ICAS-86-5.10.3

RECENT IN-FLIGHT DATA AND ELECTROMAGNETIC RESPONSE OF AN AIRCRAFT STRUCTURE STRUCK BY LIGHTNING

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Today, lightning aircraft interactions constitute a major problem due to both increased use of composite materials on structure and complex on-board electronic equipment. The optimization of complete protection of new aircraft against lightning can be achieved if the main properties of these interactions are well understood.

During the last decade only a few results were obtained on aircraft struck by lightning in flight. Important programs have been recently carried out in France and in the USA with instrumented aircraft flying in storm conditions.

For the first time, accurate measurements on lightning currents, electromagnetic fields on the structure, and electromagnetic fields inside the fuselage have been analyzed.

Some of the most important features of these measurements are the pulse waveforms and the very fast rise time of the signals which confirm the possibility of high induction coupling on wiring and equipment.

In this paper, we present a general view of the aircraft instrumentation; we describe the in-flight results and we discuss the physical mechanisms which occur during lightning attachment.

1 - INTRODUCTION

It is obvious that up to the present, little thought has been given to the processes of the electric or electromagnetic interactions between an aircraft and the atmospheric medium in which it travels. Only artificially provoked phenomena such as nuclear electromagnetic pulses (NEMP) have been studied in detail over the last few years in the attempt to evaluate the vulnerability of certain items of airborne equipment to an incident electromagnetic wave and in the instance provide adequate protection.

This situation can be explained in part by the fact that aircraft structures built until recently and the relatively limited degree of sophistication of aeronautical equipment electrical and electronic functions considerably reduced the effects of electrical activity created in the atmosphere. Recent and rapid developments in the area of structural materials and navigational avionics require that these problems be studied indepth, especially since all-weather flight capability is close to being a reality.

The solutions proffered for canceling out the effects of atmospheric electric or electromagnetic interference (electrostatic interference - direct or indirect effects of lightning) are most often empirical given the lack of detailed knowledge on the properties of the mechanisms at work and especially due to a virtually complete absence of appropriate in-situ measurements.

It has to be admitted that these mechanisms, particularly, those related to the attachment of a lightning channel to an aircraft's structure, for example, are extremely complex and at present, we are far from stating a satisfactory analysis in terms of the basic physics of the phenomena; moreover, in-flight acquisition of reliable data necessitates the development of high technology instrumentation only recently available; finally, might we add that in-flight experiments pose problems of costs and safety which can only be overcome through very strong motivation since this type of experiment can only be carried out through the joint effort of several laboratories and specialized services.

Large scale research has been carried out in this domain (1) (2) and testing on aircraft is in progress in the United States (FAA, USAF, NASA) (3) (4) (5) as well as in France (DRET, DCAe) (6) (7). Significant data are now available whether in the area of electrostatic interference or in the area of lightning. The simultaneous operation of microphysic, thermodynamic or dynamic instrumentation has enabled us to approach the basic properties of the atmospheric medium at the origin of the phenomena under study and the new sensors and high performance acquisition systems now available are able to provide data with a temporal resolution which is satisfactory for analysis of the electromagnetic response of structures to external stress.

The aim of this paper is to present a few typical cases of aircraft behavior under certain flight conditions; the results proposed are those obtained from experiments run using two aircraft carrying instruments. The first case involves electrostatic phenomena involving triboelectric and atmospheric electric field effects on the potential of the aircraft; examples of these effects will be used to give a quantitive description of the electrical behavior of the aircraft and its influence on the interference it can provoke. The second case, based on recent experiments with a TRANSALL, will be used to show up the atmospheric conditions under which an aircraft is struck by lightning. Without pretending to make a detailed analysis of the processes at work, we will broach the reactions of a structure under the electromagnetic field stresses caused by a direct lightning strike.

2 - AIRCRAFT-ATMOSPHERE ELECTRICAL INTERACTIONS

Electrical interaction between the aircraft and atmosphere occurs when phenomena outside the aircraft create variations in the charge $\sigma(t)$ and current $j(t)$ densities on the surface of the aircraft. These phenomena will cause interference on the systems aboard if the variations of $\sigma(t)$ and $j(t)$ have a frequency spectrum wide enough to span the frequencies of the radionavigation and radiocommunication equipment or to cause electric field $E(t)$ or magnetic field $H(t)$ components to penetrate inside the structure by diffusion or direct coupling.

In principle, slow variation of the aircraft's potential or the steady increase of an outside electric field will not have a direct incidence on the aircraft; an aircraft with respect to its environment can reach a potential of several MV without any consequences on its operation.

In general, the variation of the potential of an aircraft in flight or of an external electric field will only be of consequence by the electrical discharges they cause.

We can define three phenomena of atmospheric origin which cause electric or electromagnetic interaction with an aircraft (figure 1).

