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The Interaction of Lightning with Aircraft and the Challenges of Lightning Testing

Aircraft are struck by lightning in flight with some regularity and are required to have demonstrated protection against this threat; much of this demonstration is provided by simulating in test the effects of lightning on aircraft structures, components and systems. Clearly these tests need to be carried out in a representative manner and guidance on how to do this is provided in the Aerospace lightning standards and guidance materials produced by the SAE/EUROCAE committees. Nevertheless, there are challenges; for example, due to dramatic differences in both scale and conditions between a lab and the inside of a cloud, achieving sufficient representation of every aspect of the lightning phenomena can be difficult. Before considering these challenges we discuss the phenomenology and effects of lightning and how they are addressed in the lightning standards, in order to provide some background.

Introduction

The incidence of lightning strikes on aircraft in civil operation is of the order of one strike per aircraft per year and it is vital, from a safety point of view, that these strikes do not endanger the aircraft. Earlier generation aircraft, which were predominantly constructed from aluminum and with mechanical controls and electromechanical instrumentation, had a greater inherent immunity to lightning effects. On modern aircraft, the structure is increasingly constructed from composite materials, in particular carbon-fiber composite. There is also an increasing reliance on electronic avionics systems for primary control of the aircraft. Both of these aspects have made aircraft manufacturers pay greater attention to lightning protection and its certification through testing and analysis. Reproducing lightning and its effects under lab conditions can present certain challenges.

In this paper we will explore the interaction of lightning with aircraft, as well as the methodology of testing and we will discuss the challenges faced in simulating the lightning-aircraft interaction in a laboratory.

The lightning threat

Lightning arises from the breakdown of air by the electric fields generated via triboelectric charging in and around cumulonimbus clouds. These electric fields are well below those required to breakdown the gaps between the cloud and ground or between clouds, however, local field enhancements within a cloud (most likely from ice particles [1], though the process is not entirely understood) can be high enough to initiate the growth of leaders (a filamentary discharge [2]) that propagate towards regions of opposite charge. Once a leader creates a conducting bridge between charged regions, the flow of a return stroke current - the 'flash of lightning' - can occur. The return stroke neutralizes all of the unfulfilled leader branches giving the perception of the classic forked lightning pattern.

Strikes on aircraft in civil operation are of the order of one strike per aircraft per year; however, the probability of an aircraft being struck while stationary on the runway in Europe is approximately one strike every hundred years. The reason for the high strike rates while airborne is because the aircraft modifies the electric fields in its vicinity, which acts as a catalyst for lightning attachments: an uncharged aircraft located in an electric field will become polarized and the local electric field values at the aircraft surface will be magnified at those extremities aligned with the field, especially where the radius of curvature of the conducting structure is small, such as on wing tips, the tail tips, radome protection strips, etc., see figure 1.

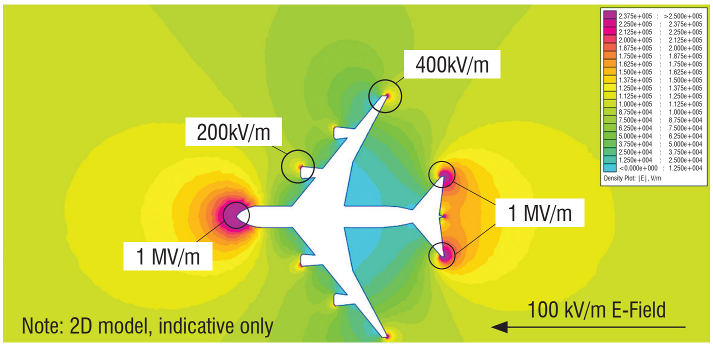


Figure 1 – An indicative 2D electrostatic model of an aircraft in a 100 kV/m ambient field. The field magnitudes at the extremities are significantly enhanced compared to the ambient field, due to charge redistribution and to the sharp curvature of the structure. In moving to a 3D model, the field values would tend to be further enhanced by additional curvature in the extra dimension

Three dimensional computer studies [3] indicate that field enhancements over the ambient of up to a hundred times can occur for some field directions, see Figure 1. Hence, ambient fields as low as 30 - 300 kV/m (typical within a thundercloud or in the vicinity of an approaching leader) will be sufficient to cause corona breakdown at the aircraft extremities.

This corona breakdown can result in the development of bi-directional leaders extending from the aircraft extremities, which may eventually connect with oppositely charged regions in the cloud, see figure 2. In the classic cloud to ground scenario, one of the charged regions would be ground. Through this process, the aircraft triggers a lightning strike, with itself being the direct path of the return stroke current flowing between the two attachment locations.

