Lightning: its effect on aircraft

The latest glass-fibre and carbon-fibre composite materials now being used in the aircraft industry do not offer as much protection against lightning strikes as the aluminium alloy used previously. Scientists at the United Kingdom Atomic Energy Authority (UKAEA) laboratory at Culham, England, have been working on the problem.

by PHILIP LITTLE

Enquiries about high current tests simulating the effects of lightning strikes were first made at Culham by UK aircraft manufacturers in 1970. Some work was done with limited equipment capable of providing the simple test current pulses then required. These early studies included tests on a Westland helicopter, on the European Airbus and on Concorde.

At about the same time the Ministry of Aviation Supply (now the Ministry of Defence) requested feasibility studies from Culham and another UK laboratory on the effects of lightning strikes to aircraft and means of simulating these effects in the laboratory. As a result, a contract was placed with Culham to build a facility for lightning testing, to undertake a program of applied research and to act as an advice centre for the UK aerospace industry. In this way the Culham Lightning Studies Unit (CLSU) was established in 1972, with support from the Ministry of Defence and the Civil Aviation Authority.

The Unit is now internationally recognised for its expertise in lightning protection for aircraft. Its staff consists of five professional engineers and scientists, with appropriate technical and general support to make up a team of nine full-time members, sometimes supplemented by other Culham staff. Superb lightning simulation facilities have been constructed to test aircraft and aircraft components by passing current pulses representative of severe lightning strokes through them in a realistic manner.

Aircraft of course are a very safe form of transport, and usually if lightning strikes an aircraft negligible damage results. The average aircraft is struck about once a year. A few burn marks and a slight pitting of the skin are normally the only lasting consequences, though the strike itself may be a very startling event.

Sometimes more severe structural damage occurs, and obviously strikes to the fuel vents or fuel jettison pipes are particularly hazardous. Electrical and electronic systems are also very susceptible to damage by lightning.

Modern aircraft rely on complex electronic systems, including computers, for communication, navigation and other essential functions. The actual flight control of future aircraft may be performed through electronic systems guided by an on-board computer, so interference with such equipment must be avoided.

The problems of protecting aircraft against lightning have become more difficult with the introduction of new materials which replace the aluminium alloy previously used. A metal skin affords a degree of protection which glass-fibre or carbon-fibre composite materials fail to provide, and such materials are increasingly used in the aircraft industry — for excellent reasons. In order to understand the hazards, consider what happens when lightning strikes an aircraft.

Thunder and lightning

Fig. 1 shows the base of a thundercloud, a region of high potential where strong electric fields exist due to an electric charge (usually negative) produced in the cloud base. When the field is strong enough, breakdown occurs and a bright channel grows out of the cloud, advancing in steps towards the ground along a tortuous path that shows frequent branching. This is called a stepped leader.

Any aircraft close to the cloud will begin to produce electrical discharges from sharp extremities (nose, wing tip, rudder, etc) in the form of a glow or corona discharge and these also may grow into stepped leaders. If one of these meets a cloud leader the aircraft becomes part of the current channel.

The leader continues to grow toward ground, with the aircraft carrying the current pulses which flow as the leader advances. When the leader reaches the ground if forms a bridge between cloud and ground, and a heavy current pulse flows back up the channel and through the aircraft. This is the first return stroke, typically carrying 30kA. It causes intense and rapid heating in the channel, which becomes very bright as the pulse passes, and expands rapidly. This expansion causes the thunder always associated with lightning.

Sometimes after a pause of a few hundredths of a second another, faster leader and another return stroke may appear, and this may be repeated several times. In a severe storm, up to thirty re-strikes have been recorded, though the average worldwide is about three. The peak current for re-strikes is typically 10kA. After the last return stroke a current of several hundred amperes continues to flow for a few tenths of a second, and occasionally this continuing current appears between earlier re-strikes. The whole event is called a lightning flash.

During the time of the strike, of course, the aircraft is moving, and this movement causes the attachment point of the lightning arc to move over the surface of the aircraft (Fig. 2).

Thus an arc which is initially attached at the nose will move backwards with respect to the aircraft, so that successive positions of the attachment point will be further aft. The rear attachment point cannot move backwards, but some extension of the channel does occur. The direction of air flow over the aircraft skin largely determines the motion of the arc attachment points.

The attachment point of the arc does not slide smoothly back along the skin of the aircraft, but moves in a series of steps, of variable length, which roughly follow the airflow across the surface. Instabilities in the arc may produce kinks and bends, so that later attachment points may not lie driectly behind the first point. If painted surfaces are involved the step length will be longer because the potential along one step must break down the insulation provided by the paint (Fig. 3).