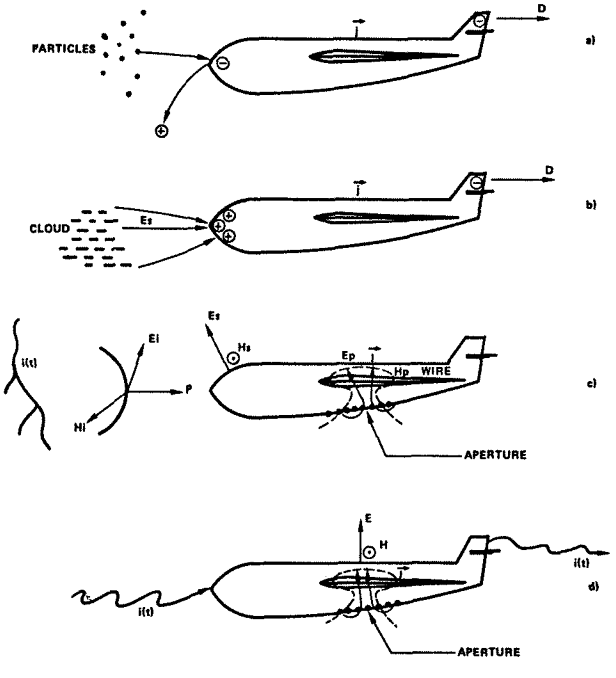


Fig. 1 - Electrical interactions between an aircraft and the atmosphere

1. The most frequent phenomenon is that resulting from the impact of particles (mist, hail, snow) on the structure of the aircraft (figure 1.a). Upon contact with the structure, an electric charge separation process is established on the surface and results in the transfer of a charge with a negative polarity on the surface and the evacuation of a charge with the opposite polarity towards the atmosphere. The mechanism can be extremely efficient under certain atmospheric configurations, since an impact current density of around 300 m $A.m^{-2}$ has been observed. As a function of this impact current ic, the aircraft's potential will increase according to the formula:

$$ic = \frac{1}{C}\,\frac{DV}{dt}$$

Taking a capacity C of 10^{-9} F and a total impact current of 10^{-3} A, a value of 10^{6} $V.s^{-1}$ is reached for the term dV/dt; the triboelectric process being able to establish itself over several tens of seconds, we can assert that potential V can tend towards very high values. However, as soon as V reaches sufficient values, the electric field on certain regions of the structure become greater than the critical value of 30 kV/cm and electrical sparking D will occur and transfer part of the accumulated electric charges to the atmosphere.

Under these conditions, electric potential V of the aircraft will be determined by the differential relationship:

$$ic - \Sigma\, id\ (V) = C\ dV/dt$$

The term Σ id (V) represents the sum of the discharge currents formed on the region of the structure where a strong electric field is located, the discharge currents themselves being a function of the local electric field hence the potential V of the aircraft.

At equilibrium, the potential Vo of the aircraft satisfies the equation:

$$dV/dt = 0 \text{ or } ic - \Sigma\, id\ (Vo) = 0$$

The various currents id (Vo) are responsible for the radio interference on the antennas. A means of protection would be to install an adequate number of high performance dischargers.

Furthermore, it is imperative that the total structure of the aircraft be equipotential electrostatically to prevent surface electrical sparking; this state of equipotential can be had by using antistatic coatings with controlled surface resistivity (typically from 1 to 100 MΩ□). (1) (2).

2. The second phenomenon (figure 1-b) is related to the proximity of electrically charged cloudy regions; a gathering of convective clouds is the center of electrical activity resulting from the combined action of particles of different natures, ascending or shear air movement and temperature gradients. The separation of carrier charges causes the formation of a strong electric field spread over several kilometers.

The outside field Es will move charges of opposite polarity over the structure of the aircraft creating a distribution of electrostatic fields essentially related to the geometry of the aircraft; if the local electrostatic fields at one or several points on the aircraft exceed the critical field of 30 kV/cm, discharges D will form and change the aircraft's potential.

The resulting interference is analogous to those described above, hence, the means of protection to adopt are the same (dischargers and antistatic surface treatment).

3. The third phenomenon corresponds to lightning striking the aircraft. As shown by diagrams c and d on figure (1), lightning can be in the proximity, i.e., the discharge arc does not reach the aircraft; or, a direct hit wherein the current wave travels over the structure.

Under the first configuration, the aircraft is submitted to an electromagnetic field created by the discharge current i(t); to the incident components Ei and Hi, there will correspond a distribution of surface components Es and Hs related to the structure of the aircraft. The problem to handle is similar to that of NEMP, the frequency content of components Ei and Hi being near that of an electromagnetic pulse. Fields Es and Hs will have a direct influence on the antennas aboard and can penetrate inside the structure by diffusion (the effect is relatively negligible for standard metal structures) or directly through electromagnetic operatures. The presence of the internal fields Ep and Hp will create interference on the circuits and equipment.

Under the second configuration, the discharge mechanism will directly affect the aircraft. At first, the structure will undergo heavy fluctuations in potential due to the approach of the discharge streamer, current build-up at different regions of the aircraft "adapt" the aircraft to the lightning channel. After this first phase, the aircraft is in the channel of the discharge and consequently will undergo its stresses (build-up and extinctions, current wave, return current if the lightning reaches the ground).