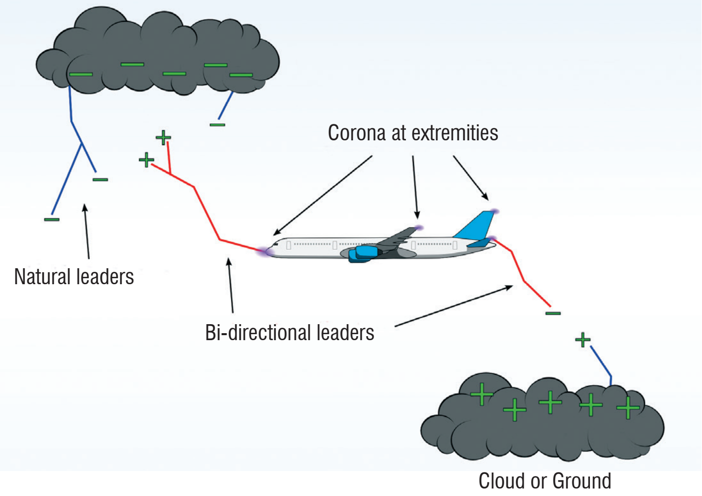


Figure 2 – Illustration of bi-directional leader development (Triggered attachment)

As well as this bi-directional leader development [4, 5] being initiated with the thundercloud field (triggered attachment); it can also be initiated by an existing natural leader channel approaching the aircraft (intercepted attachment). The former tend to be intra-cloud strikes and the latter tend to be the generally more severe cloud to ground strike. Only about 1 in 10 strikes are intercepted attachments, which explains the reason for the relatively high strike rate of airborne aircraft compared to that of those on the ground.

During the return stroke, and also during the progression of the leader from the aircraft to ground, the aircraft can move relative to the lightning channel. An attachment point to a surface therefore moves relative to the channel, causing it to be stretched along the fuselage of the aircraft. This stretching reaches a point where the gap between the channel and the aircraft surface breaks down and a new attachment is formed.

This process continues, so that the arc sweeps back along the aircraft surface in a discontinuous fashion, with dwell times at each attachment point varying according to the nature of the surface, the local geometry and the current waveform. When the lightning arc has been swept back to a trailing edge, it may remain attached at that point for the remaining duration of the flash.

Lightning testing

The leader interaction (both triggered and intercepted) and the subsequent return stroke can be thought of as two distinct phases; (i) the attachment process, which determines where the arcs (leaders) develop from the aircraft; and (ii) the high current return stroke phase.

In the first phase, the aircraft is exposed to high and fast changing electric and magnetic fields during the development of leaders. Consequences arising from this could be the breakdown of dielectric materials (for example radomes, dielectric covers and canopies during the attachment), as well as repetitive electrical transients induced on wiring. Severe damage can also be caused by the high current discharge, which follows a path made available by the HV breakdown. An internal arc through a punctured dielectric will cause physical damage to the dielectric, but also has implications for underlying systems, which may then have very large currents injected onto them. The methods used to assess susceptibility to dielectric puncture during this phase are assessed during High Voltage testing.

The second phase is the high current return stroke phase; this includes the high energy impulses of the first return stroke and the subsequent restrikes, and the long duration slow components. These different component types can have quite different effects on aircraft structure and systems.

Lightning waveforms and levels can vary widely, so an idealized lightning waveform, as defined in ED-84 (see next section on standards), is used for testing. This is shown schematically in figure 3. This idealized waveform is divided into four components, A to D. Note the huge differences in time scales and magnitudes in these four current components.

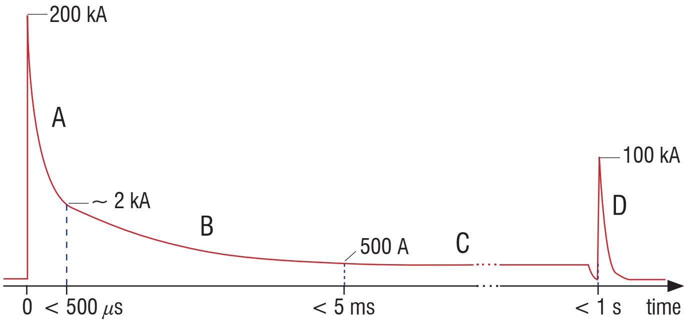


Figure 3 – Schematic of the ED-84 standard high current waveforms (note that the amplitude and time scales are not linear) [6]

Component A is associated with the initial return stroke attachment location, for instance, near the nose and tail of the aircraft. Component D is associated with a re-strike, as the arc is swept along the aircraft. The peak current of the D is half that of the component A, but its Action Integral, the energy associated with the waveform, is an 8th (2 MJ/Ω for the A and 0.25 MJ/Ω for the D). This is due to this difference in the rise and fall times of the two components.

Components B and C form the long duration slow components, also known as the intermediate and continuing currents respectively. A long component C will only be injected at trailing edges where the lightning arc hangs on and cannot sweep to a further aft location.

Fast component damage (A and D)

- Joule heating, proportional to the action integral of the lightning waveform, can cause thin conductors to fuse explosively, leading to damaging overpressures. In carbon-fiber materials, this heating can melt and vaporize the epoxy, leading to delamination damage of the carbon-fiber;
- Magnetic forces arising from the high currents can crush, or drive together/pull apart conductors;
- The acoustic shock caused by flash heating of the air by the lightning channel (thunder) can cause damaging overpressures, particularly inside radomes;
- Current flow within the structure can cause arcing and sparking across interfaces potentially igniting fuel vapor/air mixtures;
- Changing magnetic fields, created by the current flowing in the airframe, generate induced transient voltages in the wiring, which can cause damage or interruptions to the aircraft avionics systems.

Slow component damage (B and C)

- Metals, particularly aluminum alloys, are not significantly damaged by the fast components, however, the charge transfer associated with the slow component can create local melting and puncture. Similarly, carbon-fiber composite can be damaged by the heating process of an attached arc. This is especially important for fuel tank skins.

