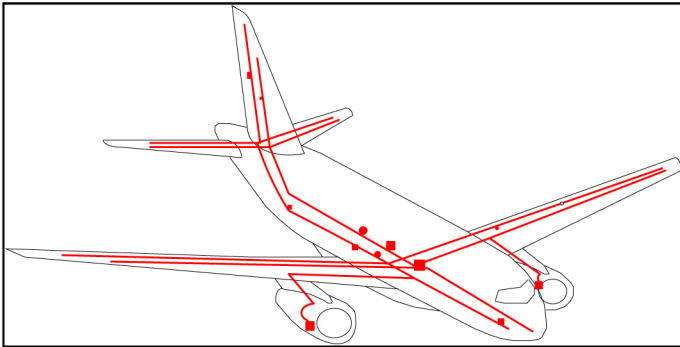


Figure 4. Simplified architecture, aircraft single hydraulic system.

Knowing that commercial aircraft, made of Carbon Fiber Reinforced Polymer (CFRP), have multiple independent hydraulic systems with all components located in non-pressurized areas - with long and electrically continuous loops - it is reasonable to consider that each hydraulic transport element will be exposed to secondary lightning effects. Due to the CFRP structure, lightning pulses are stretched out in time to some extent and the threat is also present inside the pressurized vessel. Induced currents on hydraulic transport elements on aircraft with metal skin are typically in order of a few tens or hundreds of Amperes, while on aircraft with composite skin, lightning current amplitudes are much higher.

Based on analysis, it has been estimated that fluid transport elements made of aluminum, titanium, and corrosion resistant steel (CRES) on aircraft with composite structure, will be exposed to the high current pulses in the region of 5 - 9 (KA), with length of 30 -150 (μs). The threat also has a DC follow-on current, in the range of 2 - 400 (A) for 250 (ms).

1.1. Magnetic Forces on Hydraulic Tubing

One of the lightning effects on hydraulic transport elements is a magnetic force, which can cause structural damage. When hydraulic tubes are acting as parallel conductors, tubes will be exposed to the magnetic force $F(t)$ which can be approximated and calculated as:

$$F(t) = \frac{\mu_0 * I_1(t) * I_2(t)}{2\pi} \times \frac{Z}{D} \quad (Eq. 2)$$

Where:

$F(t)$ = Magnetic force (N)

D = Distance between hydraulic tube centerlines (m)

Z = Length of the parallel hydraulic tubes (m)

$I_1(t)$ = Pulse current in the first conductor, (A)

$I_2(t)$ = Pulse current in the second conductor, (A)

μ_0 = Magnetic constant in air, $4 \pi 10^{-7}$ (H/m).

The force between two hydraulic tubes is attractive if the two currents flow in the same direction, and repulsive if the currents flow in opposite directions. If those two currents are equal with peak pulse, then the amount of force is proportional to the square of the induced lightning stroke current amplitude. How long the magnetic force will be present depends on the time duration of lightning induced currents. The maximum induced force, as a function of the distance between two parallel hydraulic lines, is shown in [Figure 5](#).

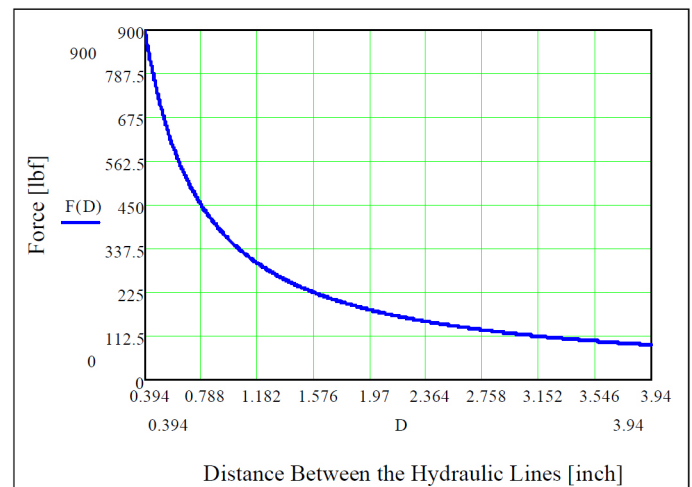


Figure 5. Max induced magnetic force on parallel hydraulic tubing with 6.56 feet (2m) length, and 10 KA peak pulse current present on both tubes, as a function of distance D between two hydraulic lines.

The specific energy of the impulse current thus determines the load which causes a reversible or irreversible deformation on hydraulic tubing. Special attention may have to be paid to the long and parallel hydraulic lines traveling over flat and open surface. One such example is shown in [Figure 6](#), where

hydraulic lines are traveling in parallel configuration from the bulkhead through the Nose Landing Gear Bay.