Interference is obviously greater in this case, since the energy of the phenomenon affects the aircraft; other than the penetration by the electromagnetic field already mentioned, other disturbance effects will be created by the direct passage of the current wave (thermal effects, electrodynamic effects, derived currents, etc.).

After a brief description of the measuring set-up used on the aircraft, we will attempt to show up the main factors affecting the behavior of the aircraft under the configurations cited by basing ourselves on some significant examples.

3 - MEASUREMENT SET-UP USED IN-FLIGHT

a/ The first series of tests, solely devoted to the analysis of electrostatic phenomena, were run using a METEOR NF 11 from the Flight Test Center (CEV-BRETIGNY) (figure 2). The external structure of the aircraft was treated to prevent the occurrence of uncontrolled surface discharges.

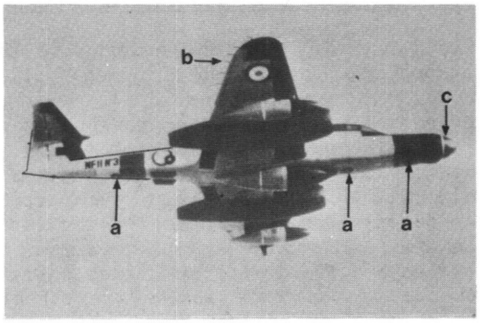


Fig. 2 - "METEOR NF 11-03" instrumented aircraft
a) Field mill sensors
b) Potential dischargers
c) Triboelectric current sensors

The instrumentation onboard, consisted in the main of:

- three triboelectric current sensors installed on the radome (SI1) and on the wing leading edges (SI2 and SI3)
- five electric field sensors (E1 to E5) installed at apropriate locations on the structure
- instrumented potential dischargers for measuring discharge current; during testing the number and type of dischargers were changed
- five electric radio noise receivers, covering the VLF-VHF band, to correlate the level of interference with the electrical state of the aircraft.

A detailed description of the instrumentation, given in the articles referenced (6) and (8), especially regarding the methods of analysis for the measurements from E1 to E5, will allow determination of the aircraft potential and of the three components of the atmospheric electric field.

b/ Experiments on lightning were made using a French Air Force TRANSALL operated by the Brétigny Flight Test Center.

This aircraft's instrumentation was especially optimized; for a complete description refer to papers (9) (10) and (11). For the analysis given in this paper, we will only refer to the following measurements (see figure 3):

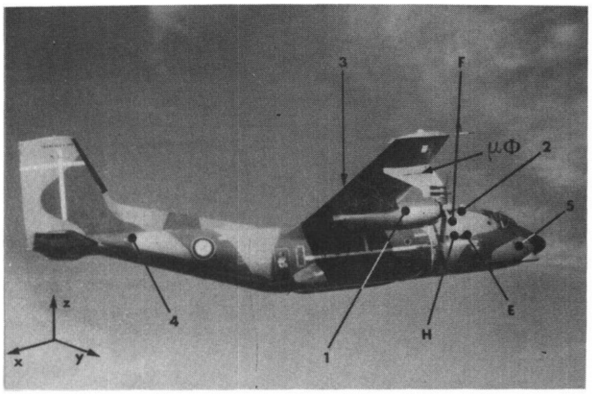


Fig. 3 - Lightning experiment with the Transall aircraft

- measurement of the aircraft's potential and of the three components of the atmospheric electric field by E1 to E5
- measurements of the E and H components of the electromagnetic field on the external structure of the aircraft in a region to the fore of the fuselage
- microphysic measurements using sensors on the two pods installed under the wings; these were used to plot the dimensional spectrum of the mist and ice particles by the PMS sensors (FSSP, 1D-C, 1 D-P) and 2D-P); the liquid water content was measured by using a JOHNSON-WILLIAMS sensor.
- cloud cell detection by the 3 mm radar onboard
- definition of the aircraft's trajectory by an inertial platform and overlaying by ground tracking radars.

4 - ELECTROSTATIC INTERACTIONS

4.1 Influence of Triboelectric Phenomenona

We will present two sequences of typical measurements obtained in flight. Variations of four parameters are given on figure (4):

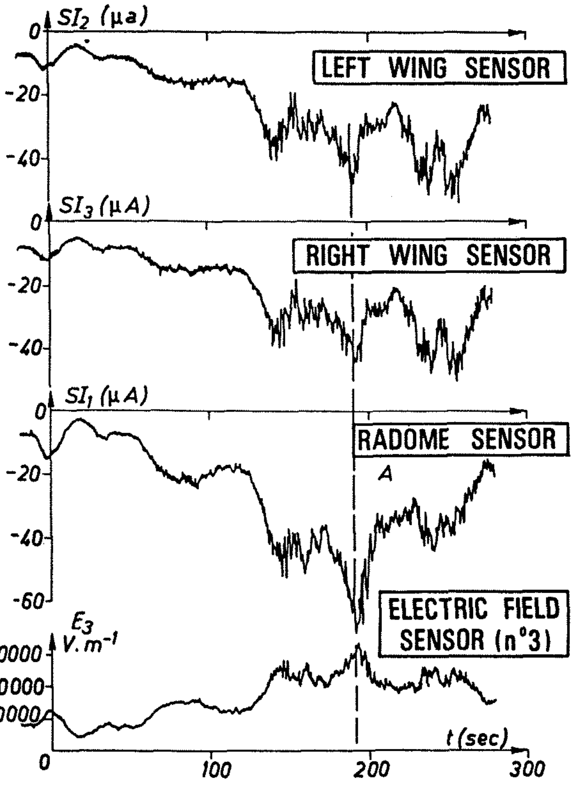


Fig. 4 - Triboelectric currents detected on aircraft

a/ impact current SI1 measured by the sensor coverting the front of the radome.

