Applying a 3D Dipole Model for Lightning Electrodynamics of Low-Flying Aircraft

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ABSTRACT

In this paper we apply a detailed electrostatic model of an aircraft to be used in an experimentally validated, new electric-charge-based circuit model for studying aircraft-lightning electrodynamics. The model is used to evaluate the electrodynamics of an aircraft under a thundercloud. As commercial and military aircraft continue to be subject to direct lightning flashes, we have previously developed a dipole model to characterize electrical currents and electric potential fluctuations on an aircraft for alternative design strategies to minimizing the severity of lightning-aircraft dynamics. With the increased severity of thunderstorms due to global warming, the need to predict and quantify electrical characteristics of the lightning-aircraft electrodynamics is greater, but they are normally not measurable. That dipole model is used here in a new a simple matrix formulation and applied to low-flying aircraft to compute the lightning channel voltages and currents after the aircraft is struck by lightning.

***Keywords*:**
Aircraft, Dipole modelling, Electrodynamics, Lightning, Transmission line modelling.

1. LIGHTNING EFFECTS ON AIRCRAFT

Lightning flashes originate by a complex process from cloud-based charge centres [1,2]. Positive charges accumulate in the upper region of a thunder cloud and negative charges in the lower region. The strong electric fields produced initiate electric breakdown. Scientific methods are available to trace the lightning channel leader initiated by aircraft during landing or take-off under a thundercloud at very low altitudes [2]. The great current magnitudes and rapid rise times of cloud-to-ground flashes are the most hazardous for an airplane [3]. 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 the aircraft industry to restructure aircraft design and properly protect and shield its electronic devices.

The SAE [4,5] has specified the idealized waveforms' component of current and potential for qualification tests. A full-scale vehicle lightning-induced coupling test is reported in [5]. However, because of the cost and personal bodily risks for such physical aircraft-lightning tests, computer simulation studies are preferable when it comes to studying lightning-aircraft electrodynamics. Different kinds of geometrical and electrical models have been proposed for aircraft representation and computer simulation under various conditions and parameters [6−11]. These models are used to simulate and to find the airframe resonances, dynamic currents and charges on the aircraft for studying aircraft-lightning electrodynamics. An electric circuit model which yields results validated when compared to laboratory tests of model aircraft has been recently presented [12] which we extend here through a simple matrix formulation.

2. PRE-STRIKE MODELLING OF AIRCRAFT

The aircraft geometry used in this research simulation model is the Airbus A380 passenger aircraft with a fuselage approximately 72-m long, and 6-m high, the same as in [12]. Following the description and methodology in [12], 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 [12]. The radome, wings and the tail of the aircraft are the most prominent edges to 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

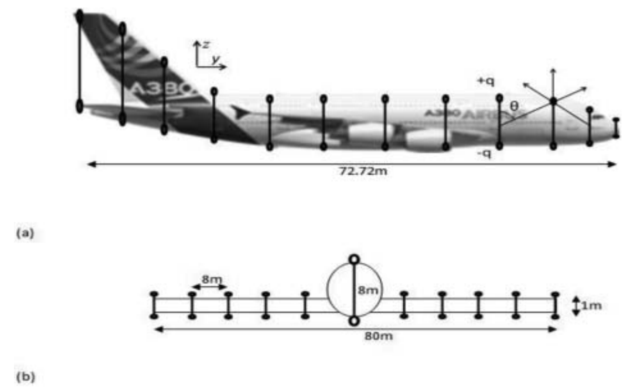

Figure 1: (a) Dipole representation along fuselage from nose to tail and (b) dipole representation along wings [12].

of charge separation. As noted in [12], the dipole model proposed and verified in that paper is a very powerful tool for minute representation of different shapes of aircraft frame to determine the best geometrical shape and fuselage material for reduced electric stress. And because that model has been validated in the laboratory with aircraft models, we feel confident extending its use here in this paper.

In this paper a new matrix formulation of that dipole electrostatics of aircraft is presented. This matrix formulation of the thundercloud-induced electric charges on aircraft and ground yields a solution of the capacitive elements of the aircraft. The computed capacitive elements are readily used in the aircraft-lightning electrodynamics during the lightning return stroke phase of the electrodynamics or the severe transient interaction phase. 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. When the per unit length capacitance was not significantly altered the number of dipoles was deemed sufficient.

