Lightning in aeronautics

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Abstract. It is generally accepted that a civilian aircraft is struck, on average, once or twice per year. This number tends to indicate that a lightning strike risk is far from being marginal and so requires that aircraft manufacturers have to demonstrate that their aircraft is protected against lightning. The first generation of aircrafts, which were manufactured mainly in aluminium alloy and had electromechanical and pneumatic controls, had a natural immunity to the effects of lightning. Nowadays, aircraft structures are made primarily with composite materials and flight controls are mostly electronic. This aspect of the "more composite and more electric" aircraft demands to aircraft manufacturers to pay a particular attention to the lightning protection and to its certification by testing and/or analysis. It is therefore essential to take this risk into account when designing the aircraft. Nevertheless, it is currently impossible to reproduce the entire lightning phenomenon in testing laboratories and the best way to analyse the lightning protection is to reproduce its effects. In this context, a number of standards and guides are produced by standards committees to help laboratories and aircraft manufacturers to perform realistic tests. Although the environment of a laboratory is quite different from those of a storm cloud, the rules of aircraft design, the know-how of aircraft manufacturers, the existence of international work leading to a better understanding of the lightning phenomenon and standards more precise, permit, today, to consider the risk as properly controlled.

1. The lightning phenomenon
Lightning finds its origin in the clouds of vertical development such as cumulonimbus. Within this kind of cloud, complex phenomena cause the water droplets and ice crystals to charge electrically by friction. These particles are distributed, within the cloud, mainly into two groups of opposite electrical charges. When the electric field reaches a threshold value (of the order of a hundred kilovolts per meter) an arc is formed between the cloud and the ground (20% of cases) or between two clouds (80% of cases).

In the case of lightning strike on an aircraft, the aircraft is flying in an area where the ambient electric field reaches a value of several tens of kilovolts per meter. This field can vary very slowly (about one second) when it is produced by the storm cloud or quickly (tens of milliseconds) when initiated by a natural lightning develops. Two different processes can lead to a lightning discharge as presented in the figure 1:
• In about 90% of the cases, the aircraft, by its presence, triggers the lightning. Indeed, around the aircraft, the electric field is amplified by the geometry of the object. On its surface, the electric field can exceed the ionization value of the air. It then develops from the aircraft, two electrical discharges: one called “positive” because it moves in the direction of the field, the other called “negative” as it moves in the opposite direction.
In about 10% of the cases, the aircraft intercepts an arc of lightning triggered naturally.

In 90% of the cases, the aircraft triggers the lightning discharge

In 10% of the cases, the aircraft intercepts an approaching leader

Figure 1. Scenarios of lightning strike in flight.

This initiation phase is concluded by the junction of these bidirectional discharges with those coming from the cloud and/or the ground. The circuit is then closed and a large amount of electrical charges can then flow into the channel thus formed: the established current phase. It consists of a continuous hundred amperes with a duration of hundreds of milliseconds that on which are superimposed impulse discharges current of several tens of thousands of amperes with a duration of hundreds of microseconds.

Figure 2. Typical current waveform recorded during a lightning measurement campaign in flight [1].

Furthermore, during the phase of a lightning strike, the aircraft continues to move at a certain speed while the lightning channels remain motionless in the air. This phenomenon, called sweeping is the result of the displacement of the lightning arc on the fuselage of the aircraft in a discontinuous manner.

2. The standardized environment
The complexity of the lightning phenomenon and its interaction with a plane is impossible to simulate, in its entirety, in testing laboratories. The best way to demonstrate the resistance against lightning of an aircraft is not to reproduce the phenomenon, but is to reproduce these effects. The effects of lightning on an aircraft are divided into two types:

- **Direct effects**: they represent all the thermomechanical damages to the aircraft structure and external equipments caused by the direct attachment of the lightning channel and/or conduction of the current lightning.

- **Indirect effects**: represent all electrical transients induced by lightning inside conductive components in an aircraft such as electrical circuits.

Civil certification authorities, such as EASA (European Aviation Safety Agency) and FAA (Federal Aviation Administration), require, through text indicating the basic recommendations, to protect aircraft against catastrophic effects of lightning. Standard committees, such as EUROCAE (European Organization for Civil Aviation Equipment) and SAE (Society of Automotive Engineers), establish guides and normative documents that explain how to achieve these recommendations. Among these works, there may be cited:

- **ED-84/ARP 5412A** [2] which defines the waveforms (current, voltage, external and internal environment) used to reproduce the effects of lightning.