b/ impact currents SI2 and SI3 observed on the two identical sensors located at the same location on the leading edge of the wings.

c/ finally, the measurement of the electric field at one point or the struture; the development of this parameter is significant of the development of the aircraft's potential (6).

The first two graphs, SI2 and SI3, are exactly superimposable, which shows the reproducibility of triboelectric phenomena when the impact parameters are identical (geometry, impact velocity, local aerodynamics).

Furthermore, curve SI1 shows a temporal development similar to that of SI2 and SI3 with a factor of proportionality which is related in part to the electrode pick-up surface area and in part to the aerodynamic conditions proper to the radome environment.

If the values of the currents corresponding to point A (maximum rate) are summed on figure (4), a total impact current value of $1.15\ 10^{-3}$ A is obtained.

Finally, the last curve shows a strong correlation existing between impact current development and the variation of the electric field normal to the aircraft; note that at point A, the field exceeds 6.10^4 V/m.

To confirm this correlation, we give two curves on figure (5) plotting the impact current on one of the two sensors on the wings and the corresponding electric field. During this sequence the aircraft penetrated two neighboring clouds separated by an undisturbed medium of a very short distance. As for the preceding sequence, electric field E is directly related to the impact current measured during the cloud phases and that the signals are near zero in clear air. This would indicate that outside cloudy regions and in non electrically active cloud regions (absence of electric field), the potential of the aircraft is solely dependent on triboelectric effects.

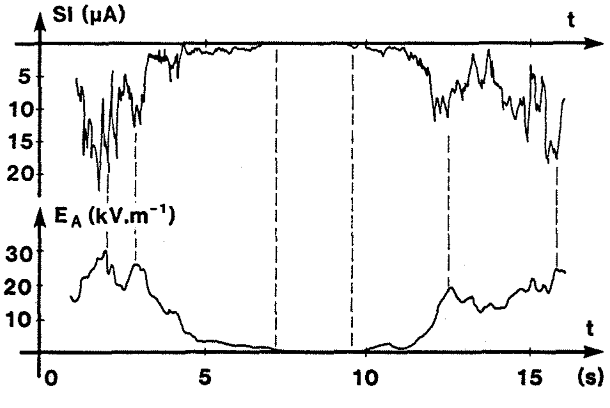


Fig. 5 - Impact current and electric field on the aircraft structure

We have mentioned that the aircraft's electric potential is defined by a differential equation showing the difference between the impact currents and the discharge currents. We have *several flights with different potential discharger* set-ups. The state of equilibrium shown on figure (6) was brought about by simultaneous variations of the aircraft's potential and the sum of the currents evacuated by the dischargers. A strong correlation between the two parameters (minima regions (A and B) and the maxima (C)) can be noted and we observe that the discharge current tends towards zero when the potential cancels out.

A deeper analysis of the relation between the sum of currents Σ id and potentiel V of the aircraft shows up a quadratic relation, complying with the therory of corona discharges.

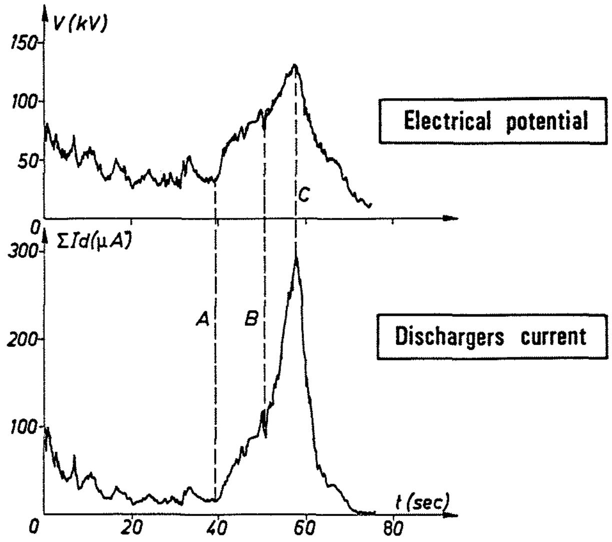


Fig. 6 - Aircraft potential in flight

4.2 Combined Influence of an Atmospheric Field and Triboelectric Effects

The twofold influence is observed when the aircraft approaches, then, penetrates inside electrically active convection cells.