3. ELECTROSTATIC CHARGE, CAPACITANCE: PRESTRIKE

The pre-strike dipole modelling of electrostatic charges on an aircraft gives a succinct representation of the distribution of charge build up on the aircraft surfaces and can be used for post-strike analysis since the capacitances will not change. The method makes use of 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. Aircraft build up static charges just by virtue of flying through the atmosphere [13]. However, the breakdown of the static charges occurs as the aircraft enters a charged electric storm. The pre-breakdown charges and capacitances are determined here based on the dipole model.

The dipole model incorporates the 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 tail end of the aircraft (Figure 2). 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 cylindrical Gaussian surface. The surface charge layer on the aircraft surface is modelled as a line charge with an electric dipole moment per unit area. The field of an electric dipole on the top and bottom of an aircraft surface is obtained by representing an aircraft as a floating electrode [14] isolated in space and charged to a specific voltage. The floating electrode is discretized into finite lengths placed on the top and bottom of the aircraft thus forming a series of line charges with an electric dipole moment per unit area. The aircraft dipole model is shown in Figure 2. Note that any number of dipoles is sufficient to compute the capacitance of an aircraft. However, to accurately represent the aircraft geometry, more dipoles are required.

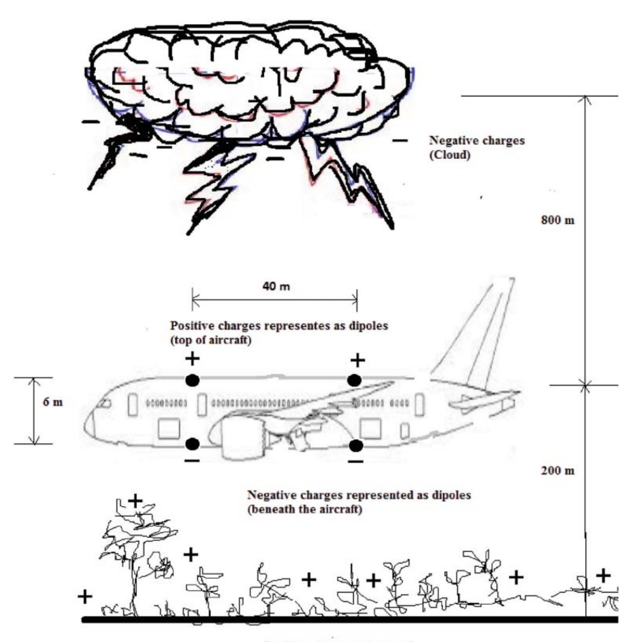

Figure 2: The charge geometry.

4. EQUATIONS OF DIPOLES AND CLOUD CHARGE

The cloud charge is assumed to be 1000 m above ground and its image charge 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 close to ground, say at a height of 200 m. The equations for the geometrical and physical properties of the cylindrical Gaussian surface are expressed elegantly in terms of the generalized matrix of the potential coefficient functions. We may use the fact that the potential from a discretized conductor due to the charge on itself is mainly from the middle and therefore can be approximated as from a flat circular disk-like conductor [14]. The potential V everywhere on the 4 discretized pieces at charges q_1 to q_4 of the aircraft and V_{Cl} on the cloud, then will be each due to itself and the other 4 charges. For q_1 (with 3 similar equations for q_2 to q_4), we have

$$\frac{3.52}{D^{i}_{\text{self}}}q_1 - \frac{1}{d_{\text{sep}}}q_2 + \frac{1}{d_{\text{dis}}}q_3 - \frac{1}{\sqrt{d_{\text{dis}}^2 + d_{\text{sep}}^2}}q_4 + \frac{1}{\sqrt{0.25\ d_{\text{dis}}^2 + A_{\text{altop}}^2}}q_5 = 4\pi\varepsilon_0\ V \tag{1}$$

and for Q_{Cl} on the cloud, we have

$$\frac{1}{\sqrt{0.25\ d_{\text{dis}}^2 + A_{\text{altop}}^2}}q_1 - \frac{1}{\sqrt{0.25\ d_{\text{dis}}^2 + (A_{\text{altop}}+6)^2}}q_2 + \frac{1}{\sqrt{0.25\ d_{\text{dis}}^2 + A_{\text{altop}}^2}}q_3 - \frac{1}{\sqrt{0.25\ d_{\text{dis}}^2 + (A_{\text{altop}}+6)^2}}q_4 + \frac{3.52}{\sqrt{A_{\text{Cyl}}}}Q_{\text{Cl}} = 4\pi\varepsilon_0 V_{\text{Cl}}, \tag{2}$$