- **ED-91/ARP 5414A** [3] which defines the zoning concept: the plane is divided into zones (see figure 4) where a lightning threat will be applied according to the fact that the location will be the site of a direct attachment of the lightning arc, of the sweeping process or also of the conduction of the lightning current. The concept of zoning permits to adapt the lightning protection to the zone of interest and so to optimize the cost and weight of the solution.

- **ED-105 / ARP 5416A** [4] which defines the test methods to reproduce the effects of lightning.

- **But also other guides as AC20-53B, the AC25-981C dedicated to fuel areas or the ED-113 which defines the all the steps that are required for certification to direct effects purpose.**

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**Figure 3.** External standardized current waveform representative of an aircraft lightning strike.

- **Component A**
  - \( \frac{di}{dt} = 140 \text{ kA/µs} \)
  - \( 2.0 \text{ MA}^2\text{s} \)

- **Component B**
  - \( 2 \text{ kA} / 10 \text{ C} \)
  - \( 200-800\text{ A} / 200 \text{ C} \)

- **Component C**
  - \( \frac{di}{dt} = 200 \text{ kA/µs} \)
  - \( 50 \mu s < dt < 1 \text{ ms} \)
  - \( 30 \text{ ms} < dt < 300 \text{ ms} \)
  - \( 3 \text{ by } 20 \text{ pulses} \)

- **Component D**
  - \( \frac{di}{dt} = 140 \text{ kA/µs} \)
  - \( 0.25 \text{ MA}^2\text{s} \)
  - \( 2 \text{ kA} / 10 \text{ C} \)

- **Component D/2**
  - \( 13 \text{ pulses} \)
  - \( 1.5 \text{ s} \)
3. Lightning tests

The tests are one way to demonstrate the resistance of the plane to the effects of lightning. Because of the scale difference between the thundercloud and the facility, tests have to be conducted in a rigorous manner (in accordance with the rules defined in various standard documents) and an inappropriate experimental setup can generate unrealistic results. For each kind of the lightning arc effects, one or more tests will be associated with. To demonstrate the resistance to direct effects, high voltage and high current tests will be performed. Similarly, to demonstrate resistance to indirect effects, equipment and system tests will be conducted.

3.1. Direct effects tests

Due to the electrical power limitation of generators in facilities, it is actually impossible to reproduce simultaneously the voltage and the current damages on aircraft. So, it has been decided to divide these tests into two large categories in order to reproduce the effects of lightning: high voltage testing and high current tests.

3.1.1. High voltage tests. These tests are performed with standardized voltage waveforms [3] representing the variations of the electric field during a lightning strike. Their purpose is to:

- Determine the primary attachment points on a structure and permit to calculate the zoning of the aircraft. Zoning can also be considered as a first barrier because it permits aircraft manufacturer to associate a lightning threat to a zone and so, to adapt the protection that will be associate.
- To test the dielectric parts of an aircraft (such as radome, antenna ...) to possible puncture.

Two voltages waveforms are mainly used for these tests: a faster waveform A dedicated to reproduce the reattachment of the arc channel in zone 2 and the slowest waveform D more appropriated for initial attachment regions in zone 1 (see figure 5).

These tests need to generate arcs of some meters which are often produced by Marx generators. The current flowing in these arcs such generated is often limited to few thousand of amperes and it is not enough to assess the resistance to high current damages.
Figure 5. Voltage waveform A (on the top) and voltage waveform D (on the bottom).

The length of the arcs that can be generated and the volume of the testing facilities are limited that is why it is necessary to perform the tests on mock-ups representative of the aircraft in terms of geometry. Nowadays, these tests tend to be abandoned and replaced by an electric field modelling more reliable.

Tests on antennas and radomes are performed using two waveforms representative of a lightning strike phase:

- A waveform representing the slow variations of the electric field during an arc attachment to the structure.
- A waveform representing the fast variations of the electric field during an arc reattachment of the structure during the sweeping process.

These tests permit to evaluate the lightning protections associated to each part of the aircraft, e.g., lightning strips diverters for radomes.

3.1.2. High current tests. These tests are performed according to the normative current waveforms A, B, C and D defined in Figure 3 which permits to reproduce the power and energy associated to each zone in order to evaluate the thermomechanical damages. Their purpose is to:

- Generate arcs in order to study the behaviour of the structure during an arc attachment. These tests are called arc attachment tests.
- Generate a current flow within a sample. These tests are called current conducting tests.