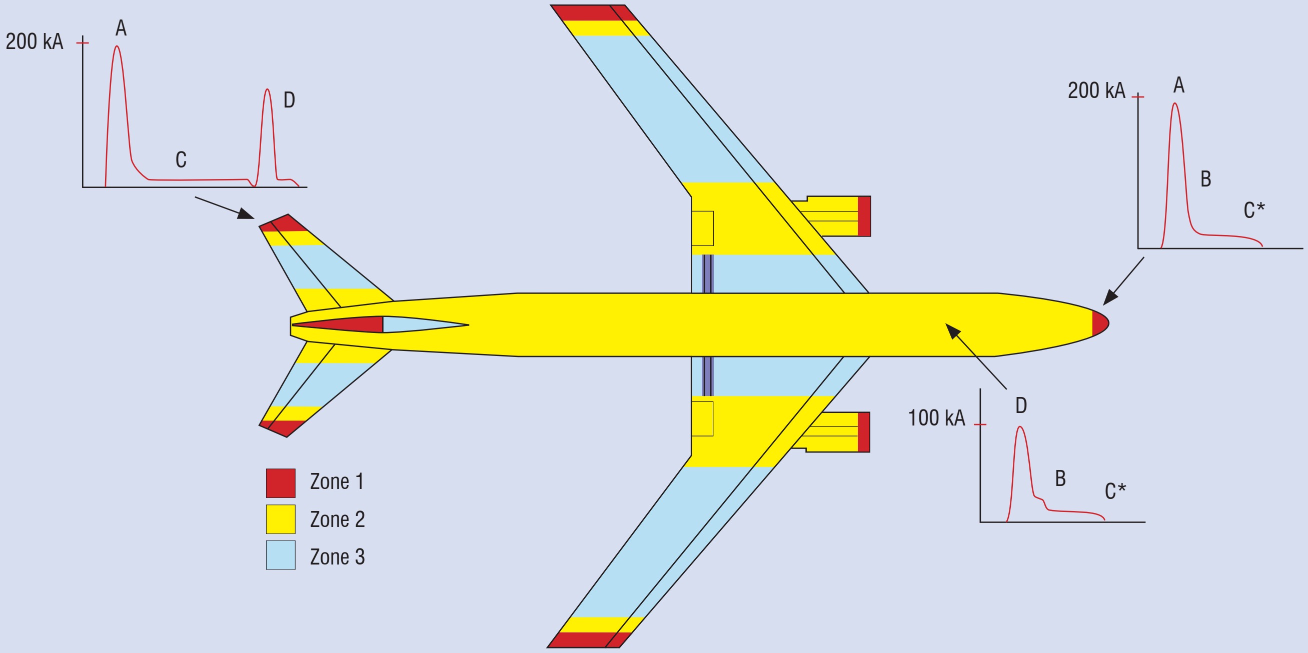
The methods used to protect against this potential damage are assessed during High Current and Induced Effects testing.

Knowing that these different components can cause different types and severity of damage, and therefore require different types of protection to be installed and tested, it is important to classify an aircraft into different zones, according to the type of lightning attachment likely to be encountered [7].

Test standards and certification

Regulations and test standards define procedures for the certification of aircraft structures and systems against lightning damage and also define the lightning characteristics to be considered.

Box - Simplified aircraft zoning



Zone 1 - High probability of initial lightning flash attachment (entry or exit).

Zone 2 - High probability of a lightning flash being swept from a point of initial attachment.

Zone 3 - Any aircraft surface other than those covered by zones 1 and 2. In zone 3 there is a low probability of a direct attachment, however, zone 3 areas may carry substantial lightning currents by direct conduction between two attachment points.

Zones 1 and 2 are further subdivided into A and B regions, depending on the probability that the flash will hang on for a protracted period of time. An A region is one in which there is a low probability that the arc will remain attached (*e.g.*, at the leading edge of a wing) and a B region is one in which there is high probability that the arc will remain attached (e.g., at the trailing edge of a wing).

The civil regulations set by the European Aviation Safety Agency (EASA) and the Federal Aviation Administration (FAA) in the USA give the basic requirements. These are short and fairly non-specific, and with little or no guidance. For example, the structural requirements of 25.581 state little more than that 'the aircraft must be protected against catastrophic effects from lightning' [8].

In order to provide guidance as to how such requirements can be achieved, the European Organization for Civil Aviation Equipment (EUROCAE) Working Group 31 and the Society of Automobile Engineers (SAE) AE2 committee in the USA were founded to produce guidance documents.

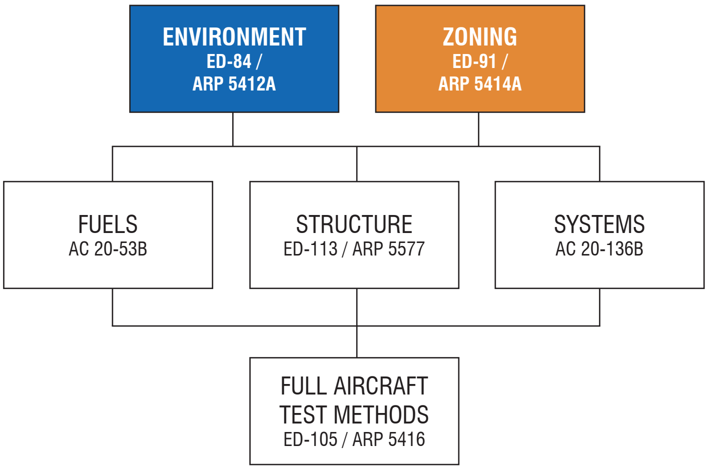


Figure 4 – Diagram showing the structure of the guidance documents produced by EUROCAE WG31 and SAE AE2 committees

The upper tier in figure 4 defines the lightning interaction with aircraft, in terms of the waveforms ED-84 [9] and the zoning ED-91 [10].

