GROUND TESTING OF AIRCRAFT ANTISTATIC PROTECTION

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Abstract

Static charge accumulation on aircraft structures can bring about sparks between conductors, streamers over the insulating surfaces, and coronas at the sharp points and edges. All these discharges induce radioelectric noise on navigation/communication equipment, reducing its operational performance and impairing flight safety.

The principles of a good protection against these harmful effects are well known. Sparks can be avoided by a careful bonding of all the metallic parts of the aircraft ; superficial electric charges can be evacuated before initiation of a flashover, if the surface resistance is kept below a certain value by using conductive paints or coatings ; coupling between corona discharges and the navigation/communication systems can be reduced drastically by a careful design.

However, the practical application of these principles has in the past suffered from the lack of a ground test methodology. Recently, new electrical instruments have appeared on the market for testing protective devices and treated surfaces. With these instruments, conformity with the standards can be assessed, and, moreover, an analysis of the spurious effects of charging on the various navigation/communication systems can be performed on the ground.

I. Introduction

Electrostatic charging of aircraft, a phenomenon which normally arises in flight when meteorological conditions are adverse, results in electrical discharges which interfere with the navigation and communication systems(1,2). These disturbances are particularly harmful in the following cases:
a) general aviation aircraft, where coupling between discharges and antennas is high, as a result of the small size of the vehicle ;
b) structures comprising large areas of composite-material insulating panels ;
c) avionic systems using digital electronics and integrated circuits.

As the tendency of modern transport aircraft is to use more and more composite material and digital electronics, and as general aviation aircraft is more and more expected to operate under all-weather conditions, electrostatic charging becomes a problem worthy of attention.

In particular, the development of control configured vehicles depends on their survivability under adverse atmospheric conditions : suppression of static precipitation interferences is essential for reducing their vulnerability.

Assessment of harmful effects of static charging can hopefully be performed on the ground by simulation ; hardening methods have been defined and can be easily applied(3); verification of their efficiency can also be made on the ground(4). This shows that in the near future aircraft manufacturers and airlines will probably use a standard procedure for eliminating static charging problems and associated hazards. The research work described in this paper is a step towards the definition of such a procedure.

II. Static charge generation mechanisms

Three types of electrification processes can cause aircraft charging :

a) frictional electrification ;
b) engine exhaust charge separation ;
c) atmospheric electricity induction.

The most energetic process for aircraft charging is frictional electrification, due to uncharged precipitation particles striking the aircraft skin. In these conditions, uncharged ice particles acquire a positive charge and leave the aircraft negatively charged. Another example of this process is the case of helicopters hovering in dust above a dry sand desert.

Engine charging is relevant to the case of jet aircraft operating at low altitude ; the corresponding mechanism is not yet understood in detail, but seems to be connected with the difference in mobility, in the ionized combustion gases, of the negative and positive charge carriers. In general, positive carriers are less mobile and are more easily transported in the exhaust stream, leaving a negative charge on the aircraft, but operational conditions can change the direction of this effect. It has been observed in military jet aircraft using afterburning at high altitude, that the exhaust stream acts as a discharger and reduces the aircraft's electric charge.

Induction charging, observed when the aircraft is submitted to a high atmospheric electric field, is linked to dissymmetries in the aircraft body. Under the influence of charged clouds, the aircraft is polarized : positive charges are accumulated on one side, negative charges on the opposite side. Surface features having a high curvature provoke electrical discharges locally and, if these features are unevenly distributed between the positive and negative sides, a net aircraft charge will result. Charging currents depend on the aircraft size. A Jumbo jet can collect a current of several mA.

III. Induced discharges and associated radioelectric noise

Aircraft charging can bring the aircraft potential up to hundreds of thousands of volts ; when a steady state potential is reached, charging is balanced by discharging, essentially due to corona discharges sustained at the sharp points or edges of the structure.

Electrification can also result in differential charging, i.e. local charging of insulated conducting parts or of dielectric surfaces. Differential charging results in voltage gradients and induces local discharges, in the form of sparks between conducting parts or surface streamers over insulators. These discharges are many orders of magnitude more energetic than the coronas mentioned above, and, in the case of an untreated aircraft, often are the main source of radioelectric disturbances.

