Observations on the Electrostatic Discharge Threats to Aircraft Body and to Aerospace Electronics

J. Fisher[1], Hikma Shabani[2], P.R.P Hoole[2], M.R.M. Sharip[2], K. Pirapaharan[1], Al Khalid Hj Othman[2], Norhuzaimin Julai[2], R. Harikrishnan[3] and S.R.H. Hoole[4]
[1]*Department of Electrical and Communications Engineering, Papua New Guinea University of Technology, Lae 411.*
[2]*Department of Electrical and Electronic Engineering, Universiti Malaysia Sarawak, Malaysia.*
[3]*Department of Electrical Engineering, University of Malaya, Malaysia.*
[4]*ECE Dept., Michigan State University, East Lansing, MI, USA.*
hikmash@hotmail.com

***Abstract*—Electrostatic Discharge (ESD) is a well-known threat to aerospace vehicles and microelectronic systems. This is especially so with the increased use of non-metallic, composite material for the aircraft body. Moreover, the severe lightning flashes to aircraft also commence with ESD on the aircraft body. The ESD results in the initiation of positive leaders that grow towards the thundercloud from one part of the aircraft. Moreover, a negative leader is launched towards the ground or another cloud. In this paper, we discuss the induced electric charges due to the vertical electric field component of the thundercloud charge center. Further, the electric currents induced on the surface of the aircraft body or equipment by the horizontal component of the thundercloud generated electric field is examined. From the electrostatic fields computed prior to the initiation of corona or the initial leader, we show that in addition to the most commonly identified part of the aircraft from which leaders are initiated, namely the radome, the main wing tips, the curved surface of the mid-wing and the stabilizer tips experience highly enhanced electric fields. These electric field enhancements may also lead to the generation of electric breakdown.**

***Index Terms*—Aircraft Electronics Protection; Airborne Static Electricity; Aircraft Design.**

I. INTRODUCTION

As the aerospace industry expands into both manned and unmanned commercial and military vehicles, preventing electric field enhanced aircraft initiated lightning strikes and protection against serious damage and accidents become a major concern to the aerospace industry [1-4]. When an aircraft flies into the environment of an electrified cloud, it enters into an enhanced electric field region surrounding the cloud, which in most cases has a large negative charge center in its lower region. The electric fields will induce an electric dipole charge over the body of the aircraft, with positive electric charges on the top surface of the aircraft and negative electric charges over the underbelly of the aircraft. This results in an electric dipole charge structure over the entire aircraft body. These can be sufficiently enhanced to result in electric discharges, for instance, resulting in positive leaders emanating from the radome of the aircraft as shown in Figure 1. With this, at another extremity of the aircraft, as also shown in Figure 1, a negative leader may develop from electrostatic discharges occurring at another electric field enhanced part of the aircraft body. The negative leader will move towards the ground or another nearby thundercloud. It is important to determine the electric field enhanced areas of the aircraft in order to design preemptive measures to reduce lightning strike risks, even to design and to maintain the aircraft to reduce electric field enhancements in these high-risk areas of the aircraft body [5-6]. A knowledge of the electric charges induced on the aircraft body and the electric field distribution is also essential to decide on the safe placement of sensitive microelectronic systems associated with aircraft measurement, communication and navigational systems [7].

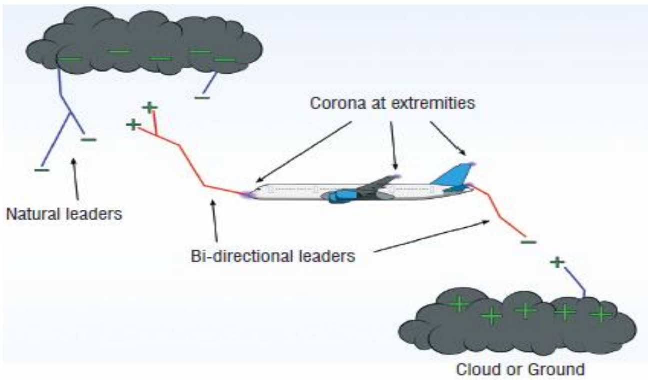

Figure 1: Aircraft initiated lightning leaders resulting from initial ESD on the surface of the aircraft body close to thundercloud electric charge centre [1]