At trailing edges where further movement of the attachment points is impossible the arc hangs on to the rearmost conductor available to it. The remaining current pulse flows into the same point, and here the most severe arc damage occurs. If an initial attachment occurs at a trailing edge or on the tail the whole stroke current flows into one point. The longest possible hang-on time is taken to be the time between re-strikes, for the rapid rise of current in a re-strike causes very large induced voltages along every section of the channel and any bends are likely to be short-circuited by breakdowns. The generally accepted figure for this maximum time is 50ms.

The surface of the aircraft can be divided into three zones on the basis of the behaviour of these attachment points. Initial attachments are said to occur in Zone 1 – this includes all the sharp extremities of the aircraft. Areas to which the attachment points may sweep are defined to be Zone 2 – these lie in the slip-stream behind the forward Zone 1 areas. The remaining surface areas, defined as Zone 3, are unlikely to experience direct attachments but may carry lightning currents between attachment points, so that in these regions also some effects of lightning may be seen.

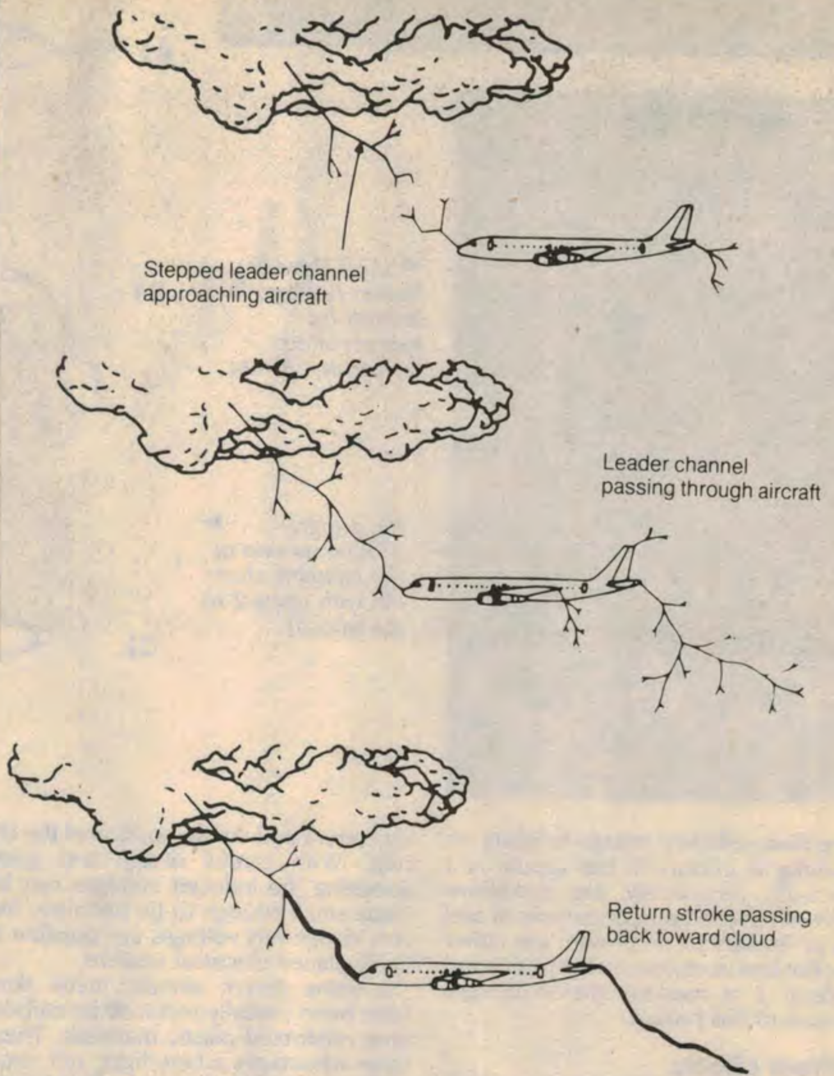


Fig. 1: how an aircraft becomes part of the lightning channel.

Fig. 4 shows one example of zoning on a typical aircraft.