A corona discharge is characterized by a strong dissymmetry between the electrodes. In the laboratory, a point electrode with a small radius of curvature is placed in front of a large blunt electrode. In the case of aircraft charging, this blunt electrode is virtual. When a voltage is applied between the two electrodes, the electric field is maximum in the vicinity of the point electrode (called the "stressed" electrode). In a small volume close to the point, electronic avalanches are triggered by seed electrons. Ionization increases and a local plasma is generated. In the case of negative corona (which accounts for about 90 % of the cases) electrons diffuse far away from the active region and attach themselves to oxygen molecules, giving rise to a negative-ion space charge. When this space charge reaches a given threshold, its electric field -which is opposite to the field due to aircraft charging- balances the applied field and the discharge is quenched. The discharge resumes when the negative space charge has been swept away. This is the origin of the Trichel pulses, a characteristic feature of the waveform of the negative corona current, which is made by a succession of such pulses typically having a peak amplitude of 1 mA and a rise time of a few nanosecondes (figure 1). Fourier analysis of these pulses gives a spectrum shown in figure 2. It is easy to see that this noise emission will interfere mostly with the low-frequency navigation systems (OMEGA navigation, 10 kHz) and the high frequency automatic direction finders (100 kHz). Interference on V.H.F. systems (V.O.R and I.L.S) is an order of magnitude lower. MLS systems (1 GHz) will practically not be affected.

Sparks and surface streamers correspond to much stronger peak currents (from several amperes to thousands of amperes). The radiation effects associated with these currents -whose spectrum broadly resembles the corona spectrum- are therefore very important, and induce saturation of radio receivers or even breakdown of electronic components.

This is why a first step in the electrostatic treatment of an aircraft shall be a careful elimination of differential charging, which suppresses sparks and surface streamers.

Radioelectric noise emission due to aircraft charging and discharging has been analysed elsewhere(1) (2) (5). Coupling of noise sources with sensitive points of the avionic system (and particularly with the antennas) has also been analysed in original and review papers(3) (5) (6). Minimizing the coupling between corona discharges and antennas is the key to corona interference alleviation.

IV. Disturbances experienced in communication and navigation systems

The most noticeable effect of radiointerference due to electrical discharges induced by aircraft charging is the audio noise superimposed on communications. It can sometimes be so strong that comprehension is impaired, and the pilot is cut off from a major source of information.

A very common disturbance is the saturation of the servo loops of the automatic direction finders (ADF). In this case also, the pilot is left without information as to his location. As a large number of developing countries use the ADF as the sole navigation system, owing to its low investment cost, saturation of ADF servo-loop by static charging is a danger when flying over these countries.

More exceptionally, disturbances in VHF systems, such as VOR or ILS, have nevertheless been observed on untreated aircraft, where progressive static charging resulted in successive saturation, for example, of the ILS localizer loop and of the ILS guide-slope loop. Further charging even resulted in flag disappearance, leaving the pilot in a very dangerous situation(7).

Let us finally mention that even in a large aircraft, where corona to antenna coupling in weak, OMEGA operation can be disturbed by aircraft charging, particularly if the OMEGA signal has been subjected to strong absorption by specific propagation conditions, which is the case in particular over ice caps(8).

V. Hardening techniques

Elimination of differential charging can be performed by a proper bonding of all metallic parts of the aircraft, and by a proper control of the surface resistance of all dielectric surfaces, especially of dielectric surfaces exposed to impact of atmospheric aerosols. If surface resistance is kept low, electrostatic charges cannot accumulate, and the associated potential cannot reach the spark-over threshold. Special mention should be devoted to radomes and antenna covers, for which a compromise should be reached ; the surface resistance should be low enough to let the static charges relax, and high enough to avoid attenuation of the radio waves traversing the surface. This compromise can easily be obtained by using antistatic paints available on the market.

It is therefore possible to eliminate sparks and surface streamers both by careful bonding of all metallic pieces and by application of the proper antistatic paint.

