IN-STRIKE DYNAMICAL MEASUREMENTS OF CONTACT RESISTANCES

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ABSTRACT

Assemblies representative of aircraft junctions made of two materials and a fastener have been subjected to lightning current waveforms in laboratory. Current distributions on the different parts of the assemblies have been measured. An electrical equivalent circuit of the assemblies has been built. An inverse method has been designed to extract the dynamical in-strike electrical parameters (resistances, inductances, generators) of the circuit from the measured current distributions. It is shown in particular that the in-strike contact resistances between the different parts are systematically very small, even when the pre- or post-strike values are large. This effect is related to the appearance of internal discharges in the gaps of the assembly.

1 INTRODUCTION

The design of Carbon Fiber Reinforced Plastic (CFRP) panel assemblies in fuel tank areas of aircrafts is primarily driven by structure requirements related to mechanical strength constraints and aerodynamics. However, other constraints have to be taken into account also and lightning is one of them. It may induce strong electrical currents circulating into the aircraft structure and in particular in the fuel tank area. This might result in possible sparkings and generation of hot spots with potential hazardous effects if precautions were not taken. Junctions between different material panels are areas where these phenomena are more likely to occur. A research program aiming at understanding the conditions of occurrence of such phenomena at these locations has been undertaken. Different kinds of junction representative of various aircraft technologies have been tested in laboratory against standard aeronautical lightning environment. Current distributions in the different parts of the assembly were measured, and light emitted by possible sparking phenomena detected.

The present paper focuses on the analysis of the measured current distributions. The main objective of this analysis is to extract information on the in-strike dynamical electrical impedances of the different parts, and to correlate them to the ones measured before or after the strike. Two characteristics of the injected lightning current are expected to have significant effects on the in-strike impedances. One is the fast rise time of the lightning strike current which is typically of a few micro-seconds, such that inductive effects cannot be neglected. Another one is the high value of the peak current, typically of the order of 100 kA, such that the dependence of the material and junction resistances on the current intensity cannot be neglected anymore. The main focus of the paper is on these dependences which bring non linearities in the electrical modelling of the junctions.

The present study is justified by the fact there have been only a few attempts to study the non-linearities of the resistances at junctions in the aerospace community (for an example see [1]). But it should be pointed out that the interest of the present investigation goes beyond the limits of this community. For instance, knowledge of the dynamical performance of ground electrodes under lightning current is a problem of interest for a large community involved in the protection of ground based facilities. Ionization of the soil and inductive phenomena are known to be two key physical ingredients controlling the performances of earthing systems [2]. Simple phenomenological models have been used for many years to describe intensity-dependant grounding resistances [3] but more sophisticated ones involving sparking and ionization regions have been built recently to describe breakdowns and filamentary arc paths in ground [4]. Besides, there is a growing use of composite materials in structures and equipments which have to be protected against lightning, wind mills is a noteworthy example, and controlling the electrical behaviour of material junctions is also a need in this context.

The present abstract is organized as follows. In section 2, the assemblies considered in the present study and the test set-up are described. Section 3 shows the electrical model of these assemblies, typical measured current distributions and the impedances extracted from such measurements. Section 4 is a conclusion on the lessons learnt from this study on the occurrence of sparking.

2 ASSEMBLIES AND TEST SET-UP

A typical aircraft junction in a wing box consists of two panels, named skin (outer part) and rib (inner one), which are assembled together with rows of fasteners. In the present study, the skin is made of CFRP, the rib and the fastener of metal. We focus on the vicinity of a single fastener in such a row and we consider the behavior of the assembly when a lightning arc is attached on the fastener head. A schematic picture of this area is shown in fig. 1 in a plane containing the axis of symmetry. The samples under test consist of two disks representing skin and rib assembled by a central fastener. The skin may be covered by a metallic mesh designed to reduce possible damages induced by lightning strike and is painted. Sealant may be inserted in the gaps between the different parts, in particular between skin and rib, and also between fastener and panels. The metallic nut may be isolated from rib also by a paint layer.