Each waveform is associated with a specific damage. Continuous waveforms (B and C) can cause surface damages due to the energy deposition by the root arc and this damage is mainly effective on metallic materials. The pulse waveforms (A and D) can cause damages by Joule’s effect, acoustic shock wave and strong magnetic forces but can also generate sparkings which could ignite fuel.
vapours in the tanks. The damage after test must be correlated with specifications and criteria defined by the aircraft manufacturer: mechanical strength, acceptable level of puncture...

The measurements associated with this kind of test are very important because they have to measure currents, voltages, temperatures, mechanical deformations, energy from spark...

![Figure 6. Neutral filtered picture of a 400A continuing arc.](image)

During these tests, the currents which are typically generated are about tens to hundreds of thousands of amperes and the voltages involved are of the order of tens to hundreds of thousands of Volts. These voltages cannot generate electrical arcs with important lengths but are sufficient to breakdown small dielectric thicknesses (such as paints). The arcs generated have lengths of 5 to 10cm and the test electrode has a jet diverter: an insulating ball made with araldite which deflects the anodic jet and thus avoids the contamination of the specimen by the shooting electrode.

3.2. Indirect effects tests

These tests are applied to the equipments for which a protection is required. Their philosophy is based on the diagram below:

![Figure 7. Principle of the lightning indirect effects tests.](image)
At the beginning of the aircraft design, the manufacturer defines a TCL (Transient Control Level): This is a stress lightning level that the equipment could be submitted during a worst-case lightning strike of the aircraft. This level is estimated by calculation, analysis and/or experience from another aircrafts. Then, the aircraft manufacturer applies a margin in order to determine the ETDL (Equipment Transient Design Level) which is the level of certification required to the equipment manufacturer. Tests permit to complete the certification principle. It exists:

- Equipment tests in order to ensure that the equipment under test is able to sustain the ETDL but also to define the susceptibility or faulty level: it is the ETSL.
- System tests in order to measure levels on wiring and equipment and to verify that the measured level (ATL) is lower than the specified (TCL) level.

This principle permits to certify equipments in parallel with the development of the aircraft. The final verification on systems is used to validate the hypothesis.

3.2.1. Tests on systems. These tests occur at the end of the development of the aircraft. Lightning current injections are made directly on the equipped aircraft and permit to define the ATL through measurement of transfer functions. For each equipment, the “worst case” lightning strike is identified: the entry point and the exit point, the type of waveform to be applied depending on the spectral content. At each injection, measurements of current and/or voltage are conducted on the bundles and cables inside the aircraft.

Figure 8. Lightning indirect effects tests on a system equipped with a coaxial current return.

The injections are performed with intensity current generally lower than those imposed by the standardized documents. This is due to:

- The difficulty by the current generators to generate a waveform simultaneously with a fast rising front coupled with a large amount of current.
- The reluctance of aircraft manufacturers to inject a severe current waveform on a plane.

The calculation according to the normalized waveforms is made by extrapolation assuming that the answer of the system is linear. Even more, it is also currently impossible to generate repetitive pulse component such as H or D/2.

In addition, a coaxial current return is used in order to be as close as possible to a lightning strike in flight.
3.2.2. Tests on equipments. For equipments, an internal lightning environment is also defined in the same way that the waveforms shown in Figure 3. These voltage and current waveforms come from analysis and experience but also take into account the location of the equipment in question, its criticality in respect of the safety of flight.

In this context, two types of tests are performed:
- Damage tolerance tests in order to validate the protections.
- Functional tests following predefined acceptance criteria.

4. Conclusion
Lightning is a phenomenon which has to be considered by aircraft manufacturers when developing the aircraft. Nowadays, the demonstration of its capacity to withstand the effects of lightning is largely performed by ground testing. Normative documents are used to guide manufacturers and testing facilities to ensure representative tests and thus reproduce the effects of lightning.

However, many questions still arise. Due to the technological limitation of generators laboratory, it is not possible to simultaneously reproduce all the electrical parameters of a strike: for example, what is the influence of di/dt on the damage or on the appearance of a spark? What could be the influence of repetitive lightning waveforms on the answer of the system in terms of transfer function? Many studies are still needed to better understand the phenomena and perhaps refine the margins of protection taken by manufacturers.

Nowadays, more predictive modelling [5], [6] can help manufacturers and laboratories to better define the lightning tests.

5. Bibliography
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