However a problem arises from the fact that an antistatic paint layer is generally inesthetic and easily damaged ; a superficial protective coating should be applied over the antistatic layer. This protective coating is generally insulating because conductive white paints have not yet come out on the market. As soon as static charges accumulate over this coating, the electric stress across the protective paint increases up to the point where electrical breakdown occurs : multiple microscopic puncture due to a large number of small sparks is then experienced by the superficial coating which loses its insulating properties, while keeping its protective and decorative qualities. After a short conditioning period, these small sparks are therefore less active and their effect can be neglected in the assessment of the disturbances due to aircraft charging.

The aircraft designer is therefore left with the corona discharges, which cannot be eliminated since they are necessary for obtaining the steady state balance between charging and discharging mechanisms. Reduction of the disturbances provoked by corona discharge is obtained in the following ways :

a) by reduction of the coupling between coronas and antennas ;

b) by reduction of the corona noise emission corresponding to a given discharge current.

Reduction of the coupling is produced by using passive dischargers, i.e. sharp metallic points connected to appropriate parts of the structure (for example, trailing edges of the wings). The radius of curvature of these points is such that coronas are preferentially sustained at their tips rather than at any other part of the aircraft. The active zone, which generates the radioelectric noise, is kept far away from the structure if the discharger tip is connected to the wing by a long resistor : this decreases the capacitive coupling between active zone and aircraft. A further reduction of coupling is obtained if the discharge is oriented perpendicular to the ratio frequency field lines near the trailing edge. According to Nanevicz and Tanner, the noise collected on the antenna is minimum in this case(6). Compared to the emission of an unprotected trailing edge, the noise is decreased by 50 dB (ortho-decoupling).

Reduction of the corona noise emission for a given discharge current can be obtained if instead of a metallic point, a bunch of carbon fibers embedded in an insulating resin is used(9). It has been shown that, in this case, a large number of uncorrelated microdischarges are produced. The noise reduction can reach 100 dB if ortho-decoupling is also used(10).

VI. Necessity of a test procedure

If the principles of a good protection against the harmful effects of static charge accumulation on aircraft structures are well known, the practical application of these principles has for a long time been a matter of empiricism. It was believed that protection against static charging could only be assessed by performing a full in-flight experiment ; but such an experiment is a very expensive task ; its analysis is hampered by the non-reproducibility of meteorological situations, the inconvenience of recording, storing, packing and correlating a huge quantity of data, and the lack of flexibility. At any rate, such an experiment is possible only as a research tool, but cannot be applied as a standard testing procedure at the factory or on the field. It is highly desirable to define a method for verifying, at the production stage, that the antistatic protection rules have been correctly applied during the construction of the aircraft, and, at the exploitation stage, that the protective devices and the treated surfaces are in good condition.

The present paper constitutes a step towards the definition of a standard procedure for testing aircraft charging phenomena and protections, in the laboratory, in the factory and on the field. Until such a procedure is operational and universally adopted by the research institutions, the aerospace industries and the airlines, a full protection against communication/navigation disturbances is not ensured during flights in very adverse atmospheric conditions.

In this paper, solutions are proposed for meeting the requirements of a safe protection. In order to apply the test method quickly and efficiently, specific instruments have been designed and implemented at ONERA, and are already available on the market in France. A general description of their performance is given below.

VII. Test procedure requirements

The proposed test method shall fulfil the following functions :

a) check the bonding between metallic surfaces, even if these surfaces are covered by an insulating coating ;

b) measure the value of surface resistance of semi-conductive coatings or resistive paints deposited over insulating substrate, even if these coatings are covered by a layer of highly insulating material ;

c) simulate tribo-electric charging or charge collection separately on any surface element of the aircraft, in order to determine the location and the nature of the more sensitive spots, and to assess the effect of the charging of these elements on the navigation/communication systems ;

d) verify that the coupling between dischargers and antennas is minimum, i.e. that the position of the dischargers is optimized, and that the noise collected by the antennas for a given discharge current is in conformity with the value announced in the specifications and has not increased because of some deterioration experienced by the dischargers.

During all this testing procedure, the aircraft shall be electrically grounded, or, if global operation of the dischargers is required, it shall be insulated by dielectric slabs placed below the wheels. This insulation shall be matched with the voltage limit due to the operation of the dischargers, in order to avoid flashover between aircraft and ground. A high resistance bleeder shall be used, for safety, to discharge the aircraft below the threshold voltage of the dischargers.