A typical striking scenario of such a junction is the following. Lightning arc attaches to the bolt head because of local electric field enhancement. Lightning current flows through the structure and spreads among the different parts. The metallic mesh plays a key role in diverting a significant part of the current flow. Depending on the quality of the contacts, voltage drops build up between the different parts. The voltage drop may induce electrical breakdown and discharges between rib and nut, leading to unwanted sparking inside wing box. Moreover, voltage drop between bolt and panels may also induce breakdown and discharges in the gap between bolt and panels, leading to overpressure in this confined volume, eventually leading to hot matter ejection between nut and rib, again inside wing box. It is therefore reasonable to assume that the design parameters such that the size of the metallic mesh, the quality of the electrical contacts

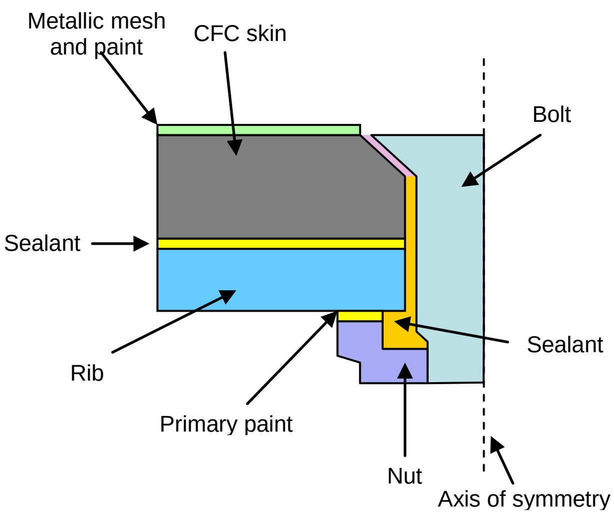

Figure 1. Junction at the fastener scale.

between fastener and panels, the size of the gap between them…should play key roles in the occurrence of sparkings. Consequently, a standard junction type was defined, and derived types were obtained by changing one by one each of the above mentioned design parameters with respect to the standard one. Several samples of each type were manufactured.

These samples were inserted in a lightning current generator circuit suited for lightning direct (structural) effect studies, as shown on fig. 2. The injected current waveform can be described by a double-exponential function,:

$$I(t) = K(e^{-\frac{t}{t_1}} - e^{-\frac{t}{t_2}}) \qquad (1)$$

where t_1 and t_2 are of the order of 10 µs and 20 µs respectively. The peak current ranges from 50 to 100 kA and the action integral from 65000 to 250000 A^2s. Notice that what we call lightning strike in this paper is the application in the laboratory of this standard waveform, which describes in fact a single strong return stroke, without consideration of the different phases (initiation, multiple strokes...) which occur in reality.

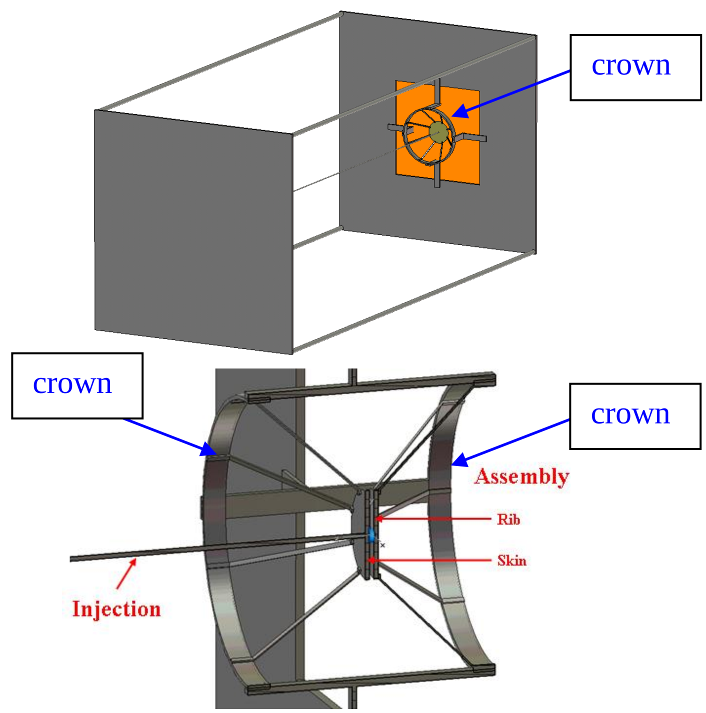

Figure 2. Test set-up. Upper part: global view, showing the current injection in the central part of the sample, the 8 branches connecting one side of the sample to a circular crown (the symmetrical part on the other side is hidden), the 4 bars connecting the crown to a return plate and 4 return conductors of the generator. Lower part: close-up in the vicinity of the assembly under test. The sample is shown cut along a diameter. 4 return conductors on each side connecting the sample to the 2 crowns as well as 1 of the 4 return bars are shown.