We have illustrated these effects using the graphs shown on figure (7). This sequence is also significant for radio electric interference appearing on the aircraft.

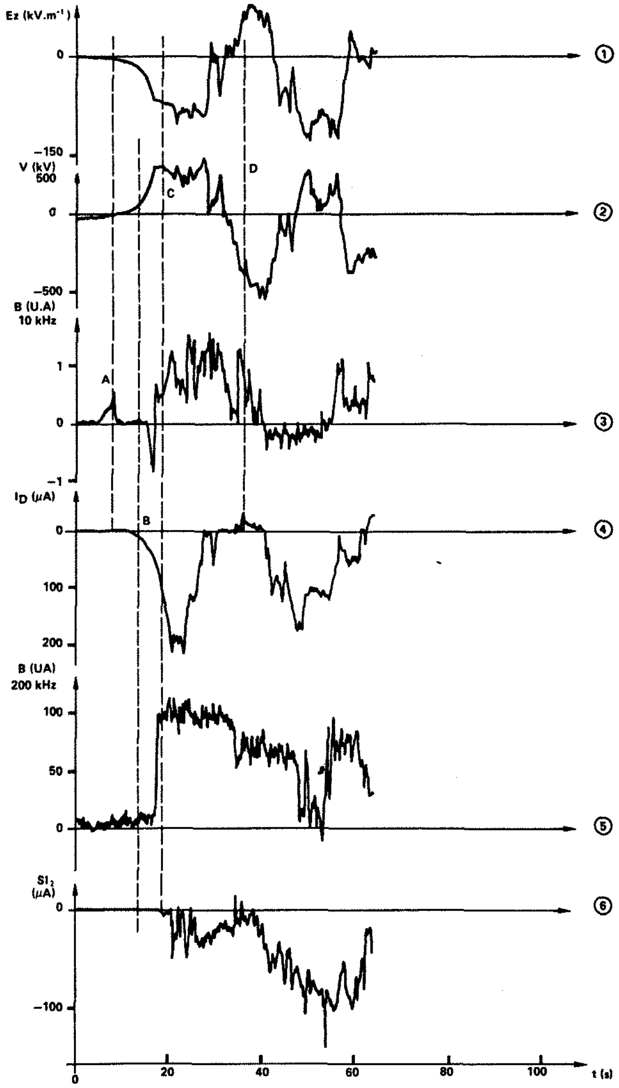


Fig. 7 - External field effect on an aircraft structure

At time t = 0, the aircraft approaches an active cell; on curve 1 there is an increase towards the negative values in field Ez; this field increases from 0 to 75 kV/m during the first 20 second time period. During this same period, the aircraft's potential (curve 2) which is near 0 at the start increases to 450 kV, which means that is has stored up positive charges. This charge transfer is due to microdischarges on the structure of the aircraft, which though slight, are sufficient to create a transient disturbance on the VLF receiver at 10 kHz as indicated by the noise signal corresponding to point A on curve 3.

At time t = 15 s, field Ez is high enough for the discharger with the lowest operating threshold (here the discharger located at the top of the vertical stabilizer) to begin emitting negative charges into the atmosphere (curve 4). At the same time, a sharp increase in noise at 200 kHz causing saturation on the radio-compass (curve 5) and an increase in interference at 10 kHz are observed.

Giving that the impact current probe sensor SI2 (curve 6) does not give any indication of triboelectric effect, we can consider that the entire first phase of interaction on the aircraft is due to the effect of the atmospheric field. Starting at point C, there is a stabilization of the outside field and the aircraft's potential; the clear air-cloud transition is obvious; at the same time, triboelectric impact appears. The electrical behavior of the aircraft is hence related to the twofold influence of the atmospheric field and the triboelectric effects.

However, in comparing curves 1 and 2, we observe that the atmospheric field has a stronger influence on the aircraft's potential, the discharger even emits positive current in the positive field region (point D).

5 - DIRECT LIGHTNING STRIKE ON THE AIRCRAFT

A direct strike occurs when the aircraft penetrates very active convective cells where the electric field exceeds the critical build-up field.

We propose to first draw an overall picture of the possible behavior of the aircraft in the phase preceding the strike, and secondly, the consequences of lightning on the structure of the aircraft.

a/ Analysis of the Atmospheric Configuration

The example chosen is that of a flight on board a TRANSALL 04 on 7.06.84 at a mean altitude of 3500 MSL, outside temperature was - 10°C. As shown on figure (8), the aircraft penetrated a series of neighboring cells whose contours showed up on the radar over a distance of 18 km at a speed of around 100 ms^{-1}. The aircraft was struck by lightning while transiting between two consecutive cells.

To clearly show up the microphysical aspect of the environment encountered, we have plotted several significant medium parameters on figure (9) (cloud particles and local dynamics). We also included on the same figure the electrical properties of the aircraft during the entire sequence under study.