If any voltage generator is used for operations (c) or (d), its output impedance shall be kept very high, to insure safe operation.

Operations (a) and (b) are to be performed without damaging the superficial layer of paint.

Operation (c) shall be clean, i.e. without projection of particles or aerosols which could change the electrical properties of the surfaces or those of the environment. It shall be sufficiently well resolved in space to separate the effects of the charging of various elements (radome, fairings, antenna covers, canopies) on each navigation/communication system, and to permit the observation of local sparks due to a faulty bonding.

The validity of simulation (c) shall be confirmed by visual/auditory observation of the behavior of the navigation/communication instruments. Under such simulation tests and for a given electrostatic protection, an experienced pilot, seated in the cockpit, wearing earphones and watching the displays, shall identify the situation as similar to a real flight with different atmospheric conditions.

VIII. Verification of bonding

The first step in testing aircraft on the ground for static charging is the drafting of a check-list of all the metallic parts of the structure. Bonding of all these pieces should be checked, even if they are clamped or riveted together. The presence of insulating gaskets -teflon gaskets for example- or even corrosion of the rivets can impair the bonding. A reference point should be selected in the structure : the terminal generally provided for grounding the aircraft during refueling can be used, as well as the negative electrode of the power supply. Resistance between all the pieces included in the check-list and this reference point should be measured. If the pieces are not painted, an ohmmeter can be used. If they are covered by an insulating layer of paint, the only way of checking the bonding is with a capacitive method. For example, by using an electrode in contact with the insulating layer of paint, an alternating current at audio frequency is injected through the layer into the metallic piece. The second electrode of the audio generator is connected to the reference point. A high impedance sensing electrode measures, through the same layer, the A.C. voltage of the piece. If this voltage is not negligible with respect to the forcing electrode voltage, the bonding is not correct. The two electrodes can be arranged on the same measuring head, which can be used in the same way as a medical doctor uses a stethoscope (figure 3). This method takes advantage of the fact that, for static electricity elimination, bonding requirements are by no means stringent : two conductors can be considered as bonded if the resistance of their connection is lower than 10^5 Ω. Two problems arise when the design of the corresponding instrument is considered :

a) the response should be independent of the thickness of the layer of paint, and of the pressure exerted by the operator on the measuring head ;

b) the device should be able to discover a poor bonding even in the case where the piece has a large capacitance with respect to the reference metallic structure.

The solution results from a compromise between sensitivity and reasonable elimination of false alarms, which determines the choice of the operation frequency. The study of such a device was performed at ONERA and has led to the manufacture of a standard instrument sold under the trade name CORAS.

Note that our definition of bonding, in the case of static charging, is different from the conventional definition, which involves very low bonding resistances (milliohms). Our opinion is that this last definition can be restricted without any danger to the case of connections likely to transport lightning currents.

IX. Surface resistance measurements

The second step in testing aircraft on the ground for static charging is the drafting of the check list of all the insulating items appearing on the surface, and more particularly of the dielectric pieces exposed to tribo-electric charging (radomes, windshields, canopies, fairings, antenna covers, plastic wing-tips, glass-fiber flaps, pneumatic de-icing devices). If these pieces are not coated with a resistive layer, they can be the source of charge accumulation. The first effect of charge accumulation is corona initiation at the small radius of curvature points of the metallic pieces close to the charged dielectric. A second effect, which arises in the case of unprotected dielectric antenna caps, is corona initiation followed by sparking between the enclosed antenna and the dielectric cover (this implies local breakdown of the dielectric). A third effect is the initiation of a surface streamer.

The check-list should include measurements of surface resistances and measurements of the bonding of these surfaces. Dielectric surfaces are considered as having a good antistatic protection if their surface resistance (resistance of a square mesh) is below a threshold value ; they are unproctected if their surface resistance is above this value. They are bonded or unbonded according to whether the value of the resistance between a line located on their periphery and the reference point is below or above a threshold value.

Antistatic coatings are generally covered by an insulating layer or protective paint ; this is why only a capacitive method can be used to perform the measurement of surface resistance. This can be made if CORAS is used. The CORAS has a second head especially designed for that purpose. The surface resistance is measured in the same way as the resistance of a shunt ; the current is measured, and forced through the protective paint by two concentric ring electrodes ; two high impedance amplifiers connected to two intermediate rings measure the voltage. The electrode arrangement is located in the mobile head of the CORAS.