The middle tier contains procedures that the applicant can follow, to provide an acceptable route to compliance. There are separate procedures to cover the certification of Structure, Fuels and Electrical/ Avionic Systems, each of which has its own regulation.

The procedure may also include a requirement to carry out tests, and there is guidance material on this in the lower tier, mainly in the comprehensive testing document ED-105 [11].

Challenges and issues

Lightning tests need to be carried out in a representative manner and, as discussed, guidance on how to do this is provided in the Aerospace lightning standards and guidance materials produced by the SAE/ EUROCAE committees.

Nevertheless, there are challenges; for example, due to dramatic differences in both scale and conditions between a lab and the inside of a cloud, achieving sufficient representation of every aspect of the lightning phenomena can be difficult.

In the following sections, some of these challenges are outlined and the approach to mitigating them, where possible, is discussed.

Zoning

The guidance for zoning gives a series of templates for different aircraft geometries deduced from in-flight data.

There is a limited amount of data publicly available and there is also the question of data reliability, as it is not easy on a large metallic aircraft to find arc attachment points, and especially to determine the sequence of events behind the observed attachment points. Since arc attachment is a statistical process, extensive data is required to determine zone boundaries reliably.

There are various other ways of zoning an aircraft, although they each have limitations:

- **Model tests** use a scale model of the aircraft to perform multiple attachment tests in various field orientations, to determine the probability of attachment at any location. Tests must be carried out and interpreted with care, since the curvature on a model's features will be very different from the full scale aircraft and thus the local electric field won't be to scale, affecting the probability of attachment. Also, the "leaders" produced in a lab are much shorter (by an order of magnitude) than in flight;
- **Rolling sphere method** [12] is an empirical approach that uses the 'striking distance' – the closest distance that a leader can approach an object before attracting an "answering" leader– to determine initial attachment locations on an aircraft. This method, using a conservative sphere radius of 25 m, tends to predict larger areas for initial attachment than ED-91;
- **Electromagnetic modeling** uses complex electric field modeling and a model of leader development from the aircraft, offering a scientific method for deducing lightning strike zones and, in general, the results correlate with observed data [13].

In practice, a combination of these approaches may be used.

Attachment to radomes

Radomes are dielectric covers over antennas that can be subjected to high electric fields and initial lightning attachments, particularly to the nose radome. Diverters can be fixed on the radome shell, from which lightning attachments can develop, rather than from the metallic antenna beneath the radome and thus prevent the lightning from puncturing it.

The tests should address the different electric field and antenna orientations. Most strikes are triggered by the aircraft, in which case the leaders propagate out from the radome over long distances. They may also be triggered by an approaching leader, but even here it would be expected that the approaching leader would be tens of meters away before the radome leader develops. In each case, the attachment location is determined by a leader developing from the radome.

The challenge in HV testing is to perform tests with reduced breakdown gaps (typically one meter, due to equipment limitations), which correctly simulates an event that typically develops over a distance of at least tens of meters.

Historically, HV impulse tests to radomes used rod electrodes connected to a high voltage generator. This produces an electric field distribution around the radome that is dissimilar from that experienced in natural lightning. The maximum electric field gradient will be at the rod electrode, rather than the stress raisers on the radome. Leaders are then likely to develop from the electrode, rather than from the radome, quite unlike what we expect for in-flight strikes.

The use of profiled or de-stressed electrodes is therefore preferred and this is specified in the test standard ED105. The recommended technique is to mount the radome above a large de-stressed plate electrode, which gives a more realistic electric field environment.

Where dielectric breakdown is a concern, historically a faster rising waveform, waveform A with a rise time of 1 to 2 μs, might be thought to give the most severe test. In-flight data suggests that, for initial attachments, a slower waveform, waveform D with a rise time of 50 μs to 250 μs, is more appropriate, at least for the lightning scenario involving an approaching stepped leader. Such tests have reproduced in-flight failures on some radomes that use segmented diverters. No such failures occurred when testing with the faster waveform, hence the slower waveform (waveform D) is both more appropriate and more severe; in ED-105 it is the mandatory test waveform for initial attachment regions.

Triggered lightning can occur within an even slower quasi-DC electric field environment. Work at Cobham has shown that, if the radome is held within a high DC field, corona and leader development from metal fixtures inside the radome can spray charge on the inside of the radome and this can lead to radome puncture.

A coating of an anti-static paint would prevent puncture from such fields. However, when the field causes a leader to develop from the radome, the antistatic paint would be too resistive to conduct the required charge and a connection from the leader to the aircraft would be established via a surface flashover or a radome puncture.

In DC conditions, backed strips certainly behave differently when under impulse conditions - the resistive backing strip, if present, goes into corona (as would the tip if as anti-static paint coated). However, the tests performed in the Joint Radome program [14] already suggested that the change from the A to D waveform was successful in reproducing the in-flight failures that had not been demonstrated by the earlier test standard.

