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Three Dimensional Electric Dipole Model for Lightning-Aircraft Electrodynamics and its Application to Low Flying Aircraft

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***Abstract*— In this paper we review a new electric charge based circuit model for studying aircraft-lightning electrodynamics and its application to an aircraft taking off or landing. As commercial and military aircraft continue to be subject to direct lightning flashes, there is a great need to characterize correctly the electrical currents and electric potential fluctuations on an aircraft to determine alternative design approaches to minimizing the severity of the lightning-aircraft dynamics. Moreover, with the increased severity of thunderstorms due to global warming, the need arises even more to predict and quantify electrical characteristics of the lightning-aircraft electrodynamics, which is normally not measurable, using a reliable electric model of the aircraft. Such a model is advanced here.**

Keywords-aircarft--dipole modeling; aircraft-lightning electrodynamics; transmission line modeling; lightning-aircraft interaction

I. INTRODUCTION

Lightning is a natural phenomenon and the flashes usually originate from charge centers in a cloud produced by complex processes. Positive and negative charges accumulate in the upper and lower regions of the thundercloud respectively, producing strong electric fields that can initiate electric discharges. Scientific evidence is available to trace the lightning channel leader initiated by aircraft during landing or take-off under a thundercloud at very low altitudes [1]. Cloud-to-ground flashes which have great current magnitudes and fast rise times would seem to be the most hazardous for an airplane to encounter [2]. Since an aircraft can become a part of the natural lightning discharge process, the direct and indirect effects due to lightning strikes are recognized as a threat to flight safety. Thus, it is vital for aircraft industries to restructure the aircraft design and properly protect and shield its electronic devices.

The SAE committee in its report entitled “Lightning Test Waveforms and Techniques for Aerospace Vehicles and Hardware” discussed in [3] and [4] specified the idealized waveforms’ component of current and potential for qualification tests. A proposed test setup for full-scale vehicle lightning-induced coupling test was reported in [4]. However, since high-cost equipment and high-risk characteristics are required for physical aircraft-lightning tests, computer simulation studies have been developed to study lightning-aircraft electrodynamics. Different kinds of geometrical and electrical models have been proposed for aircraft representation and computer simulation under various conditions and parameters [5], [6], [7], [8], [9], and [10]. These models are used to simulate and to find the airframe resonances, dynamic currents and charges on the aircraft for studying aircraft-lightning electrodynamics.

The aircraft geometry used in this research simulation model is the Airbus A380 passenger aircraft with a fuselage approximately 72 m long, and its height is 6 m. The aircraft’s body is subdivided into a number of dipoles, each directed along the z axis and placed along the y axis with induced positive charge at the top pole and equivalent negative charge at the bottom of the aircraft fuselage as shown in Figure 1 [11]. The radome, wings and the tail of the aircraft are the most prominent edges to be get struck by lightning strikes due to more charges accumulating at these edges. These aircraft charges initiate the top and bottom leaders from these points. The mathematical dipole model for a metal aircraft with a single charge is used to determine the capacitance of the aircraft skin using the potential coefficients of the dipoles. The vertical and horizontal fields at a dipole due to other dipoles have been taken into account for the calculation. Note that it is possible to account for the conical radome, sharp tail and wings by using dipoles that gradually decrease in distance d of charge separation. The dipole model we propose herein is a very powerful tool for minute representation of the different shapes of aircraft frame and to determine the best geometrical shape and fuselage material to reduce electric stress.

The capacitance calculated is in Farads per meter. The aircraft body, from radome to tail, is divided into 12 segments. Each wing is divided into 11 segments. Once the capacitance for each segment is calculated, the per unit length capacitance is calculated for each region of the segment. It is noted that the per unit length capacitance was not significantly altered by changing the number of dipoles used.

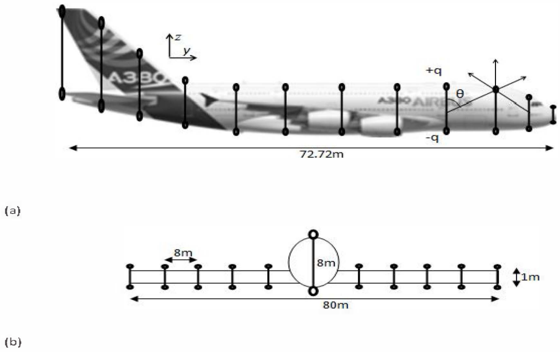

Figure 1 (a) Dipole representation along fuselage from the nose towards the tail (b) Dipole representation along wings [11].