Although direct measurements of electric currents and electric fields have been made by flying instrumented aircraft into thunderclouds and in to thundercloud vicinity, these are limited in scope because of the immense expense involved in carrying out this experiment, with the onboard measurements being confined to specific thunderclouds which were investigated, specific to points on the aircraft where the sensors are placed, as well as the limited number of events observed (e.g. a total of about 50 lightning strikes to a CV580 aircraft) [4]. Only about three types of aircraft have been used for these experiments. Measurements are made only in around five different locations on the aircraft [4]. Seeing the need to develop a well attested computational testbed for aircraft design, testing and protective measures on any type of aircraft (e.g. commercial, cargo and military aircraft) at different locations and inclinations with reference to the thundercloud, work is being done to develop an electromagnetic testbed which is in the process of being extended to several important aspects of aircraft-thundercloud interaction, both before and after a lightning strike [8-10]. An electric dipole based method was proposed and its results were successfully compared to laboratory-based measurements [8]. It has been used to model the aircraft in great detail and further tests were carried out for both cloud to ground and cloud to cloud lightning strikes in which an aircraft becomes part of the lightning flash channel [9, 10]. Computer-based simulation studies are also being carried out on the electrostatic environment of the thundercloud and the electric charges and electric fields produced on the aircraft surface before the aircraft is struck by lightning [11]. In this paper, specific observations are made on the prestrike electric field which is perpendicular to the aircraft body, the electric field which is parallel to the aircraft body that generates electric currents and the specific regions in which the induced electric charges are large resulting in electric fields that exceed the breakdown electric field of the air surrounding the aircraft. The reliable simulation and the development of simulation for certification continue to be areas of intense research and development [12, 13].

II. Electric Field Induced on the Aircraft and its Components

Consider the thundercloud charge center as a sphere with charge Q and the aircraft at a distance R below the electric charge center [12]. Then the electric field of the charge center at any distance r is given by $E = Q/4\pi\varepsilon r^2$. Therefore, at a distance x along the surface of the aircraft $r = (R^2 + x^2)^{1/2}$ and the vertical electric field on the aircraft surface at distance d is $E_v = QR/4\pi\varepsilon(R^2 + x^2)^{3/2}$ and the electric field along, i.e. tangential to the surface of the aircraft is $E_h = Qx/4\pi\varepsilon(R^2 + x^2)^{3/2}$. The electric charge induced at distance x in a narrow strip of dx is $dq = \varepsilon E_v(2\pi x dx)$. Hence the total charge induced on the surface of the aircraft over a radius of d, is obtained by integrating dq for limits of $x = 0$ to $x = d$, to yield an induced electric charge of $q = Q[1 - R/(R^2 + x^2)^{1/2}]$. This electric charge will also be induced on the underside of the aircraft, with the sign reversed, thus resulting in a dipole electric charge produced on the aircraft by the thundercloud charge center.

Consider now the horizontal electric field E_h along the surface of the aircraft. It will produce an electric current given by $J = \sigma E_h$ where σ is the conductivity of the aircraft body. For aluminum body aircraft the conductivity is large, whereas for carbon composite aircraft, the value is low. Using the expression, we have already got for the surface electric field, the current along the aircraft surface is given by $J = \sigma\, Qx/4\pi\varepsilon(R^2 + x^2)^{3/2}$. The value of this current remains small since in general $x << R$, yielding $J = \sigma\, Qx/4\pi\varepsilon R^3$. However very close to the cloud, with a large thundercloud electric charge (e.g. $20C$), significant surface current can flow along the aircraft or aircraft equipment (where shielding is poor as in the case of aircraft with composite body), and may give rise to an electric field build up over a few milliseconds or so before the electric breakdown commences on the aircraft body, as seen in Figure 2. However, in most cases where the aircraft is far away from the thundercloud (say, $500\ m$), it is the vertical electric field E_v that induces the electric charge on the aircraft surface leading to the breakdown and subsequent sharp, transient of currents as seen in Figure 2.

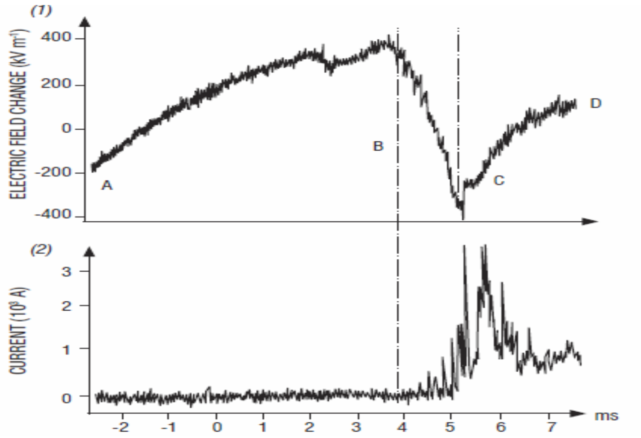

Figure 2: Electric field and current on the surface of C-160 aircraft before and after lightning initiation [4]