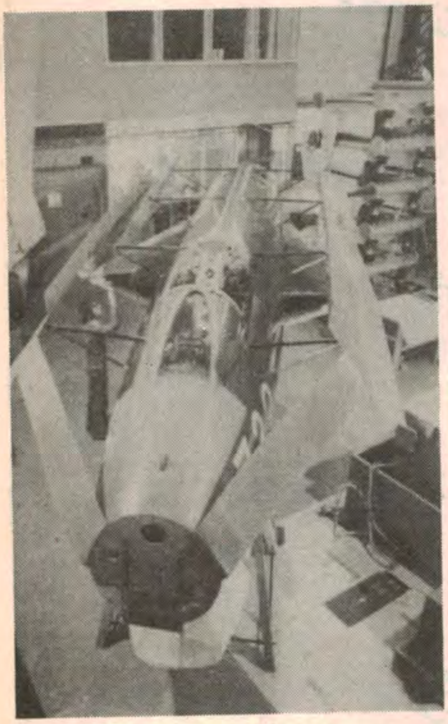
Every flash differs from every other flash, and statistics about the peak current, the rise time of the current pulse, the charge transferred and other parameters have been painstakingly gathered in many countries. Sometimes positive charge is lowered to ground, and very frequently discharges between clouds occur that never transfer charge to ground at all. Internationally-agreed standard current waveforms for testing aircraft and aircraft components have been developed on the basis of the characteristics of ground flashes, since these are considered to be the most severe.

Direct effects

A current pulse through a resistance dissipates energy, leading to heating effects and possible vaporisation. If enclosed conductors are vaporised, mechanical pressures can build up and split the container, as trees are split when the sap is vaporised. Mechanical shock waves from the heating effect and magnetic effects of the current pulse can also cause damage by distorting the aircraft structure.

The main risk of melting and puncture occurs after the initial stroke, at the tail of the peak current pulse which has an average amplitude of around 2kA. For currents of this level, the charge transfer determines the damage to the attachment point and is an important consideration where fuel tanks are placed immediately beneath the skin.

Any one of the components of a lightning strike, from the initial high current strike to a severe re-strike, could provide



◄ *LEFT: Hawker Hunter fuselage fitted out for indirect-effects testing at Culham.*

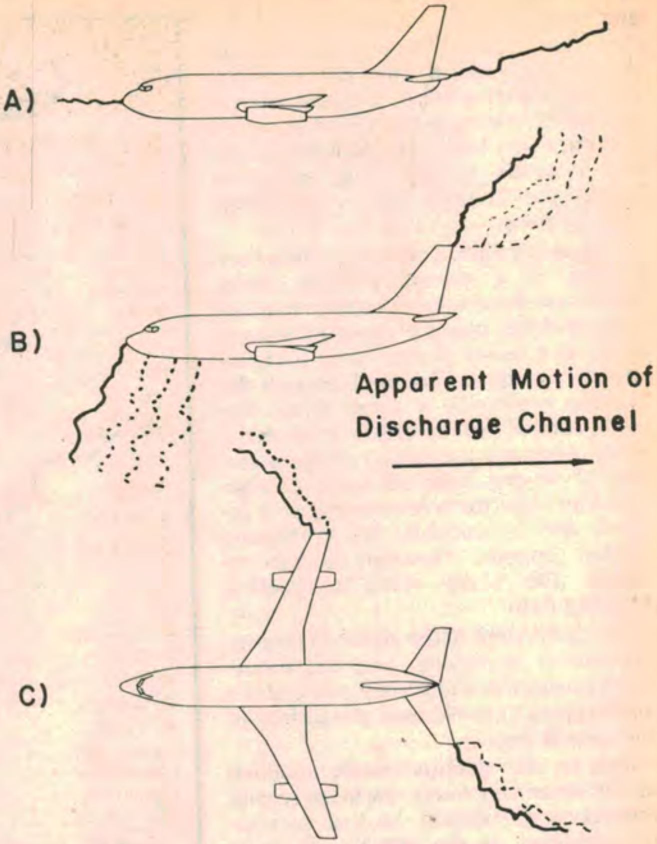


Fig. 2 (right): relative motion of the lightning channel with respect to the aircraft. ►

more than sufficient energy to ignite an inflammable mixture of fuel vapour at a fuel vent. Fortunately the conditions under which the appropriate mix of fuel and air is likely to be present are rather rare, but fuel vents are always positioned in Zone 3 in modern aircraft designs because of this hazard.

Indirect effects

Indirect effects of lightning are of two kinds. The first arises when the current pulse in a continuous metal conductor, such as a metal aircraft without windows or gaps of any kind in the skin. Fast-rising currents flow at first only on the outer surface, causing any direct damage immediately.

The current diffuses into the skin slowly, and a voltage pulse appears later on the inner surface. Its magnitude is determined by the skin thickness and conductivity, the shape of the aircraft, and the form of the current pulse. Such a voltage pulse is injected into electrical circuits connected to the inside of the aircraft skin as an indirect effect of lightning, but the voltage is small when metal skins are used.