II AIRCRAFT ELECTROSTATIC CHARGE AND CAPACITANCE COMPUTATION USING THE DIPOLE METHOD

The dipole modeling of electrostatic charges on an aircraft gives a succinct representation of the distribution of electrostatic charge build up on the aircraft surfaces. The method makes use of an elementary theory of electrostatic induction on the distribution of charges within an object that occurs as a reaction to the presence of a nearby charge. The analogy is applied to an aircraft as it goes through a charged electric storm causing migration of polarized charges on the surface with positive charges on the top. Aircrafts build up static charges just by virtue of flying through the atmosphere [12], however, the breakdown of the static charges occurs as the aircraft enters into a charged electric storm. The pre-breakdown charges and the capacitances of are determined based on the dipole model.

The dipole model incorporates a real geometrical dimensions of an aircraft with surface charge distribution represented by diploes of various separation distances placed along the top and bottom radome, wings, fuselage, and the tail end of the aircraft. The cloud charge and its image charge are taken into account as the two charges highly influence the overall electric field on the surface of an aircraft. The cloud charge is determined based on the spherical Gaussian surface. The surface charge layer on the aircraft surface is modeled as a line charge with an electric dipole moment per unit area.

The field of a line charged electric dipoles on the top and bottom of an aircraft surface is obtained by representing an aircraft as a floating electrode [13] isolated in space and charged to a specific voltage. The floating electrode is discretized into finite length placed on the top and bottom of the aircraft thus forming a series of line charge with an electric dipole moment per unit area. The aircraft dipole model is shown in Figure 2.

Notice that any number of dipoles is sufficient to compute the capacitance of an aircraft however, to accurately represent the aircraft geometry, more number of dipoles are required. The cloud charge is assumed to be at a distance of 1000 m above ground and its image charges is at a distance 1000 m below ground. Thus, the earth is assumed to be a perfect conductor for the electrostatic computation, its effect being more significant when the aircraft is closed to ground. The potential coefficients as determined from the charge at points in space and its geometries is given as a matrix shown in Figure3.The diagonal elements of the potential coefficient matrix representing the voltage contribution to the dipole charge on itself where as the off diagonal elements represent the mutual contribution by other charges within the vicinity. The aircraft capacitance is determined from the potential coefficients matrix.

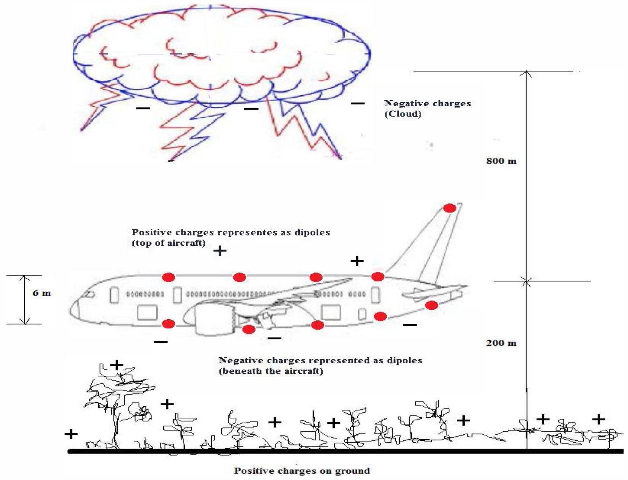

Figure 2 The charge geometry

$$d = \begin{pmatrix} 11.131 & 0.167 & 0.125 & 0.1 & 1.25\times 10^{-3} & 8.333\times 10^{-4} \\ 0.167 & 11.131 & 0.1 & 0.125 & 1.241\times 10^{-3} & 8.375\times 10^{-4} \\ 0.125 & 0.1 & 11.131 & 0.167 & 1.25\times 10^{-3} & 8.333\times 10^{-4} \\ 0.1 & 0.125 & 0.167 & 11.131 & 1.241\times 10^{-3} & 8.375\times 10^{-4} \\ 1.25\times 10^{-3} & 1.241\times 10^{-3} & 1.25\times 10^{-3} & 1.241\times 10^{-3} & 9.93\times 10^{-4} & 5\times 10^{-4} \\ 8.333\times 10^{-4} & 8.375\times 10^{-4} & 8.333\times 10^{-4} & 8.375\times 10^{-4} & 5\times 10^{-4} & 9.93\times 10^{-4} \end{pmatrix}$$

Figure 3 The charge potential coefficients

The capacitance calculated is in Farads per meter. The aircraft body, from radome to tail, is divided into 12 segments. Each wing is divided into 11 segments. Once the capacitance for each segment is calculated, the per unit length capacitance is calculated for each region of the segment. It is noted that the per unit length capacitance was not significantly altered by changing the number of dipoles used.