III. Identifying Regions of Large Electric Fields and Induced Electric Charges.

Equation (1) to (7) presented in this section are the core equations used to determine the pre-lightning strike electric charges induced on the surface of the aircraft. [9]. The same equations may be used to determine the pre-lightning electric fields and electric charges induced in ground systems, including electric power systems, telecommunication installations and ground structures. As such they are pertinent tools for assessing electric threat to airborne and ground systems before the lightning leader and return strokes are initiated. The induced voltage on the aircraft is given as:

$$V_A = k \cdot q_{AD}\left(\frac{1}{r_+} - \frac{1}{r_-}\right) \tag{1}$$

where k is a constant, q_{AD} is the aircraft dipole charge, V_A is the aircraft voltage. r_+ and r_- are the distances from the positive and negative monopoles and their images to a selected point on the aircraft surface. In Equation (1) V_A and q_{AD} are unknown. The solution of the matrix equation for induced voltage requires the following two variables to be specified by the user: the electric potential of the cloud center (e.g. $-50\ MV$), the radius of the electric charge center of the cloud, the distances between thundercloud charge center, the aircraft and the earth. Assuming that the three-dimensional geometrical parameters in Cartesian coordinates (x, y, z) of the aircraft are known, dipoles are placed over the aircraft to simulate the electric charges induced on it. The ground is assumed to be a perfect conductor, and it is replaced by mirror images [10-11]. Using the Cartesian coordinates, the aircraft structure points are defined by the equation Equation (2), which gives the distance between the center points of the dipole at any given point of the aircraft. The angle between an arbitrary point on the aircraft surface and a dipole is given by Equation (3) [10].

$$dis(x_{pl}, y_{pl}, z_{pl}, k) = \sqrt{(x_{pl} - x_k)^2 + (y_{pl} - y_k)^2 + (z_{pl} - z_k)^2} \tag{2}$$

$$\theta_{pl}(x_{pl}, y_{pl}, z_{pl}, k) = \left[\cos^{-1}\left(\frac{(y_{pl} - y_k)}{dis(x_{pl}, y_{pl}, z_{pl}, k)}\right)\right] \tag{3}$$

The electrostatic potential coefficient associated with any single dipole is given by [9]:

$$q_{AD\_Coeff} = \left(\frac{1}{dis(x_{pl}, y_{pl}, z_{pl}, k)}\right) - \left(\frac{1}{dis(x_{pl}, y_{pl}, z_{pl}, k)}\right) + \left(\frac{1}{dis(x_{pl}, y_{pl}, z_{pl}, k)}\right) - \left(\frac{1}{dis(x_{pl}, y_{pl}, z_{pl}, k)}\right) \quad (4)$$

where q_{AD_Coeff} is the electrostatic coefficient associated with the electric charge dipole k due to the electric charge on aircraft surface and its image at point l. Thus, the electrostatic voltage V_A induced at a point p on the aircraft surface by n number of dipole charges on the aircraft surface is given by the following equation:

$$q_{AD\_Coeff1}Q_1 + q_{AD\_Coeff2}Q_2 + q_{AD\_Coeff3}Q_3 + \cdots q_{AD\_Coeffn}Q_n = 4\pi\varepsilon_0 V_A \quad (5)$$

From Equation (5) we may determine the electric charge at each point of the aircraft surface. Furthermore, the electric field at each point is obtained from the following two equations [8]:

$$Q_n = \left(\frac{1}{q_{AD_{Coeffn}}}\right)\Big[(4\pi\varepsilon_0 V_A) - \big(q_{AD\_Coeff1}Q_1 + q_{AD\_Coeff2}Q_2 + q_{AD\_Coeff3}Q_3 + \cdots q_{AD_{Coeffn-1}}Q_{n-1}\big)\Big] \quad (6)$$

$$E = \left(\frac{k \cdot q}{r^2}\right) \cdot \bar{u} \quad (7)$$

In order to simulate the electric charges induced on the aircraft body, a large number of electric dipoles are placed on it, with more dipoles placed on the aircraft components that are more susceptible to electric field enhancement, and the smoother surfaces, such as the aircraft wing surfaces, are assigned fewer electric dipoles, as shown in Figure 3. As seen in Figure 2, at high altitudes electric field breakdown may occur at an electric field of about 400 kV/m [2]. This value is much lower than the breakdown field of about 3000 kV/m at sea level.