After the measurements have been performed, the various metallic pieces are classified as bonded or unbonded, and the various dielectric items are classified as treated or untreated by antistatic coating, and if they are treated, as bonded or unbonded. This classification is then used for making a decision about further protection. If some cases are still ambiguous, the decision can be delayed until on the ground simulation of static charging is performed.

X. Simulation of tribo-electric charging

If the aircraft to be tested were perfectly conducting over all its surfaces areas, the charges induced by friction or collected in the atmosphere would be distributed according to the surface geometry. In this case, it would be sufficient, for performing a check on corona discharges location and on the associated R.F. noise, for example, to connect the surface to a high voltage generator, with the aircraft insulated. As field configuration can be roughly computed from model measurements, this kind of test is necessary only to verify that the passive dischargers are performing correctly, i.e. that all the corona discharges are located at their tips. We will come back to this type of measurement in the next section.

The real problem comes from the fact that no aircraft is perfectly conducting over all its surface, as radomes, canopies, windshields, fairings and antenna covers are insulating when not specifically treated to acquire total or partial surface conductivity. We want to have the following two answers.

a) For a given untreated dielectric surface, what are the consequences of a given local charging current on the operation of the navigation/communication systems of the aircraft ? This includes the anomalies induced, on the corresponding antenna, by charging both its dielectric cover and the other antenna covers.

b) If the same dielectric surface has been treated, is the applied treatment sufficient for complete elimination of all the observed anomalies, over the whole range of charging currents likely to be experienced in flight ?

By stressing that the source of radioelectric disturbances is essentially due to local coronas or streamers associated with the redistribution of charges accumulated on the insulating surfaces(1) (2), it is easy to see that local charging of these surfaces will produce approximately the same effect if the aircraft structure is grounded through a high resistance or if the aircraft is in flight. This remark opens the way to a very important test, i.e. the observation of the effects of local streamers on the performance of navigation/communication systems, and for a complete verification of streamers disappearance when the insulating surfaces have been duly treated. What one needs for performing this test is a good source for locally charging the insulating surfaces.

Taking into account the order of magnitude of the charging current to be simulated, and also its very nature (surface charging by low energy and not by energetic particles), two types of processes can be used :

a) tribo-electric charging, using a two-phase flow of air with a suspension of uncharged fine particles ; this method has yielded interesting results in the laboratory$^{(12)}$; however the particles are not drained by the airflow as in flight, and their accumulation on the surfaces raises a serious problem, which is why this method has not been used in this work ;

b) charge collection using an injector of charged particles ; this method is good as long as an efficient charge injector is used ; it is this method that has been applied at ONERA, as described below.

Instead of using very high voltage generators, ONERA has extended a method first proposed by Whewell, Bright and Makin$^{(13)}$ following previous work by Marks, Baretto and Chu$^{(14)}$. In the corresponding device, low mobility charged microparticles of ice, obtained by condensation and freezing of water vapour in humid air expanding in a supersonic nozzle, and driven by fluid friction in the jet, are used as charge carriers. This principle is applied to inject charges upon an insulating surface, in spite of the associated repulsive electric field. Note that the microparticles of ice sublime after leaving the supersonic region of the jet ; this simulation method is therefore clean in the sense that the local properties (surface resistance and breakdown voltage) are not modified when the charge injector is operating. This device is marketed under the trade name INJECO.

Figure 4 is a schematic representation of the INJECO device. Figure 5 is a photograph of the instrument. Its main characteristics are listed in Table 1. Figure 6 shows how this injection is performed when testing a real aircraft ; a first operator applies the charged flow upon a given antenna cover and, at the same time, a second operator watches the displays associated with the navigation equipment of the aircraft and estimates the noise collected by the communication receivers. Visual observation of induced sparking or streamers can also be performed (figure 7). The charging current sign and intensity can be controlled, ranging from low to high for simulation of weather conditions between fair and extreme. The difference between the cases of untreated and treated surfaces is striking and points out the importance of having a carefully applied surface treatment ; associated with the surface resistance and bonding measurements, this simulation also permits a quantitative correlation of the reduction of the surface resistances (or the improvement of the bonding) with the decrease of the noise induced by aircraft charging on avionic systems.

