

# Lightning strike effects on composite aircraft

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The present paper aims to evaluate the effects of lightning strike on composite aircraft through a numerical simulation. The simulation is based on the finite difference time domain (FDTD) method which allows analyzing the electro-thermal coupling phenomenon related to this problem. The existent dependency between the physical properties related to this problem is taken into consideration in this work and both direct and indirect effects of lightning on composite aircraft shall be evaluated. For now, the physical properties are presented and some important considerations regarding the lightning strike phenomenon on composite aircraft and its effects.

*Index Terms* — Composite aircraft, electro-thermal coupling, lightning strike.

## I. INTRODUCTION

IT IS ESTIMATED that each commercial aircraft gets hit by lightning once every year on average [1][2]. The probability of lightning strike for short-distance aircraft is higher than for long-distance aircraft [1]. Most of these cases, 90% approximately, happens when the aircraft itself triggers lightning when flying through a heavily charged region of a cloud and the other 10% happens when the aircraft intercepts a natural lightning channel [2].

Up to the year of 2014, lightning strikes have damaged more than 2500 aircraft. Within this context the most severe accident registered so far happened in 1963 when a lightning strike ignited a fuel tank crashing a Boeing 707 and causing 81 people to perish [3].

The effects of lightning can be categorized in direct effects and indirect effects. The former is related to physical damage occurring at the attachment point and indirect effects are associated with the interference due to electromagnetic coupling with systems or cabling [4].

Until the late 60's, aircraft were built essentially with a structure of metal materials, which is considered ideal for mitigating the lightning strike effects once it helps the electrical current flow, reduce the Joule effect and works as a Faraday's cage. However, new materials development and the desire for aircraft weight reduction led to the use of composite materials on its structure. These materials have anisotropic characteristics and low values of electrical and thermal conductivities therefore they are more susceptible to the lightning strike effects. Carbon fiber reinforced plastics (CFRP) have electrical resistance two thousands larger than an aluminum material [4].

Recent studies have shown that the effects of lightning on composite materials can induce fiber breakage, matrix cracking, delamination, thermal decomposition and vaporization of the resin [1]. Regarding the indirect effects, lightning strikes may damage internal electronics components. The present paper is proposed to study the interaction of lightning strikes on composite aircraft to better understand the lightning strike effects making possible to define some strategies to mitigate them.

## II. AIRCRAFT LIGHTNING STRIKE STANDARDS

There are several regulations that describe protection standards for aircraft lightning strike protection. For this study, the Aerospace Recommended Practices (ARPs) from the Society of Automotive Engineers (SAE) are taken into consideration, which was the first organization to address the effects of lightning strikes on aircraft and is a reference for the standard procedures document DO-160 provided by the Radio Technical Commission for Aeronautics (RTCA) [5]. Furthermore, most papers related to this topic follow SAE recommendations. In this study the standards SAE ARP 5412 and SAE ARP 5414 are considered. The former is about the aircraft lightning environment and related test waveforms and the latter is about the aircraft lightning zone.

The standard SAE ARP 5412 defines four current components (A, B, C, and D) for the lightning current. These components are applied to determine direct effects. Current waveform E is used to determine indirect effects. In most studies and in this one as well, only the components A and D are considered, since they represent the highest current peaks [6]. They are usually represented by a double exponential but for this study the expression presented in (1) will be used. This model is more accurate and reproduces better the physical phenomenon since it does not exhibit a discontinuity in its time derivative at  $t=0$  [7].

$$i(t) = \frac{I_0}{\eta} \frac{(t/\tau_1)^n}{1+(t/\tau_1)^n} \exp(-t/\tau_2) u(t) \quad (1)$$

where  $I_0$  is the amplitude of the current,  $\eta$  is the amplitude correction factor,  $\tau_1$  is the front time constant,  $\tau_2$  is the decay time constant,  $n$  is an integer number, and  $u(t)$  is the Heaviside step function.

## III. ELECTRICAL CONDUCTIVITY OF CARBON FIBERS

As mentioned earlier composite materials have anisotropic characteristics. However, the electrical conductivity of the dry carbon fiber multidirectional thin layers can be expressed by an equivalent electrical conductivity tensor, but first the electrical conductivity for each layer must be evaluated. Considering each layer, along the fibers' direction the electrical conductivity of the composite can be obtained from

the multiplication of the fiber conductivity with its volume fraction since the composite matrix is nonconductive. Transverse to the fibers' direction there are several methods to estimate the electrical conductivity, however only the percolation method model yields results which are in agreement with the experimental data, therefore that is the one considered for this work. The percolation theory evaluates the effects of varying the connectivity of elements (particles) on an arbitrary system and according to this theory the electrical conductivity of composite material can be expressed as a function of the volume fraction of the fillers (carbon fibers) and its conductivity. Then, for each layer the electric conductivity tensor as a function of the conductivities at the two main directions is expressed by (2) [8].

$$\sigma = \begin{bmatrix} \sigma_1 m_1^2 + \sigma_2 m_2^2 & (\sigma_1 - \sigma_2) m_1 m_2 \\ (\sigma_1 - \sigma_2) m_1 m_2 & \sigma_1 m_2^2 + \sigma_2 m_1^2 \end{bmatrix} \quad (2)$$

where  $\Theta$  is the fiber orientation,  $m_1 = \sin\Theta$  and  $m_2 = \cos\Theta$ . For the multidirectional layer the equivalent tensor is obtained by the weighted average of all layers. For the case of the anisotropic and homogeneous medium, the electric conductive tensor is symmetric.