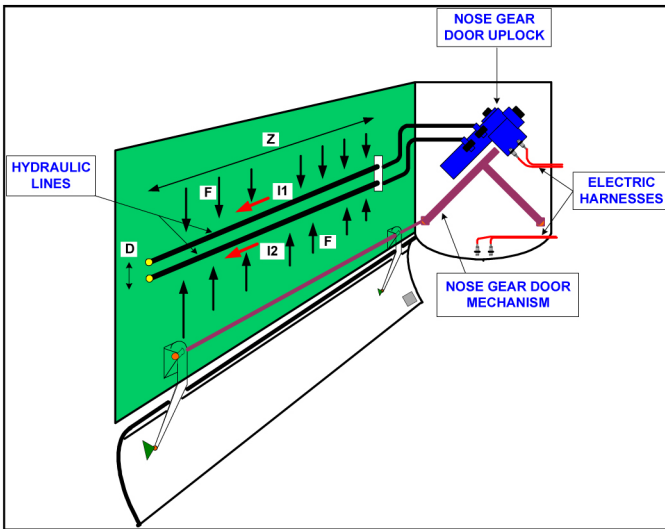


Figure 6. An example of the parallel hydraulic tubing, located in the nose landing gear bay, with lightning induced currents flowing in the same direction.

The amount of deformation is subject to the stiffness of the hydraulic tubing and material properties (Aluminum, Titanium, or CRES) and the duration of exposure to the magnetic force. Obviously hydraulic tubing exposed to the dynamic force caused by induced current pulse will have a different reaction depending on whether it is pressurized or not. For that reason, the most vulnerable parts of the hydraulic transport elements are joints between tubes and hydraulic fittings. The magnetic force amplitude depends on the peak current, but not the rate of change of current. However, the effect of this force on hydraulic tubes and joints would certainly be influenced by the time duration of the assigned lightning flash.

Depending on the tubing material, and installation location, induced peak pulse currents can vary from 5 to 10 (KA). Considering a typical example of the hydraulic lines that are 6.56 ft (2 meters) in parallel length, and 1.97 in (5 centimeters) apart, a maximum induced magnetic forces can be in a range from 45 lbf (200 N) up to 180 lbf (800 N), as shown in [Figure 7](#).

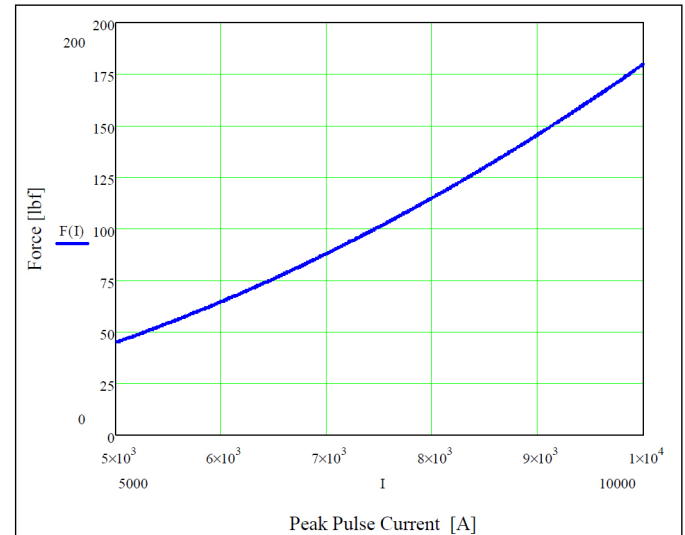


Figure 7. Max induced magnetic force on parallel hydraulic tubing with 6.56 feet (2m) length, and 1.96 inch (5 cm) distance apart, as a function of peak pulse current.

For a proper evaluation of the magnetic force effects on hydraulic transport elements, it is necessary to consider lightning multiple-stroke. Although, a multiple strike is not a harmonic function, it has 13 components where each of them has a significant presence of high frequency harmonics. Such current harmonics, traveling along the parallel hydraulic tubes, will create oscillating forces. In that case, structural damage can occur when magnetically induced mechanical oscillation frequencies are close to the natural frequency of the hydraulic transport elements. For that purpose, different hydro-mechanical conditions and different geometries have to be considered.

1.2. Heating Effect - Conductive Path

Lightning current on its path, passing through hydraulic transport elements and system components, will cause heat generation. When the resistivity of a conducting surface is too high or when cross section area is too low to absorb high current density, lightning currents can deposit significant energy and cause an excessive temperature rise. Considering that a lightning strike is a unipolar non-periodical signal, applying Fourier analysis it can be decomposed to the infinite number of sinusoidal harmonics with different frequencies. As result of that, a current distribution in the conductor cross section, called skin effect, will depend on the frequency, material relevant permeability and resistivity.

Calculated skin effect is a distance δ from conducting surface inward or a depth, where the current density has decreased to 36.8% of its nominal value. A skin effect depth can be calculated per [equation 3](#)