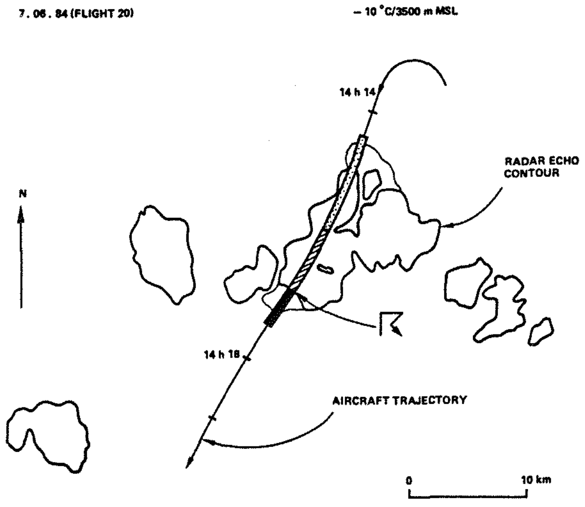


Fig. 8 - Atmospheric configuration leading to a lightning flash

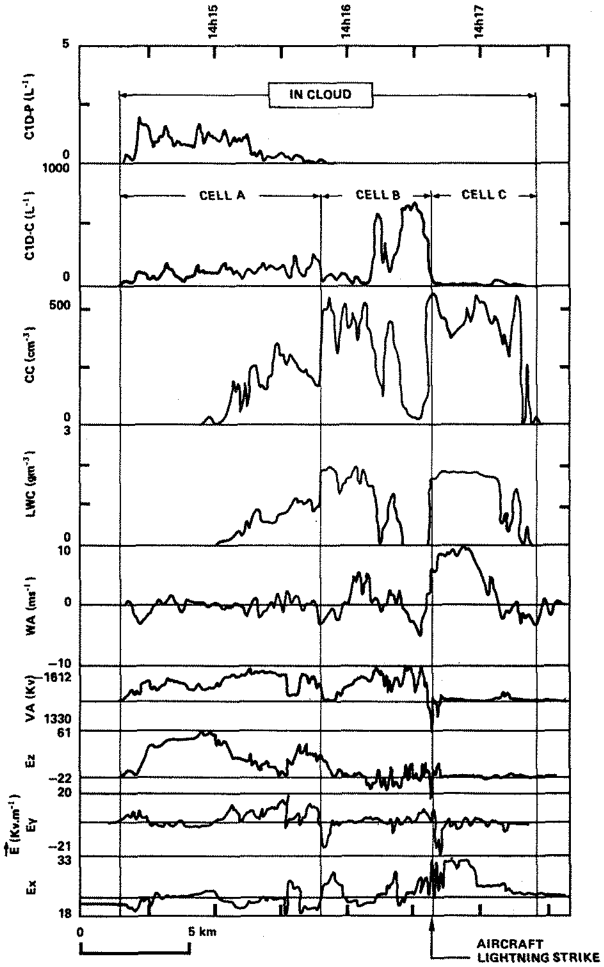


Fig. 9 - Atmospheric properties and aircraft electrical variations before a lightning flash

The first four signals clearly show up the structure of the cells encountered; as stated by GAYET (11), they are typical cells of cumulonimbus development. Cell A corresponds to a stage of dissipation without any remarkable speeds inside the cell (values of less than ± 2 ms^{-1}). This cell's population is represented by large diameter drops (0.3 to 4.5 mm) and by a low proportion of fine drops between 30 and 300 µm; however, this proportion tends to increase towards the transition zone to the next cell.

The transition with zone B is relatively clear since we observe the complete disappearance of large sized drops and a strong increase in the population of the diameter 30-300 µm drops, as well as the liquid water content. There is a strong ascensional movement at the center of the cell with a speed of around 5 m^{-1} and two descending movements at a speed of 5ms $^{-1}$ on each side. The second zone, B, is characteristic of a mature cumulonimbus.

The last cell crossed (cell C) is also highly typified microphysically:

- sharp drop in the population of drops whose diameter is included between 60 and 300 µm (curve 2).
- a sharp increase in the population of fine drops (curve 3) corresponding to a sudden increase of water concentration (2g.l $^{-3}$).
- a severe ascending movement since speed changes sharply from -5 ms^{-1} to +10 ms^{-1}.

Cell C is typical of a cumulonimbus structure in formation.

b/ Electrical Configuration

We have plotted curves 6, 7 8 and 9 on figure (9) of the main electrical parameters corresponding to:

- the electric potential of the aircraft.
- the three atmospheric electric field components.

During the crossing of cell A, the two components Ex and Ey are low, whilst the vertical component of the electric field remains high over several kilometers, reaching 6.10^4 V.m $^{-1}$. This value and the configuration of the external field clearly demonstrates the classical dipole structure of electrical charges in a convective cloud in the process of dissipation. The sharp variations of the three electric field components detected at point A are due to natural lightning near the aircraft.

The transition zone between cells A and B corresponds to a change in the atmospheric field components, inversion of the two horizontal components Ex and Ey and decrease towards zero of the vertical component. The electric field remains weak during the total crossing of cell B.

The aircraft is struck by lightning at the exact transition between zones B and C and is associated with an increase in component Ex, a growth which confirms itself after the lightning is formed since component Ex remains near 30 kV/m over a trajectory of at least 1 km.