The process of air breakdown is in part a statistical one, which means that repeated tests to a radome would be needed to achieve full confidence in the results. This is particularly so when the radome is negative and the leaders in the test set up approach the radome rather than develop from it, since the path of the leader tip approaching the radome will vary from test to test.

However, repeat tests will degrade the dielectric, so there is a limit to the number of tests that can be performed and the test standards suggest only 2 tests per radome/antenna orientation. Consequently, the statistics obtained in the tests are limited. Despite these reservations, radomes cleared by the latest test procedures appear to be surviving in flight strikes.

Fuel systems

One of the primary concerns with a lightning strike to an aircraft is the prevention of arcing and sparking within the fuel system, since this could potentially cause an ignition of fuel vapor. A frequent way of testing fuel system components is to monitor the fuel side of a component with a sensitive camera, while applying a simulated lightning strike to its exterior.

Whatever approach is used, it is required to be sensitive to a 200 μJ spark, since this has been considered historically to be the minimum energy that can pose a risk to aviation fuel/air mixtures. This 200 μJ electrical spark is simply a means of demonstrating the sensitivity of the diagnostic system; in reality, electrical sparks very rarely occur during fuel tank tests.

What is generally seen are highly visible "thermal sparks", which are burning particles ejected when arcing within a fastener location hole, leading to a buildup of pressure at the fastener/carbon composite interface, with ejection of sparks and vapor. The spark trails can be faint and the question arises of whether such a spark event seen by the camera could actually cause the ignition of a fuel vapor.

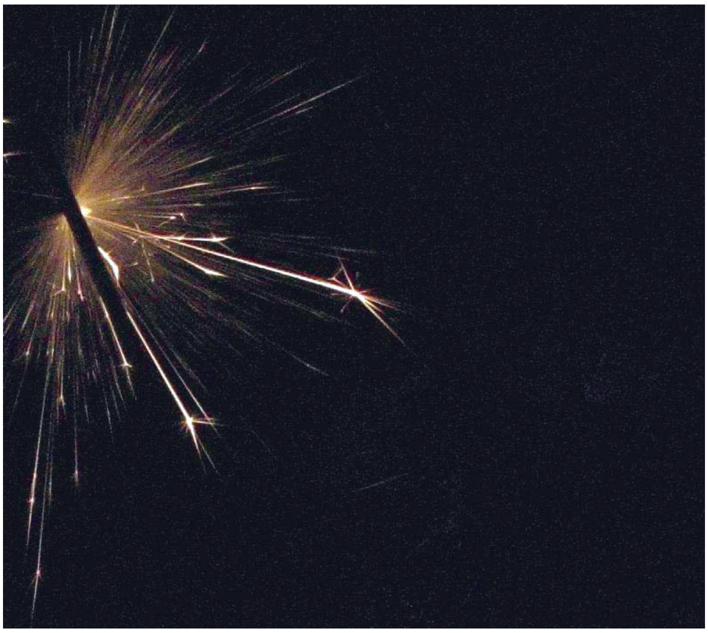


Figure 5 – Highly visible thermal sparks are sometimes seen during fuel system testing, but without necessarily igniting the gas mixture

The question is complicated, since there are many different parameters in such an event that determine whether it would cause an ignition; these are factors such as the number, speed and size of the sparks. Material is also important, since titanium and aluminum, for example, burn with much greater temperatures than steel. Although a more hazardous spark tends to appear more brightly visible on camera images, there is no reason why there should be a close correlation between visibility on film and its ignitability. However, there is good evidence to suggest that a camera capable of detecting a 200 μJ voltage spark will easily detect hazardous thermal sparks.

The conventional, and cautious, approach is to consider the observation of any spark or arc detected by the camera as a fail, but because even "safe" sparks are quite visible on film, this can lead to problems for the engineers, who require an optimum design. A solution is to use a diagnostic gas technique, in which the internal surface is encased and filled with a diagnostic gas that is shown to be sensitive to a 200 μJ voltage spark. That is, it will be ignited by such a spark with $>$ 90 % confidence.

This is an approach that is partly statistical, but with a good margin of safety, since aviation fuels would have an extremely low probability (typically < 0.1 %) of ignition from such a spark. The diagnostic mixtures are also more sensitive to ignition by the "thermal sparks" discussed above.

When gas tests are used in conjunction with cameras, they will occasionally show up faint spark trails on the cameras, without the gas igniting. This is a symptom of the high sensitivity of the cameras to thermal sparks, but for a single test (*i.e.*, with no statistical understanding of the result) such a result would normally still be considered a failure.

High current test waveforms

The high current waveforms defined in the ED-84 standard [15] are derived from natural lightning data and some aspects of the waveforms can be difficult to implement in practice. To account for this, the standard includes some leeway in the waveform definitions.

Rise time

It is very difficult to replicate both the high current and the high rise times (dI/dt) defined in ED-84 using conventional lightning generators. This is because the generator voltages required to achieve the dI/dt become impractically high (>>100 kV), giving a risk of flashovers.

For practical implementations, the standard therefore permits generators with slower rise times, typically 15 - 50 μs rather than, for example, the 6.4 μs of Component A. Historically, it has been assumed that force effects and damage caused by heating are due to the action integral and not dependent on the speed at which the energy is deposited. However, it has been conjectured that faster rise times could contribute to certain types of damage, particularly shock effects on composite skins.