As shown on fig. 2, eight return conductors connect each side of the sample to one of the two crowns, which are in turn connected together to the return circuit of the generator. Current probes installed on these return conductors allow to measure separately currents flowing on each disk of the assembly. Additionally, light emitted by possible sparking phenomena is detected by optical fibers and digital cameras.

3 RESULTS AND AND ANALYSIS

Fig. 3 shows the electrical model of the assembly. As we will focus on the differential current between skin and rib, we do not need to include the whole generator circuit in the model, but instead we consider a local model with two branches corresponding to the skin and rib parts. Defining from the quantities shown on fig. 3: $Rs=Rs_1+Rs_2$, $Rr=Rr_1+Rr_2$, $Ls=Ls_1+Ls_2$, $Lr=Lr_1+Lr_2$ as well as: $L=Ls+Lr-2M$, $R=Rs+Rr$, $\Delta L=Lr-Ls$, $\Delta R=Rr-Rs$, the differential current $i=i_s-i_r$ is a solution of the first order differential equation :

$$i+\tau\frac{di}{dt}=\frac{\Delta R}{R}I+\frac{\Delta L}{L}\tau\frac{dI}{dt}+\frac{e_{arc}}{R} \qquad (2)$$

This equation describes a circuit with time constant $\tau=L/R$ including three current generators. This equation has an analytical solution if we assume that the injected current is given by eq. (1) and that all electrical elements (resistances, inductances, generators) are constant. One important outcome of the current measurements was to show that this hypothesis is correct in a piecewise manner: the electrical parameters can be considered constant on large time intervals (in fact usually the entire strike), and when changes are observed, they occur on a time scale much smaller than the one used here, which is of the order of 1 µs. In each time interval where electrical parameters are constant, the analytical solution to eq. (2) can be used. This allows to fit the time dependence of the measured differential current to this analytical solution. This fit consists in a non linear optimization of the resistances, inductances, and generators of the circuit and can be considered as an inverse method to extract circuit parameters from measured currents. In particular, the in-strike resistances thus obtained can be compared to the pre- and post- strike values, which can be straightforwardly measured using an ohmmeter.

Fig. 4 shows an example of differential current waveform i/I, relative to the total injected current. At short times, inductive effects are dominant because injected current has a strong time dependence and differential current is positive because the skin branch has a smaller inductance

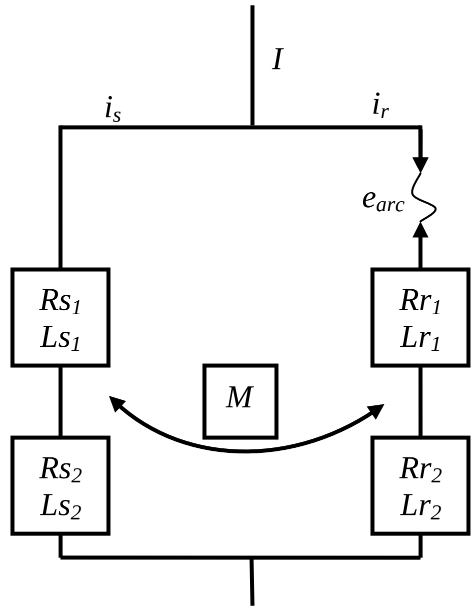

Figure 3. Electrical model of the assembly. The injected current I splits into two branches corresponding to the skin and rib currents i_s and i_r. Each branch is divided into a first portion which corresponds to the skin (resistance : Rs_1, inductance : Ls_1) and rib (resistance : Rr_1, inductance : Lr_1) disks, and a second portion (Rs_2, Ls_2 and Rr_2, Lr_2) corresponding to the eight return conductors on each side. The possible occurrence of sparks between fastener and panels is indicated by the short curved line, and the voltage drop in the arc by e_{arc}. There is a mutual inductance coupling M between both branches. These two branches merge at the level of the crowns (fig. 2).