Finally, in cell C the three electric field components tend normally towards zero.

During the entire measurement sequence, the aircraft potential remained high and always negative except during the transition between cells A and B where it was virtually zero.

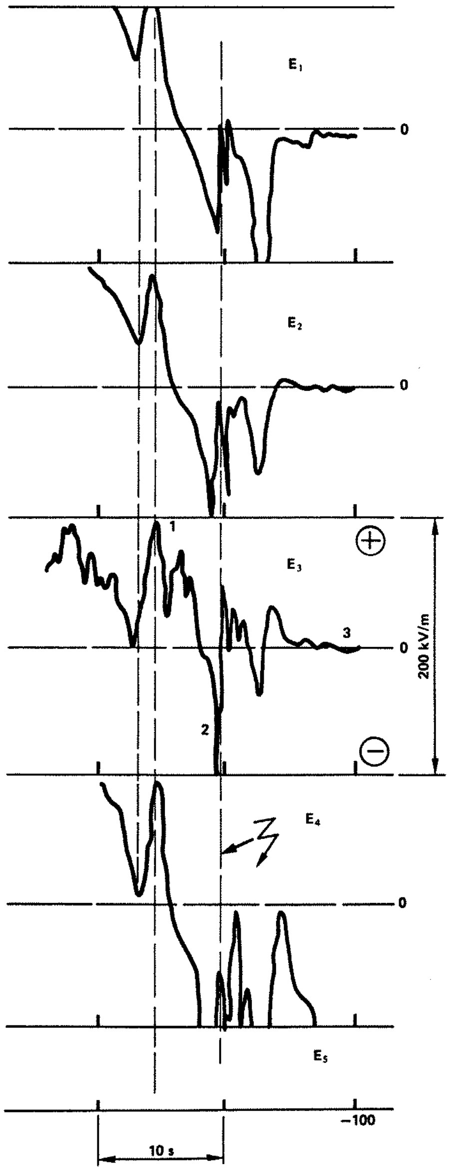
c/ Phenomena detected during the Lightning Strike

Variation in the static electric fields on the structure

May it be recalled that the TRANSALL carried five electric field sensors with a measurement range of ± 100 kV/m and temporal resolution of around 10^{-2} s.

We plotted the development of these parameters on the same time scale (except for E5 which was saturated during the whole period of the lightning phase) on figure 10. The response is relatively the same for all the sensors.

As mentioned previously, the atmospheric field's Ex component (center axis of the aircraft) sharply increases during the transition from cell B to C, the positive charges are displaced to the fore of the aircraft, causing E5 to saturate, the negative charges are distributed on the other regions of the structure (point 1, figure 10).



FLIGHT 20. 14h16'40"
TRANSALL 04

Fig. 10 - Static electric fields just before a lightning flash

A rapid phenomenom appears, which causes the simultaneous decrease in all the fields detected, then their cancellation, then an increase towards negative polarity. At the instant of the strike (point 2), the aircraft appears as being positively charged at a very high value; note that the phase immediately preceding the direct impact, observed with better definition on sensor 3, seems characteristic of the advance process of a strike leader towards the aircraft.

The strike was characterized on all the sensors by a sharp jump in the field, then a relaxation of the electric fields; signals E1, E2, E3 rapidly go back to zero whilst E4 and E5 remained momentarily saturated beyond -100 kV/m.

<u>Electromagnetic fields detected</u>

Two electric field E and magnetic field H sensors were placed to the fore of the fuselage. The E sensor shows the instantaneous development of charge density s at the point of measurement and the H sensor that of current density j circulating over the structure at the same point.

On figure (11) we plotted the development of H(t) against that of sensor E3 which was already analyzed.

We observe the appearance of four series of current pulses corresponding to the period where E3 was satured. The pulse trains are very brief and show current variations in both directions. The H field peak values reached 300 A/m which, assuming a current uniformly distributed over the fuselage, would correspond to currents with peak values of 5 kA.

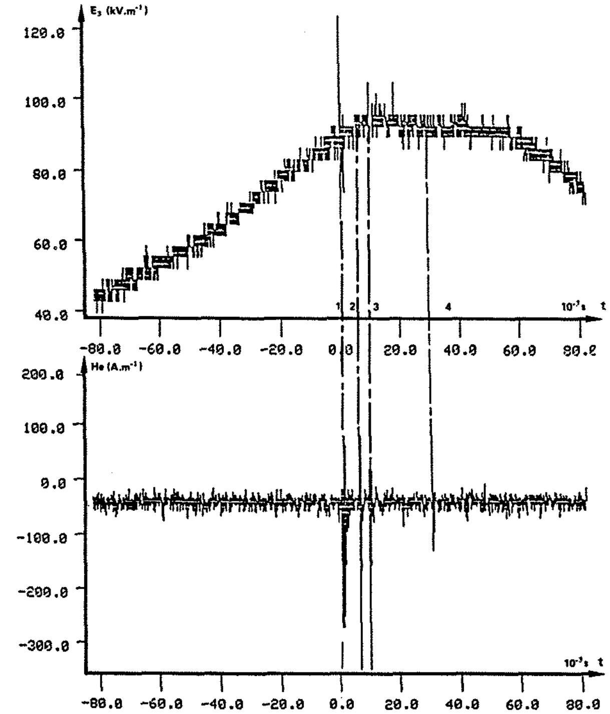


Fig. 11 - Magnetic pulses during a lightning flash.
Flight 20 - 14 h 16' 40"

By dilating the time scale (see figure 12) the succession of pulses becomes clearer, especially for the first series. At the beginning their amplitude is slight, it then increases and becomes bipolar.