where ε_0 is the permittivity of air; A_{Cyl} is the surface area of the cylindrical Gaussian surface of diameter 200 m and height 500 m; d_{dis} is the distance between the dipole segments on the aircraft surface; d_{sep} is the length of the dipoles which is the height of the aircraft; A_{altop} is the distance from ground to the top of the aircraft; D^{i}_{self} is the surface area of line charge forming the dipole on the aircraft surface; V_{Cl} is the cloud voltage which is assumed to be a negative flash of −50 MV [12]; and V is the unknown aircraft potential we seek.

The cloud capacitance is determined from the cylindrical Gaussian surface using the empirical equation from [15]

$$C_{\text{Cyl}} = \left[8 + 4.1\left(\frac{L_{\text{Cl}}}{0.5\ D_{\text{Cl}}}\right)^{0.76}\right]\varepsilon_0\frac{D_{\text{Cl}}}{2}, \tag{3}$$

where D_{Cl} and L_{Cl} are the diameter and the height of the cloud, respectively. The cloud charge going into Eq. (1) is determined from the capacitance and cloud voltage as follows:

$$Q_{\text{Cl}} = C_{\text{Cyl}}V_{\text{Cl}}. \tag{4}$$

The remaining unknown terms in Eq. (1), its like-equations on the other three dipoles, and Eq. (2) are the dipole charges q_1, q_2, q_3, and q_4 and the aircraft potential V. Since the aircraft surface is at the same potential (an equipotential line all around its surface) and each dipole has charges of the same magnitude but of different polarities at each end, the number of unknowns is reduced. Thus, any method of solving a set of linear equations by substitution may be used to solve for the aircraft potential V. For the A380 airbus in a horizontal position, at an altitude of 200 m under a −.5MV cloud, V was found to be $-.128 \times 10^6$ Volts. From the known aircraft potential, we take into account the influence of the earth. That is, we take into effect the presence of the earth by considering fictitious image charges and their influences on the aircraft charges and the capacitance utilizing the dipole moments.

The aircraft is assumed to be at an altitude of 194 m, with its top surface at a height of 200 m from ground and the bottom surface at a height of 194 m from ground. The dipoles are placed across the aircraft as shown in Figure 2, with each dipole at a horizontal distance of 40 m apart from the other. The poles of a single dipole occupy the top and bottom aircraft surface as shown. The separation between the positive and negative charges of each dipole is 6 m which is the aircraft fuselage height for an A300 Airbus. In the computations reported here two dipoles were used to cover the induced electric charges on the aircraft surface. Table 1 gives the geometrical position vectors of the dipoles along the aircraft surface.

For studying the effects of aircraft geometry, its fin and radome shape, as well as that of the wings, more number of dipoles will be used in future studies. The cloud charge is assumed to be at a coordinate of (216,1000) m midway between the dipoles as depicted in Figure 2.

Table 1: Dipole coordinates

Dipole	Coordinate	
	Positive charge	Negative charge
Dipole 1	(196,200) m	196,194) m
Dipole 2	(236,200) m	(236,194) m

Note that the aircraft is assumed to be in near-ground position with its top surface and bottom surface at 200 m and 194 m above ground, respectively. The charged cloud is at a position of 1000 m above ground. The distances between the dipole charges and the cloud charges ($d_{k,l}$) are determined from the position vectors of the dipoles x_k and y_k using the following equations:

$$d_{k,l} = \sqrt{(x_k - x_l)^2 + (y_k - y_l)^2} \quad k \neq l, \tag{5}$$

$$d_{k,k} = \left(\frac{3.52}{\sqrt{D^i_{\text{self}}}}\right)^{-1} \quad k = 0, 1, 2, 3, \text{ and } 4, \tag{6a}$$

$$d_{4,4} = \left(\frac{3.52}{\sqrt{A_{\text{cyl}}}}\right)^{-1}. \tag{6b}$$

The distance between the charges and their image charges $D_{k,l}$ is derived from the following equation:

$$D_{k,l} = \sqrt{(x_k - x_l)^2 + (y_k + y_l)^2}. \tag{7}$$

Since the image is below the x-axis the distance between source and image charges become $y_k + y_l$. The self- and mutual-position vectors of the charges are shown in the matrix d:

$$d = \begin{bmatrix} 2.489 & 0.167 & 0.025 & 0.025 & 0.00125 \\ 0.167 & 2.489 & 0.025 & 0.025 & 0.00124 \\ 0.025 & 0.025 & 2.489 & 0.167 & 0.00125 \\ 0.025 & 0.025 & 0.167 & 2.489 & 0.00124 \\ 0.00125 & 0.00124 & 0.00125 & 0.00124 & 0.005733 \end{bmatrix}. \tag{8}$$