In general, the electrical conductivity has a linear dependency on the temperature. Data relating this dependency can be found in literature for many commercial carbon fibers.

#### IV. THERMAL PROPERTIES OF CARBON FIBERS

The thermal conductivity of carbon fibers also varies with the temperature. The increase in temperature causes the thermal conductivity to increase as well. It behaves similarly to the electrical conductivity and the same way experimental data about the thermal dependency of the carbon fiber thermal conductivity for commercial carbon fibers can be found on literature. However, the thermal conductivity does not have much influence on the effects of lightning strike on composite material compared to the specific heat. Increasing the specific heat can reduce the direct effects of the lightning strike on composite laminate [4]. Values of the specific heat varying with the temperature are defined in Table I.

TABLE I  
SPECIFIC HEAT VARIATION WITH THE TEMPERATURE [4]

Temperature (°C)	Specific heat (J/kg°C)
25	1065
343	2100
500	2100
510	1700
1000	1900
3316	2509

#### V. JOULE EFFECT

When an electric current flows through a solid or liquid of finite conductivity, the electric energy is converted to heat through resistive losses in the material, this is expressed by (3), which represents the Joule effect and gives the temperature as function of the thermal properties of the composite laminate,

the current density and the electric field generated from the aircraft lightning strike [8].

$$\left[ (1 - \varphi)(\rho c)_f + \varphi(\rho c)_m \right] \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + J \cdot E - \dot{Q}_{losses} \quad (3)$$

where  $\varphi$  is the volumetric fraction of the resin,  $c$  is the specific heat;  $\rho$  is the density;  $k$  is the thermal conductivity tensor;  $T$  is the laminate temperature;  $J$  is the current density;  $E$  is the electric field;  $\dot{Q}_{losses}$  is the convection and radiation losses.

#### CONCLUSION

The main considerations about the physical characteristics for the evaluation of lightning strike on carbon fibers laminate are presented. The aircraft lightning strike standards to be used are presented as well. These characteristics are more related to the direct effects of the lightning strike. Ref. [9] is considered for the evaluation of the indirect effects. It presents a procedure developed for the electromagnetic simulation of lightning interaction to structures of composite materials. But the update procedure adopted for the electromagnetic field is the one described in ref. [10]. The authors derive an extension of the FDTD equations, proposed by Yee, to evaluate the electrical and magnetic fields in an anisotropic material. Details about the numerical simulation approach and results will be discussed in the full version of the paper.

#### REFERENCES

- [1] F. S. Wang, N. Ding, Z. Q. Liu, Y. Y. Ji, and Z. F. Yue, "Ablation damage characteristic and residual strength prediction of carbon fiber/epoxy composite suffered from lightning strike," *Compos. Struct.*, vol. 117, no. 1, pp. 222–233, 2014.
- [2] I. A. Metwally, A. A. A-Rahim, F. Heidler, and W. Zischank, "Computation of transient-temperature profiles in objects exposed to simulated lightning currents," *2003 IEEE Bologna PowerTech - Conf. Proc.*, vol. 1, pp. 194–199, 2003.
- [3] INPE, "ELAT - Grupo de Eletricidade Atmosférica - Aviões." [Online]. Available: <http://www.inpe.br/webelat/homepage/menu/infor/relampagos.e.efeitos/avioes.php>. [Accessed: 30-Sep-2016].
- [4] F. S. Wang, Y. Y. Ji, X. S. Yu, H. Chen, and Z. F. Yue, "Ablation damage assessment of aircraft carbon fiber/epoxy composite and its protection structures suffered from lightning strike," *Compos. Struct.*, vol. 145, pp. 226–241, 2016.
- [5] M. Gagné and D. Theriault, "Lightning strike protection of composites," *Prog. Aerosp. Sci.*, vol. 64, pp. 1–16, 2014.
- [6] Z. Tianchun, W. Jin, M. Keyi, and F. Zhenyu, "Simulation of lightning protection for composite civil aircrafts," *Procedia Eng.*, vol. 17, pp. 328–334, 2011.
- [7] A. Andreotti, S. Falco, and L. Verolino, "Some integrals involving Heidler's lightning return stroke current expression," *Electrical Engineering*, pp. 121–128, 2005.
- [8] A. Nikolaos, "Calculation of electrical conductivity and electrothermal analysis of multilayered carbon reinforced composites: application to damage detection," University of Patras, 2013.
- [9] M. D'Amore and M. Sabrina Sarto, "Time-domain analysis of lightning interaction to aeronautical structures composite materials," *IEEE 1997 Int. Symp. Electromagn. Compat.*, pp. 397–402, 1997.
- [10] J. Schneider and S. Hudson, "A finite-difference time-domain method applied to anisotropic material," in *IEEE Transactions on Antennas and Propagation*, vol. 41, no. 7, pp. 994–999, Jul 1993.