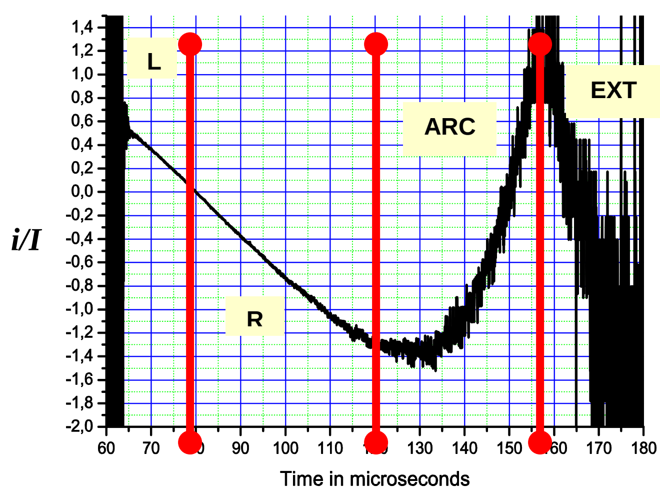

Figure. 4. Time dependence of the relative differential current i/I. The vertical lines define four time intervals. The ones labeled “L”, “R” and “ARC” correspond to intervals where one of the three generators (eq. (2)) dominates the others (#2 in “L”; #1 in “R” and #3 in “ARC”). In region “EXT”, all generators extinguish and the currents become small and noisy.

than the rib one (“L” zone). At longer times (“R” zone), resistive effects dominate as injected current is larger and with weaker time dependence. The differential current becomes negative since the resistance of the CFRP skin branch is larger than the one of the metallic rib. In the “ARC” region, i/I increases and this is due to the e_{arc}/R generator in eq. (2) which becomes dominant over the two others. This “ARC” region is useful to extract with the non linear fit described above the voltage drop in the electrical arc which takes place in the gap between fastener and panels of the assembly.

From the measurements of the skin and rib currents and the application of the circuit parameter extraction method, we obtained the following results :

- on the skin side : the in-strike CFRP-metal contact resistance is negligible as compared to the CFRP material resistance. The skin total resistance (measured between fastener head and external rim of the disk) is the sum of the material intrinsic resistance and of the fastener-material contact resistance. The pre-strike skin (CFRP+mesh) material resistance ranges from 5 mΩ (metallic mesh 370 g/m^2), 10 mΩ (mesh 80 g/m^2) to 30 mΩ (no mesh). Post-strike resistances can also fluctuate significantly according to the importance of the damages induced by lightning strikes. However, in all cases, the in-strike fastener-skin total resistances were found close the pre-strike material ones, which means that the in-strike fastener-skin contact resistances are small as compared to the intrinsic material resistances, which have similar values during and before strike.
- on the rib side : the in-strike metal-metal contact resistance is also small (a few mΩ), however not necessarily smaller than the intrinsic material resistance which is metal on this side. It is however much smaller than the pre-strike contact resistance, the fastener being in fact isolated from the rib by a layer of paint. The post-strike contact resistance can vary considerably according to the kind of damages performed by the lightning strike. It can be large if strike induces erosion between fastener and rib, creating a post-strike open circuit. It can become very small if, on the contrary, lightning strike induces a melted metallic bridge between fastener and rib which survives post-strike solidification.
- internal discharge voltage drops (in the gap between fastener and panels) were found in the range 10-50 V. In such short gaps (fastener-panel distance smaller than 1mm), one expects this voltage drop to result mainly from the contributions of the arc-material voltage drops (anodic on the fastener side and cathodic on the panel side) rather than from the intrinsic voltage drop in the arc column which is short.

4 CONCLUSIONS

We have measured current distributions resulting from lightning strikes on junctions made of CFRP and metallic parts representative of assemblies of panels in aircraft wing boxes. We have developed an inverse method which allows extraction of in-strike electrical circuit parameters (resistances, inductances, generators) from these current measurements. It was shown that these in-strike electrical parameters can be considered as constant over large time intervals, usually the entire lightning strike. The in-strike contact resistances were found systematically small and not correlated to the pre- and post-strike values.

It would be an error to deduce from this conclusion that the quality of the contact prior to the strike does not influence its effects on the assembly. The decrease of the contact resistance from a large pre-strike value to a small in-strike one is due to a fast, but significant change of the physical nature of the contact. Initially resistive material becomes conductive due to the local generation of a conductive plasma induced by the large transferred electrical current and a related large energy injection in a small confined gap. These physical changes are much more limited when the contacts have a good pre-strike quality.

5 REFERENCES

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ACKNOWLEDGEMENTS

We thank “DGA Techniques Aéronautiques” (Toulouse) for performing the lightning tests on the ElectroMagnetic Means for Aerospace (EMMA) platform.