The distances between the charges and their ground images are derived from the position vectors of the charges and shown in matrix D as follows:

$$D = \begin{bmatrix} 400 & 394 & 401.995 & 396.025 & 1.2\times10^3 \\ 394 & 388 & 396.025 & 390.056 & 1.194\times10^3 \\ 401.995 & 396.025 & 400 & 394 & 1.2\times10^3 \\ 396.025 & 390.056 & 394 & 388 & 1.194\times10^3 \\ 1.2\times10^3 & 1.194\times10^3 & 1.2\times10^3 & 1.194\times10^3 & 2\times10^3 \end{bmatrix}. \tag{9}$$

The potential coefficient is calculated using the above position vector matrices:

$$p_{k.l} = \frac{1}{2\pi\varepsilon_0} \ln \frac{D_{k,l}}{d_{k,l}}, \tag{10}$$

where $k = 0$, 1, 2, and 3 are the dipole charge numbers and 4 is the cloud charge. The capacitance of the cloud-aircraft ground system is simply the reciprocal of the potential coefficient and is defined by

$$C = p^{-1}. \tag{11}$$

The capacitance in Farad per unit length for an airbus A380 aircraft at 200 m altitude is given as

$$C = \begin{bmatrix} -12.94 & 7.645 & 1.653 & 1.5815 & 12.227 \\ 7.645 & -12.92 & 1.581 & 1.680 & 2.173 \\ 1.653 & 1.581 & -12.94 & 7.645 & 2.227 \\ 1.5815 & 1.680 & 7.645 & -12.92 & 2.173 \\ 2.227 & 2.173 & 2.227 & 2.173 & -5139 \end{bmatrix} \times 10^{-12}. \tag{12}$$

Thus, the electric charges are calculated based on the aircraft voltage and the capacitances giving

$$Q = [\,7.772 \quad 7.59 \quad -7.772 \quad -7.59 \quad 11.37\,]^t \times 10^{-5}. \tag{13}$$

5. LIGHTNING-AIRCRAFT CHANNEL MODEL

The now-widely-used long transmission line model (TLM [16,17]) is employed in modelling the lightning channel through the ionized air between the cloud, aircraft, and the ground. It comprises three cascading segments of a pi-network, each representing the lightning channel from the cloud to the tip of the aircraft, the aircraft body, and the aircraft to ground. The diagram in Figure 3 illustrates the geometrical orientation of the lightning-aircraft channel. The electrical network configuration of the channel is shown in Figure 4. The thundercloud is assumed to be at a height of 1000 m and the aircraft is near-ground at an altitude of 200 m; so assumed since most lightning strikes to aircraft occur near-ground during takeoff or landing. The earth

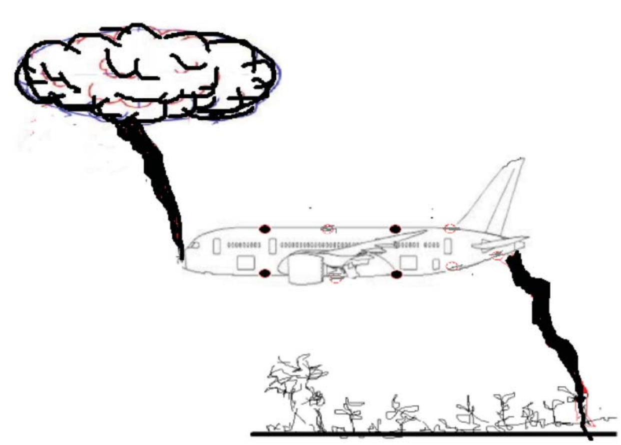

Figure 3: Geometry of the lightning-aircraft channel.