Carbon fiber skins are usually protected with an external layer, such as a copper mesh, which is sacrificially vaporized during a lightning attachment. This vaporization can be explosive and create a shock effect, which is enhanced when thick paint layers are used. It has been suggested that a faster rise time can increase the effect, therefore leading to inaccurate damage replication during tests.

Although it is difficult to look at rise time effects in isolation, it is relatively simple to test the comparative effects of a given peak current or action integral using scaled Component D (12 μs rise time) and Component A (25 μs rise time) waveforms.

Figure 6 below shows how two damage effects (mesh vaporization and shock effects) respond to these parameters on a lightweight carbon composite panel protected by aluminum mesh and with a relatively thick paint layer. The vaporization damage can be seen to be mainly dependent on the action integral, not the peak current or the dI/dt. However, the shock damage is apparently related to the peak current rather than the action integral, which may indicate a dependency on the rise time. However, there is no reported evidence at this time to suggest that tests are failing to replicate the actual observed damage to composites.

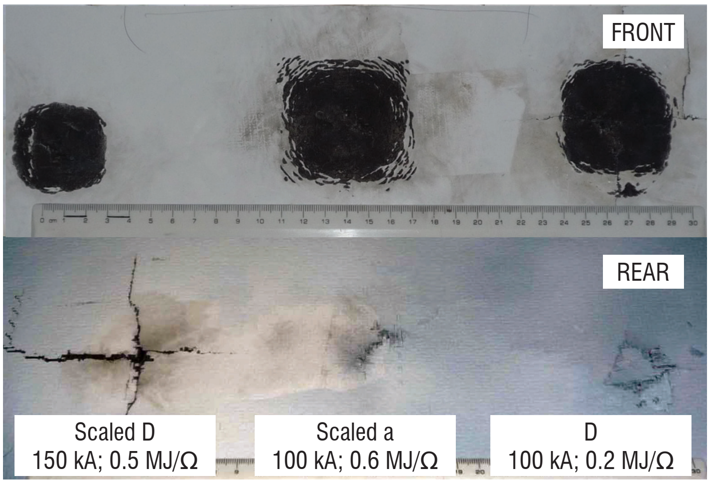


Figure 6 – Outer and inner views of a mesh protected sample tested at different levels. In such tests, the diameter of fused mesh relates closely to specific energy (action integral), but the shock effect (panel splitting) appears to be more a function of the peak current

The rise time can also have an effect on the current distribution in a sample. The current distribution is determined by both the inductive and resistive distributions of the test object. The inductive component acts to force the current to flow in the extremities of the object, away from the path of least resistance defined by the resistive distribution. The strength of the inductive response is directly related to the rate of change of the current waveform. A slower rise time can therefore have implications; on hybrid metal/composite test samples, the slower rising waveform will tend to drive a larger proportion of the current through metallic paths, which could lead to an under-test of the composite parts. Also, for high current tests, where the distribution of current is being measured for the determination of transient levels, any effect of the waveform shape should be borne in mind. The above argument also applies to damped sinusoidal waveforms, which are also allowed by the standards, since the distribution could differ significantly from a unidirectional threat.

The need to specify generic waveforms for either test or analysis purposes can lead to peculiarities. In ED84 [16], the components A and D are defined mathematically (for analytical purposes) as a simple double exponential, beginning with a high rate of rise at $t=0$, which gives the waveform an infinite second derivative (that is, the resulting dI/dt waveform rises to peak in zero time).

This can cause a problem for certain types of electromagnetic modeling approaches. There is also an inconsistency with one of the test voltage waveforms, which is derived from the dI/dt and would therefore be expected to have a zero rise time, which cannot occur in practice. Previously, this was addressed in the standard by placing a practical limit of 100 ns on the rise time. The standards committees have readdressed this and a modification of the double exponential is being introduced shortly. The new definition of current waveform leaves it effectively unchanged, but the infinite second derivative is removed and the dI/dt rise time becomes 340 ns. With this modification, the practical and theoretical waveforms for Induced Effects are consistent.

Test sequence

In lightning tests, the fast components are applied first (A/D) followed by the slow components (B/C). The components are applied in this order since it follows the order seen in real lightning strikes on the majority of the aircraft, *i.e.*, the initial high current attachment followed by the lingering low current phase.

However, at the trailing edges of the aircraft, where the lightning attachment exits the aircraft, the trailing edge will see the lingering slow component before the high current reattachment (component D) phase. This means the charge transfer associated with the slow component can create local melting, weakening the structure, before the high current reattachment. This weakening can amplify the damage caused by the concussive shock of the high current reattachment. Therefore, it is sometimes appropriate to apply a different ordering of the components where such an effect is possible.

Applying the components in a representative order during a test is complicated, since the different components are generated by different capacitor banks and applied as a single composite pulse. An accurate trigger system is required to ensure the correct timing. Achieving initial breakdown using the B and C components can be challenging, since these banks are usually implemented using much lower voltages than the A and D components.

Whole aircraft tests

Whole aircraft tests are a means of assessing the type and amplitude of transients induced into airframe wiring by a lightning strike. In this approach, a scaled down component A current is injected into an aircraft, or part thereof, and the internal threat is measured - for example the induced currents and voltages on wiring.

Two of the issues with these tests are how to build a test rig, which leads to a representative test, and how to ensure that the waveform provides the same coupling effects, albeit at a lower level, as the full threat. In addition, the complexity of aircraft avionics systems requires that a careful understanding of the cable harnesses be gained before making measurements.