Other indirect effects appear because the aircraft skin is not continuous: the changing magnetic field due to the lightning current can link directly with electrical systems within the aircraft. The field penetrates air gaps or apertures covered by electrical insulators such as glass, perspex or glass-fibre composite materials. Voltages are then induced in circuits which lie underneath any break in the metal skin; the size of the voltage depends on the rate of rise of the lightning current and on the position of the circuits. With careful design and good screening the induced voltages can be made small enough to be harmless, but very dangerous voltages are possible in badly-placed electrical systems.

In some recent aircraft, metal skins have been partially replaced by carbon-fibre reinforced plastic materials. These have advantages where light, stiff structures are needed but they have much greater (x1000) electrical resistance than metals. The direct damage done in carbon-fibre composites when a lightning current pulse flows is likely to be much greater than in metals because the energy dissipated is proportional to the resistance. Damage at an arc attachment point is also more severe. Neither type of direct damage appears with glass-fibre composites, for these are genuine electrical insulators.

Indirect effects in circuits underneath panels of cabon-fibre composites may be nearly as great as if the panels were absent, or made of glass-fibre composites. The penetration of the magnetic field is nearly as fast as through an open aperture. Very high voltages appear across a carbon-fibre panel momentarily, but the current soon moves into neighbouring metal if a parallel path can be found. Voltages inside an aircraft made entirely of carbon-fibre composite would be much higher than those inside metal aircraft. Great care must be taken in the protection of electrical equipment and wiring when composites are used, especially if digital electrical systems are involved.

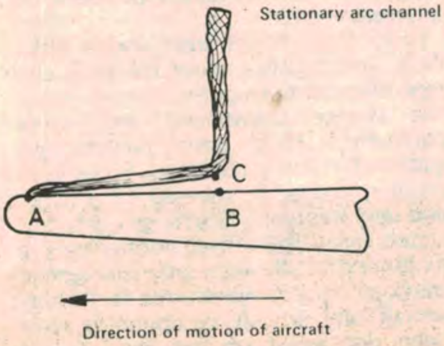


Fig. 3: attachment point formation.

Lightning in the lab

It is impossible to describe in detail here how the test current waveforms are produced in the laboratory. In the CLSU facility 20kV and 100kV high-voltage capacitor banks supply current either directly to the load or to an intermediate inductive energy store for direct effects testing. An inductive store acts as a current source, providing a current pulse almost independent of the load impedance in the same way as a lightning stroke does.

Other new techniques in lightning simulation and testing developed by CLSU include a multiple current feed to an arc. The inner conductors of six coaxial cables are extended to surround a central arc – current flows up these conductors and down the centre lead to the arc. The base plate holds the specimen and the current returns to the source via the outer screens of the coaxial cables. The whole system is balanced so that equal currents flow in each cable and no

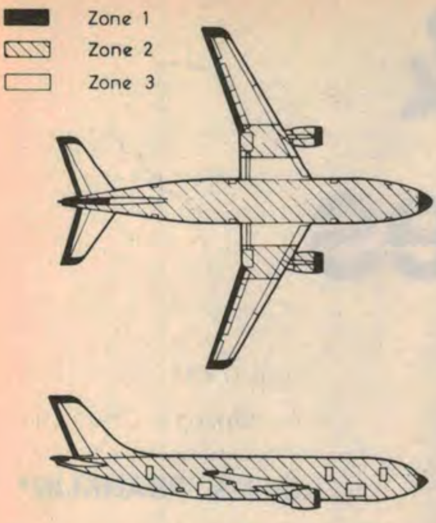


Fig. 4: typical aircraft lightning zones. Initial attachments occur in Zone 1, may transfer to Zone 2. Zone 3 is unlikely to experience direct attachments.

net magnetic field exists at the arc. If such precautions are not taken the arc is moved by the residual magnetic field due to the current leads and unrepresentative damage results.

For indirect effects testing, a low-inductance 1MV capacitor bank is used in the CLSU facility. This type of generator is needed to produce the high rates of rise of current required, and the load circuit must also be of low inductance. In addition, the current distribution around the aircraft studied must be the same as if that aircraft were remote from all other bodies if a good simulation of a lightning stroke is to be obtained. If a single wide metal strip is used as the return conductor for a current pulse along the fuselage, the magnetic field around the fuselage is stronger near the return conductor than elsewhere. Using three symmetrically disposed return conductors, a much more realistic field distribution is computed and this is confirmed by experiments.

To measure the voltages induced in cables and in small coils responding to magnetic field changes elaborate precautions against interference from spark gaps, open arcs, etc, must be taken. The diagnostic circuits must be carefully placed to eliminate the risk of voltage breakdown to the sensitive measuring equipment. The output signals are displayed on oscilloscopes and photographed, or fed into a transient digitiser for further analysis.

This data analysis system is expected to become more important in the future, as the high frequency behaviour of electonic equipment in aircraft struck by lightning becomes more important.

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