To apply this method one needs a supply of compressed air with a pressure of 6 atm, and a power supply with a voltage of 10 kV, positive and negative. Both can be readily operated in the laboratory, in the factory and on the airfield. As shown in figure 5, the injection nozzle is of light weight, and can be easily used to charge any part of the aircraft. An important detail must be pointed out : in this experiment, the radioelectric disturbances are produced by local discharges following charge accumulation on insulating surfaces. Assessment of the noise produced by these discharges is possible only if the injector itself does not transmit any discharge noise ; this property is an important advantage of the described device and its achievement was the result of a careful design involving a difficult optimization process. An interesting property of the device, of importance when working indoors, is that no ozone is produced by the discharge. This is due to the fact that ozone production is greatly enhanced by water vapour, which is fully condensed in the supersonic nozzle where the corona is sustained.

XI. Verification of the dischargers

This verification directly follows the method introduced by Tanner and Nanevicz$^{(5)}$. To avoid RF current circulation in ground lines, the aircraft reference terminal is connected to ground through a 20 MΩ resistor ; insulation of the structure is realized by thick dielectric slabs located under the wheels. To reduce the aircraft-to-ground capacitance, these slabs should be at least 4 inches thick. This operation is recommended for small aircraft, and may be difficult for large commercial aircraft (figure 8).

The first step in this verification is the evaluation of the coupling between coronas and antennas. It can be performed with a corona probe which is constituted by an insulating tube having at its tip a point-to-plane arrangement (radius of the stressed tungsten electrode 50 μm ; point-to-plane distance 1 mm) where a negative corona is excited (average current 150μA). Reference (5) describes in detail a slightly different arrangement.

The method consists of moving the reference discharge from point to point and of reading the noise current at the antenna terminals by connecting an appropriate receiver to these terminals. Next, the receiver is connected to parallel plate coupling electrodes, into which the probe is inserted. The coupling to reference point is determined from the coupling for the parallel plate electrodes (which can be computed) and the attenuation necessary to equalize the receiver noise outputs (see reference (5)).

The second step consists in the measurement of the noise induced by the coronas excited at the tip of the dischargers. To perform this measurement, it is not necessary to apply a high voltage to the dischargers, nor to divert their average current through a microammeter ; if an INJECO is used, by spreading positive charges over a discharger from a distance of about 10 cm, all the current is collected by the discharger tip. The average current can be read directly on the INJECO meter, and this simulation is made with the discharger connected to the structure as in its normal operation. This measurement can be performed by connecting a receiver to the antenna terminals and reading the noise current, or by evaluating the disturbances produced in the avionic equipment.

A third step, which is necessary only for making sure that no corona can be sustained over all the aircraft except at the dischargers tips, involves the connection of the entire insulated aircraft to a high voltage power supply. During this check, the aircraft kerosene tanks should be full, or, if not, under nitrogen pressure. The connection **to** the high voltage terminal is made through a high value resistor. In these conditions, the measurements can be safely performed by personnel working inside the aircraft. The verification consists in watching the various instruments while the high voltage is progressively raised. It is recommended in this case to instrument at least one discharger (for having a value of its average current) and to limit the maximum voltage of the power supply under a safety upper bound determined by the total maximum current of the dischargers. The insulating slabs should afford twice this voltage without flashover. If the disturbances produced during this check exceed the effect predicted from the sum of the noise induced by the various dischargers, a stray discharge is operating somewhere and should be discovered.

XII. Assessment of the antistatic protection of the aircraft

From the list established according to the method developed in § VIII and § IX, and from the measurements performed according to the method described in § X, recommendations are written up and decisions can be made about desirable improvements in bonding and antistatic coating. After complexion of these improvements, a new check is made according to §VIII, IX and X. Verification of dischargers performance, and, if necessary, optimization of their operation is then performed according to the method described in § XI.