The whole aircraft test rig includes the generator as the source of the current and a return conductor system to carry current back to the generator from the aircraft exit point. The return conductor system needs to be designed and installed in such a way that the resulting current distribution on the test object is similar to that which would be obtained during a natural strike. The usual technique is to construct a quasi-concentric cage of cables, tubes or plates around the airframe (generally co-axial).

The return cage for large transport aircraft becomes such a feat of construction that it becomes impractical; thus, a ground plane can be used as a return instead. Ground planes can cause considerable deviations from the free space current distribution, resulting in a large difference between current densities on the upper and lower surfaces of the aircraft, requiring corrections to account for the difference.

The injected current for whole aircraft testing is generally reduced, compared to the 200 kA Component A threat defined in the standards; pulse amplitudes of 1 - 20 kA with the correct 6.4/69 μs waveshape are typical. This is driven by two factors:

- Large high current generators are bulky and impractical to move to a test site;
- The desire to minimize potential damage to an airworthy aircraft.

Using a scaled waveform raises the question of representativity - the lower current levels and voltages associated with smaller generators could potentially lead to a different response to that of a full threat current. For example, arcing at material interfaces may occur with a full threat current, but not with a lower level current. Such non-linear behavior could lead to a modification in the current distribution and therefore induced transient levels.

Careful consideration must be given to any potential sources of non-linear response. For example, linkages with bearings isolated by low friction Teflon, or metal-to-metal interfaces isolated by anodizing, are structures that could produce non-linear results. Similarly, during a real strike, spark-overs might be expected to occur across tiny gaps or through paint layers; paths which would not be present in low level tests.

For some structures, empirical data is available that can be used to support a scaled current test. One such publication is the collaborative investigation between Airbus and Cobham Technical Services, which explored the linearity of a wingbox subjected to a range of injected currents that spanned 1 A to 200 kA [17]. The wingbox was constructed from a carbon composite with mesh protection. Rogowski coils and voltage sense wires were embedded in the structure to look for changes in the current distribution and induced voltages as the injected levels were varied. A high degree of linearity was observed over the whole 106 dB range of injected current. The current and voltage measurements were found to vary by ± 0.5 dB and ± 2.5 dB respectively over the injected range, with much of this variation being consistent with the measurement uncertainties in the diagnostic systems.

During whole aircraft tests, measurements of induced voltage transients will be made on selected harnesses. A wide variety of waveforms are observed, from waveforms following the injected current or its derivative (waveform 4 and 2) to transient voltage oscillations superimposed on the basic response (waveform 3) [18]. These oscillations in the airframe arise from reflections of travelling waves at impedance mismatches, where the body of the airframe meets the small radius of the arc attachment point. Similarly, oscillations in cables can be excited.

Care must be taken when interpreting these transient voltage oscillations since, in a test, the transition between the body of the aircraft and the return conductor is a short circuit. This can cause the standing waves to have a frequency and spatial distribution along the aircraft different to that expected in reality.

The measurements made during whole aircraft tests can be cable bundle currents and/or the transients on the core wires. The latter are usually made at equipment interfaces, to give the open circuit voltage and the short circuit current allowing the Thévenin equivalent generator to be deduced. These core wire measurements require disconnection of the connectors at each end, to allow measurement access to the core wire at one end and to ground the wire at the other. The screens at each of the connectors will need to be bonded to structure also and considerable care is required.

Cable bundle currents are an easier parameter to measure, however, a tricky problem is the presence of intermediate grounded bulkhead connectors in the cable run, as illustrated in figure 7. These allow currents to flow off the harness, so that different portions of the same harness can carry quite different currents. Therefore, for a complex cable run many current measurements may be required, as well as a detailed understanding of the location of the intermediate grounded connectors.

These measurements can be used to determine the current levels to be applied in screened cable tests, or used to define voltages test levels on unscreened bundles or pin test levels. The latter case also requires knowledge of the harness section lengths and transfer impedances, in order to sum [*transfer impedance* (Z) *x current* (I) *x section length* (L)] for the various sections of the one harness, see figure 7.

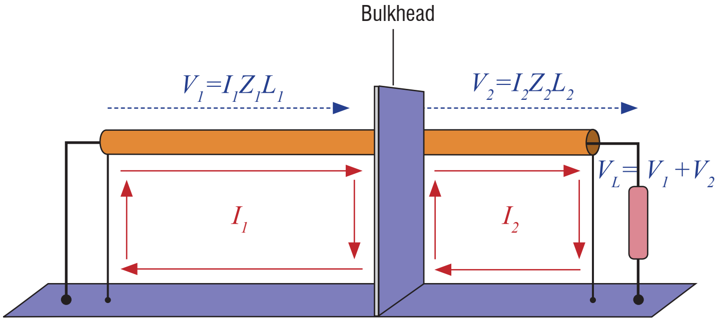


Figure 7 – The voltage at the input load (V_L) is the sum of contributions from different sections (V_1, V_2). In this example, the cable screen is effectively split into two sections, which can carry quite different currents if one has a more exposed location

Fault/Failure Simulation

On July 17th, 1996, shortly after taking off from John F. Kennedy Airport in New York, flight TW800 broke up in flight as a consequence of a center fuel tank explosion. Investigation by the U.S. National Transportation Safety Board could not identify the actual ignition source, but did suggest that this aircraft, and those of a similar age (over 25 years), exhibited considerable 'wear and tear' on bonding braids and on some of the wiring running through fuel tanks; NTSB conjectured in their report that sparking may have occurred at chafed wiring.