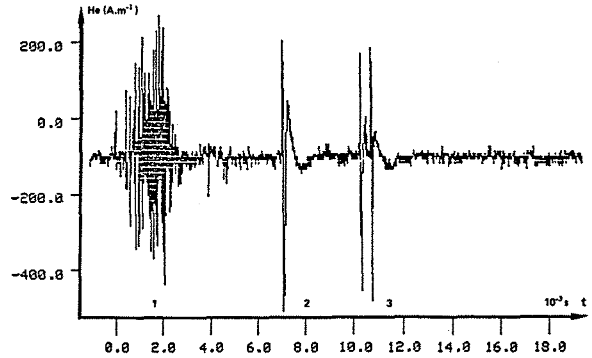


Fig. 12 - Structure of the magnetic pulses.
Flight 20 - 14 h 16' 40"

If we represent the structure of components E and H on the same time scale (see figure 13), we see that they are perfectly synchronous and we can see a repetition frequency ($T \simeq 200$ µs) which is found in most of experiments made with the TRANSALL C04.

All these pulses with very short rise times (around 100 ns) penetrate inside the aircraft's structure and create strong interference on the internal lines to the extent that the frequency spectrum excites the aircraft resonances. The most important aspect of this electromagnetic coupling is not broached in this article.

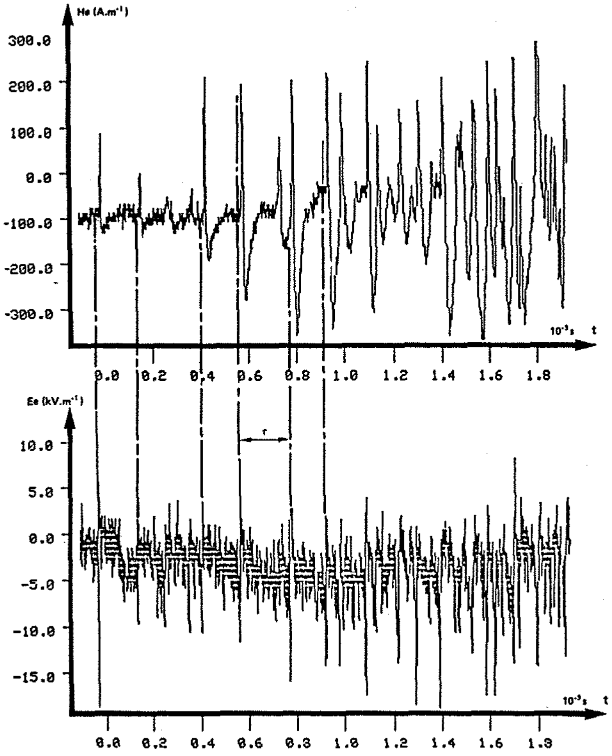


Fig. 13 - Correlated electric and magnetic pulses.
Flight 20 - 14 h 16' 40"

6 - CONCLUSIONS

Several recent inflight experiments have enables a quantitative approach to the influence of electric and electromagnetic interactions between an aircraft and the atmospheric medium.

Under the effect of particle contact with the structure of an airplane, significant variations in the aircraft's potential occur and can lead to electrostatic discharges wich cause interference on equipment aboard. Similar interference is observed when the aircraft is submitted to high amplitude atmospheric fields.

One of the most critical interactions for the operation of new aircraft with electrical flight control is that of a direct ligthtning strike. In addition to the influence of the dis charge currents directly affecting the equipment, we observe very intense electromagnetic interactions in the phase preceding complete breakdown on the aircraft.

Numerous overlays have been made on the various measurements obtained with the TRANSALL during direct strikes; these results have also been compared with those obtained in the United States by USAF on the CONVAIR C 580. The electromagnetic fields characterizing the formation of a discharge channel on the structure are comparable and hence reproducible mechanisms are at work.

These mechanisms are not yet fully explained and this will require further investigation to be carried out inflight and in the laboratory. They are most probably related to the appearance of rapid transitions in the formation of ionizing zones around the structure of aircraft under the effect of very strong outside electric fields.

At the practical level, this basic research is very important, partly because it will enable modelization of electromagnetic coupling on onboard equipment and partly because it should lead to the definition then the construction of appropriate simulation means for qualifying the aircraft and the aeronautical equipment of the up-coming generation.

Acknowledgements

This work has been supported by the Direction des Recherches Etudes et Techniques of the French Ministry of Defense (D.G.A).

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