CONCLUSION

This lecture has presented a procedure for evaluating the vulnerability of protected or unprotected aircraft to static charging, and for assessing the validity of the protection methods. The following statements can be made as experimental facts :

a) static charging produces harmful interference on navigation, communication, command and control equipment ; effects on future control configured vehicles can be a major problem ;

b) total alleviation of these disturbances is obtained by making proper arrangements including passive dischargers and resistive coatings ;

c) verification of a correct application of these arrangements can be performed with the aircraft on the ground ;

d) the corresponding procedure can easily be implemented when using specific instruments available on the market.

It is hoped that careful application of this test procedure will, in the near future, increase the reliability of avionic systems during operational use.

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CHARACTERISTICS

Generating pressure : 5 atm
Flow rate : 20 Nm³/h
Power supply voltage : ± 10 kV
Nozzle diameter : 2.3 mm
Current : 0 to 30 μA
Two polarities

Table 1 - Main characteristics of the INJECO.

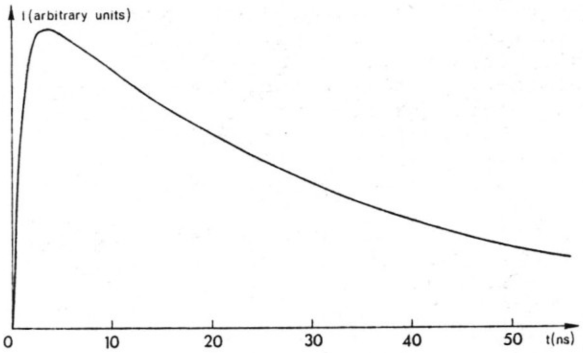

Fig. 1 - Typical Trichel pulse.

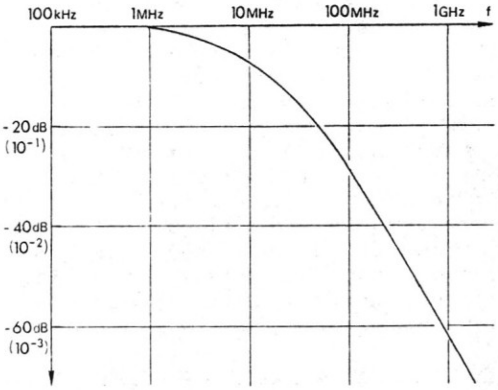

Fig. 2 - Spectrum of a typical Trichel pulse.

Fig. 3 - Using the CORAS for verification of bonding.

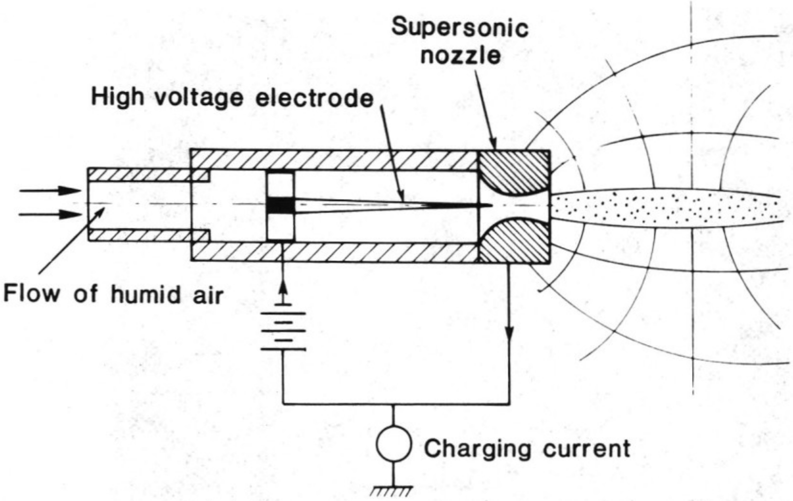

Fig. 4 - Diagram of the INJECO device.

Fig. 5 - INJECO charge injector.