III LIGHTNING AND AIRCRAFT CHANNEL MODEL

The long transmission line model (TLM) is used in modeling the lightning channel through an ionized air between the cloud, aircraft, and the ground. It comprises three cascading segments of pi-network each represent the lightning channel from cloud to tip of aircraft, the aircraft body, and the aircraft to ground. The diagram in Figure 4 illustrates the geometrical orientation of the lightning-aircraft channel. The electrical network configuration of the channel is shown in Figure 5.

The lightning cloud is assumed to be at a height of 1000 m above ground and the aircraft is near-ground at an altitude of 200 m. The near-ground is assumed as most lightning strike to aircraft occur near-ground during ascending or descending. The earth resistance is assumed for a moist condition with a value of 40 Ω.

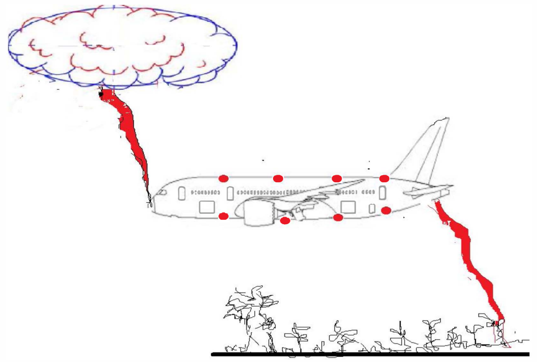

Figure 4 Geometry of the lightning-aircraft channel

Studies show that the bidirectional leader from the aircraft is connected to both the cloud and the radome of the aircraft [14]. Similarly at the other end, another leader is connected between the earth and the tail of the aircraft. In a conventional case, the lightning is initially attached from the nose to the tail and the lightning channel is mainly oriented along the fuselage axis [15]. The distributed TLM can be applied to represent the return stroke of a lightning channel with the elements of resistance (R), inductance (L) and capacitance (C) as discussed in [16] and [17]. The narrow channel is assumed to be a vertical conductor, characterized by an impedance, inductance and capacitance of 1 Ω/m, 3 μH/m and 4.6pF/m respectively [16]. The lightning discharge path via the aircraft is represented using the TLM. The channel impedance and aircraft capacitance are the significant factors to influence the rate of charge transfer to the aircraft when an aircraft is in an attached channel [18]. It should be noted that, for an aircraft over a ground plane or in a test fixture, static solutions can be used to find the transmission-line elements [10].

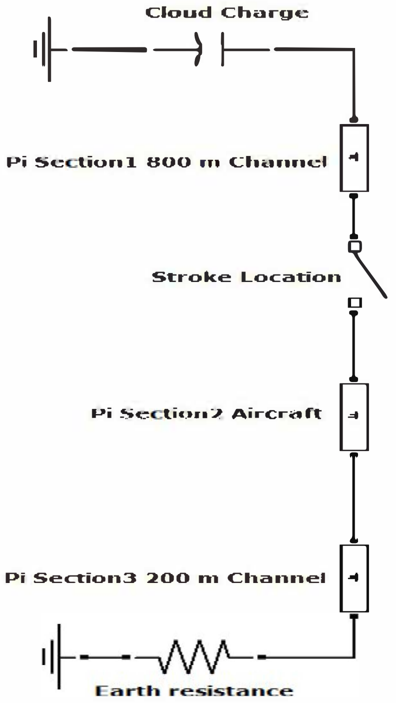

Figure 5 transmission line circuit model of the lightning-aircarft channel

IV LIGHTNING AND AIRCRAFT CHANNEL TRANSMISSION LINE SIMULATION

The network configuration of Figure 5 is simulated with the stroke location between the lightning channel from the cloud and the aircraft represented by a circuit breaker. The return stroke current propagates in both directions from the location along the lightning channel to the cloud and further from the stroke location through the aircraft to ground. The cloud potential is set at -50 MV for negative flash. Figure 6 shows the aircraft triggered current stroke reaching an initial peak value of -125 kA before damping out in about 50 ns. Comparing this current value with the adopted standardized ABCD current waveforms as discussed in [19], the first return stroke peak value is expected to be 200 kA. Further, the voltage waves induced along the cloud and aircraft channel reached a peak of about -53 MV before settling down to -50 MV within 50 ns. The aircraft –to-ground voltage reaches a minima of -60MV and pulsates within -58MV and -63 MV.