Following this incident, regulations for transport aircraft fuel tanks were modified, requiring that designs should incorporate a tolerance to anticipated wear & tear and installation faults. This has had a big effect on lightning test requirements, since the testing must cover not only the standard build, but also the possible fault/failure configurations that can arise during an aircraft's life. This requires the manufacturer to anticipate the possible fault and failure conditions and to address them within a manageable test program. Since it is not feasible to test every scenario, some selection of worst-cases for test must be made; of course, some test experience is required to identify what the worst cases are, given numerous variables, such as fastener type/size, skin layup and the anticipated lightning current threat, even before fault conditions, such as sealant loss, skin cracks and broken bond straps are considered. Manufacturers and test houses are working together through the SAE/EUROCAE committees to provide guidance on this and to ensure that a consistent approach is adopted.

Environment

For carbon composite structure, the uptake of moisture during its life can have an influence on its response to lightning currents. To assess this, artificial aging of samples for test purposes is achieved by moisture conditioning. Samples are kept in a very humid environment for a prolonged period of time (typically 70 °C and 95% RH for 1500 hours). Samples are then tested and the results compared against nominal samples, to determine the likely effect of aging on the protection methods. Although some additional loss of mechanical strength has been noted under some conditions, the effect on lightning currents appears to be small.

Investigations have been undertaken into the effects of rain and ice on segmented strip divertors. These are used to protect nose radomes from being punctured by attracting the strike and carrying the current safely over the outer radome surface [19]. This investigation involved setting up a lightning generator inside a wind tunnel that had a rain/icing facility. It was found that rain did not seem to affect the performance and the divertors still worked with thin layers of ice. However, with thick layers of ice ~1 cm thick, puncture of the radomes occasionally occurred.

Quantitative studies of the effect of ice have been conducted in the EM-Haz program [19]. The ice increases the flashover voltage for segmented strips by a factor about 2 to 3, depending on strip type and thickness of ice. The light-up voltage increases with ice thickness, up to the voltage gradient required to create a surface flashover on the radome surface or on the ice. In the test standards, ice and water are not usually specified, but clearly they can have an effect.

Ambient air pressure at cruising altitude is a fraction of its sea level value and, since this pressure determines breakdown voltage, it can be anticipated that lightning effects could have some different effects at altitude. For example, when using electrical isolation as a means of protection, this is usually taken into account by adding an additional safety factor. Thus, testing is normally conducted at appropriately higher amplitude, to compensate for the reduced voltage at flight altitudes. Tests could also be conducted at the reduced air pressure, although this is not normally required, since the effects of altitude on breakdown are well understood.

Other effects are less readily predicted and one of these is the occurrence of sparking when testing fuel tanks. Recent test programs have investigated the effect of ambient air pressure on the lightning protection of a fuel tank structure. The test sample was installed within a cell constructed around the skin/spar/rib fastened interface, allowing the pressure to be reduced to 140 Torr (the pressure at 40,000 ft.). No significant effect on the performance of the fuel tank was observed, which probably reflects the fact that sparking is caused by the fusing of contacts, rather than a voltage breakdown, so there is less pressure dependence.

Representativity

While it is necessary for the tests to be a representative simulation, there are advantages in testing manageable sized samples, both in terms of the ease of testing and the cost of sample manufacture. Most tests for determining the integrity of structural skins are performed with square flat panels. There is no evidence to suggest that the local structural damage is influenced by the use of a simple test sample. However, if the skins form part of the flight control surface, then protection against other aspects of damage, such as delamination from spars and ribs, and splitting of trailing edges, will need to be demonstrated. In these cases, it is normal to test a larger scale sample, which incorporates these critical features.

In testing fuel tank structural designs, test samples are usually relatively large; for arc attachment tests, a 600 mm x 500 mm skin sample with internal structural ribs is considered large enough for the current to distribute freely around the sample, without being constrained by the sample size or set-up. However, it becomes impractical to use such samples for testing tolerance to foreseeable fault conditions, since there will be a huge matrix of design/fault combinations to be tested. A single test sample cannot usually be used for testing many variables, since conditioning of the sample can occur after only a small number of tests. In conditioning, current paths become typically more well defined after successive tests, affecting overall current distribution and hence results may not be representative.

Thus, one practical approach is to test large numbers of samples as small coupons, supported by a smaller number of tests to more representative samples, in order to validate the results. The coupon tests are a good way of making comparative assessments to determine which faults are more significant and which types of fastener, for example, are most affected.

Conclusion

There will always be practical limitations in the way in which lightning can be simulated by test and attempts are made to ensure that the most significant effects are reproduced. However, as this paper has shown, there are inevitably compromises, both in simulating the “worst-case” lightning threat (and combining the most severe parameters) and in providing samples that are manageable enough to be tested, but whose results can also be considered representative.

Challenges also exist in regard to how tests are conducted, both in terms of the waveforms used and how the tests are carried out. By bringing together aerospace companies and lightning specialists, the WG31 and SAE committees continue to drive the development of the standards and guidance material to overcome the challenges faced in this industry ■

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Acronyms

ARP (Aeronautical Recommended Practice)
AC (Advisory Circular)
ED (EUROCAE Document)

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