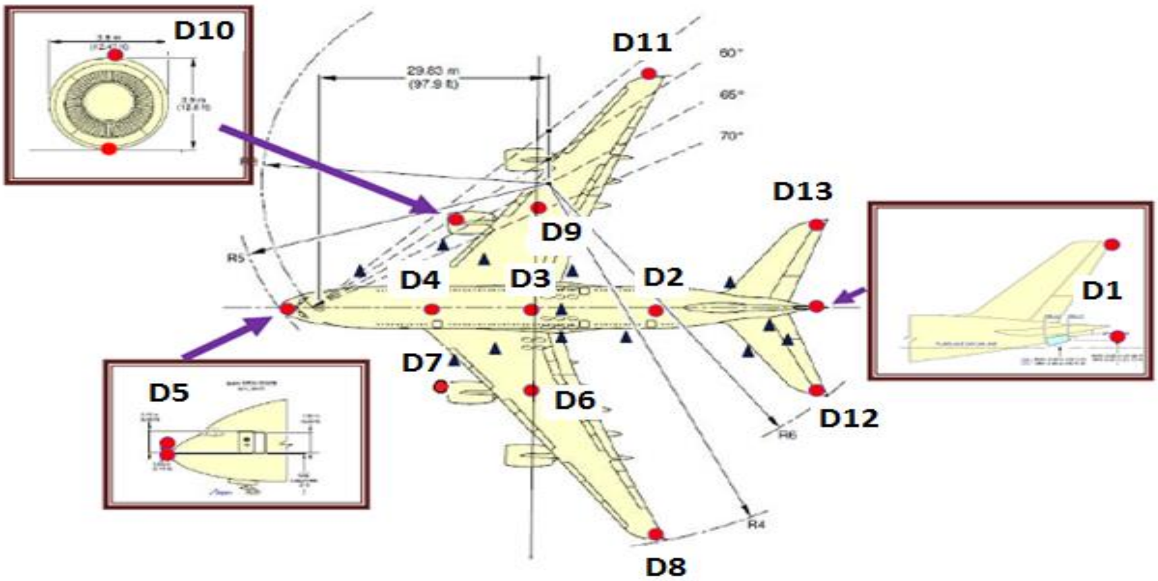

Figure 3: Electric dipoles placed on an A380 aircraft to simulate the charges induced by the thundercloud electric charge center [5, 9].

In Table 1 is shown the electric charges and electric fields calculated when the aircraft is 200 m below a -50 MV electric charge center of the cloud which is at a height of 1000 m above the ground. With a negatively charged cloud center, the electric charges obtained for the dipole charge on the top of the aircraft is positive and that on the underbelly of the aircraft is negative [9]. It is seen that for the A380 aircraft, at an altitude of 800 m and 200 m below the thundercloud charge centre, the following parts of the aircraft experience electric fields that have potential to cause electrostatic discharge or electronic circuit flashovers: the radome, the wing tip, the mid-wing, the wing surface and the stabilizer tip. The physical locations of these parts may be identified by the identifiers indicated in Table 1 and in Figure 3; for instance, D9 indicates middle of the right wing. The aircraft structure where the electric fields are marked with a star (**) are portions where the probability of electrostatic discharges are high. These include the radome, wing tips, and horizontal stabilizer tips. When designing an aircraft the challenge is to design it such a way as to minimize the electrostatic fields at these specific points where the threat is higher. Moreover, placement of sensitive navigational. communication and sensor electronic equipment at these locations should be avoided. Around the fuselage too, at reduced values for breakdown electric fields at higher altitudes, the threat should be considered.

Table 1
Electric fields for Airbus A380 at an altitude of 800 m directly below charged cloud AT 1000 m altitude

Dipole Location	Electric Field (V/m)
Rudder tip (D1)	2.412×10^5
Mid-right fuselage (D2)	2.085×10^5
Mid-fuselage (D3)	1.363×10^5
Mid-left fuselage (D4)	1.287×10^5
Radome (D5)	7.986×10^7 (**)
Mid-left wing (D6)	3.514×10^5
Left-wing engine (D7)	1.276×10^5
Tip left wing (D8)	1.252×10^7 (**)
Mid-right wing (D9)	4.495×10^5 (**)
Right wing engine (D10)	1.288×10^5
Tip right wing (D11)	1.127×10^7 (**)
Left horizontal stabilizer tip (D12)	2.873×10^8 (**)
Right horizontal stabilizer tip (D13)	2.798×10^8 (**)

IV. CONCLUSIONS

The thundercloud charge center induced electric fields that are perpendicular to the aircraft body is of greater importance than the electric fields parallel to the aircraft body with regard to the electric charges induced on the aircraft body. However, when the aircraft is very close to the thundercloud or inside the thundercloud, the parallel, or tangential, electric field may produce significant current flow and electric charge build up with time. Amongst the aircraft regions most susceptible to electric breakdown and enhanced electric fields are the radome, the stabilizer tip and the wing tip. But other parts including the middle of the wing and fuselage also experience significantly large electric fields.

ACKNOWLEDGEMENT

Authors are grateful to UNIMAS Innovation for financing this project under F02/SpSTG/1388/16/30_MyRa_Grant.

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