The lightning voltage is not a major problem for aircraft with aluminum airframes unless with climate changes that the severity of lightning flashes increases. However today's modern aircraft coming off the assembly lines are making extensive use of composite material to significantly reduce weight and, hence, fuel consumption. Unlike aluminum, composite material does not conduct and dissipate electricity. Airframes of electrically insulated carbon fiber/ epoxy composites can be damaged, particularly at the entry and exit points of a lightning direct strike, since they absorb the lightning induced voltage and currents instead of conducting and dissipating it. Thus, the magnitude of peak current and voltage observed is capable of inducing a higher electric field along the surface since the time transient is short which can have severe effects on the aircraft electrical and electronics systems.

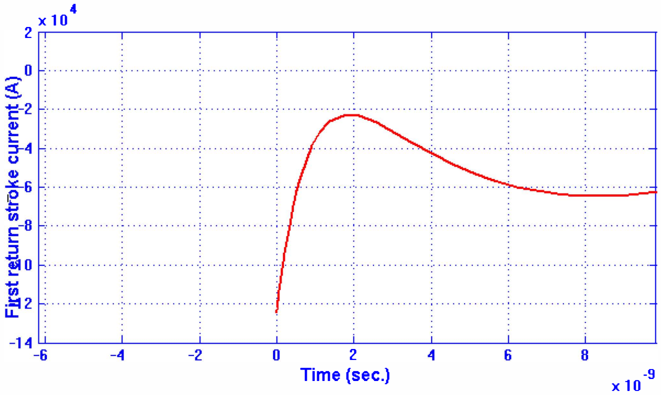

Figure 6 The return stoke current waveform

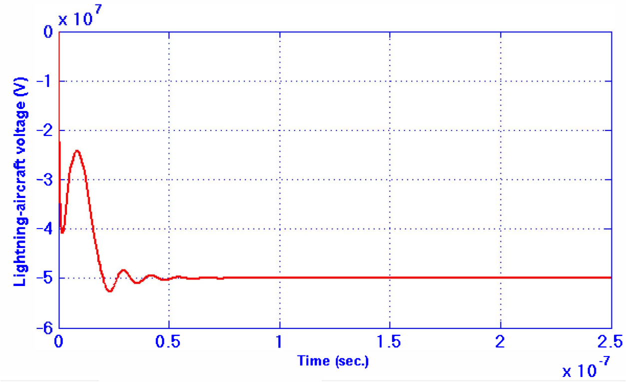

Figure 7 Cloud to aircraft lightning channel voltage

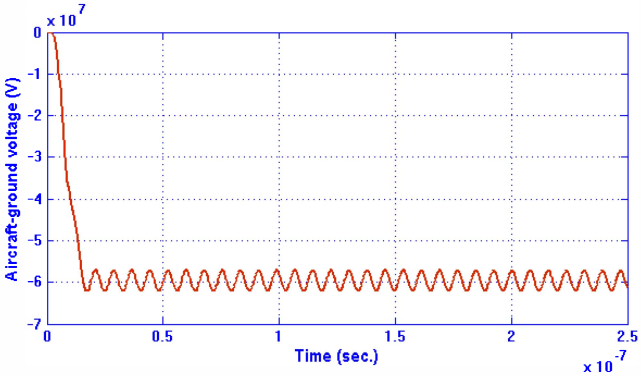

Figure 8 Aircraft to ground channel voltage

V CONCLUSION

We have presented here a useful and important electric circuit model for an aircraft attached to the lightning channel, with a new, dipole-based determination of aircraft capacitance, which when used with the lightning transmission line model provides critical time domain transients produced by the return stroke on the aircraft skin.

A significant increase of current and voltage was observed on the aircraft frame due to direct lightning strike. The capacitance based electric circuit model helps to obtain the return stroke currents for lighting strikes at different points on the aircraft, and to determine the changes in the geometrical and material design of the aircraft (of which the capacitance is a function) that may mitigate lightning effects. The results obtained can be used for further analysis of direct and indirect effects to aircraft and avionics installed within the aircraft.

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