Fig. 6 - Simulating static charging on an aircraft

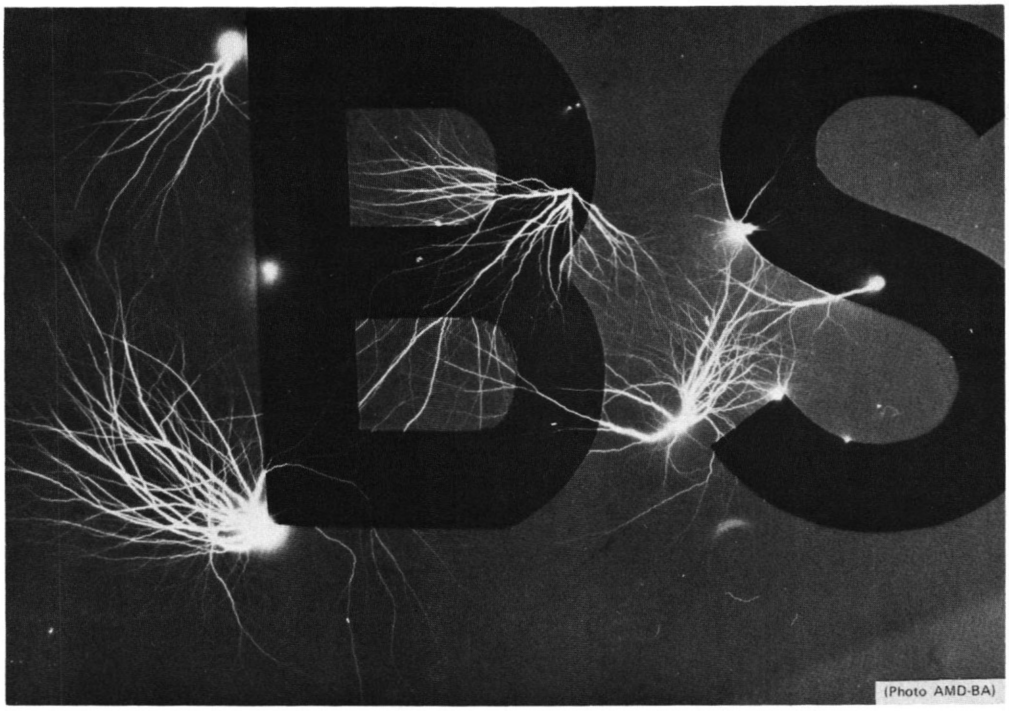

Fig. 7 - Surface streamer produced by charging the fuselage.

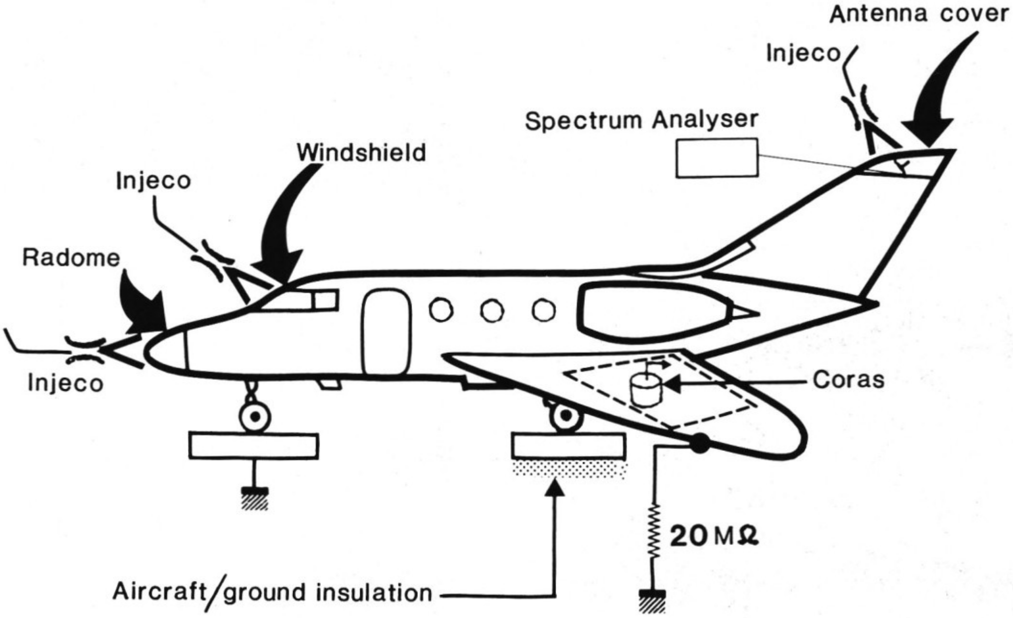

Fig. 8 - Block diagram of the experimental set-up used for aircraft testing.