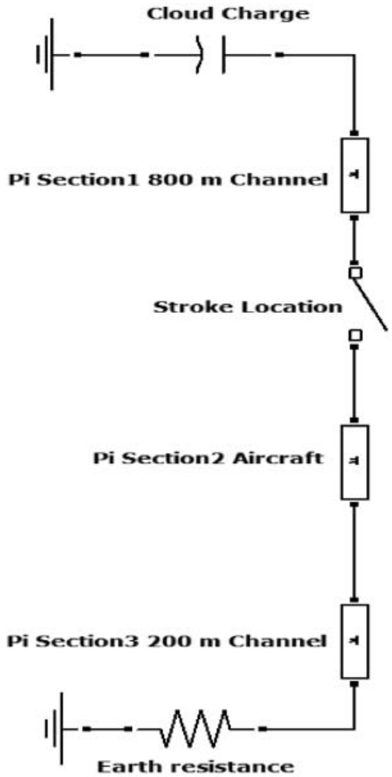

Figure 4: Transmission line model: the lightning-aircraft channel.

resistance under moist conditions is taken to be 40 Ω [18].

Studies show that the bidirectional leader from the aircraft is connected at the top (cloud) end to both the cloud and the radome of the aircraft [19]. Similarly at the other (ground) end, another leader is connected between the earth and the tail of the aircraft. The lightning is initially attached from the nose to the cloud and the lightning channel is mainly oriented along the fuselage axis [20]. 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 [21] and [22]. 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 4.6 pF/m, respectively [19]. The lightning discharge path via the aircraft is represented using the TLM. The channel impedance and aircraft capacitance are the significant factors that influence the rate of charge transfer to the aircraft when an aircraft is attached to the return stroke channel [23]. It should be noted that, for an aircraft over a ground plane or in a test fixture, static solutions as reported above can be used to find the transmission-line elements [11].

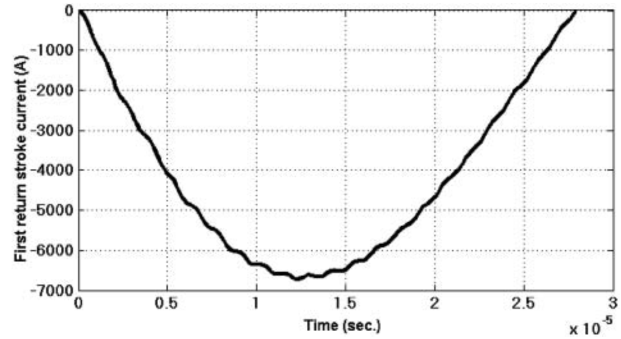

Figure 5: The return stoke current waveform.

6. LIGHTNING-AIRCRAFT CHANNEL: TRANSMISSION LINE

The network configuration of Figure 4 is simulated with the strike point location between the lightning channel (coming down from the cloud) and making contact at the aircraft radome. The return stroke current propagates in both directions from the strike point along the lightning channel to the cloud and downward from the tail of the aircraft to ground. The cloud potential is set at −50 MV for a negative flash. Figure 5 shows the aircraft triggered current stroke at the strike point reaching an initial peak value of −7.0 kA before damping out in about 200 μs. The initial, rapid rate of change of current (8 kA/μs) is observed in the first 0.5μs, whereas in the next 0.5 μs the rate of rise slows down to 4 kA/μs. These high submicrosecond rates of rise radiate large transient electric fields from the skin of the aircraft, which in the case of carbon composite skins, may slip through the metal grids embedded inside the composite skin and cause serious digital data corruption and interference of vital control or navigation systems of the aircraft. Comparing this current value with the adopted standardized ABCD current waveforms as discussed in [24], the first return stroke peak value is expected to be 200 kA. Figures 6 and 7 show the voltage transients, the shape of which were compared to laboratory measurements for confirmation of the simulation techniques employed herein [12]. What is noticeable here, with the dipole computation of the capacitances is that the voltage closer to the cloud end of the stroke (Figure 6) drops from − 50 MV cloud voltage to about −40 MV through a slowly varying transient in about 20 ms. On the aircraft itself (Figure 7), the potential variation from earth potential to −40 MV occurs with rapid oscillations of large voltage variations in the 20 ms. These sharp voltage variations can give rise to capacitive couplings of transient currents to internal systems, as well as localized transient currents over the aircraft skin due to localized transient potential gradients. Furthermore, the voltage wave induced along

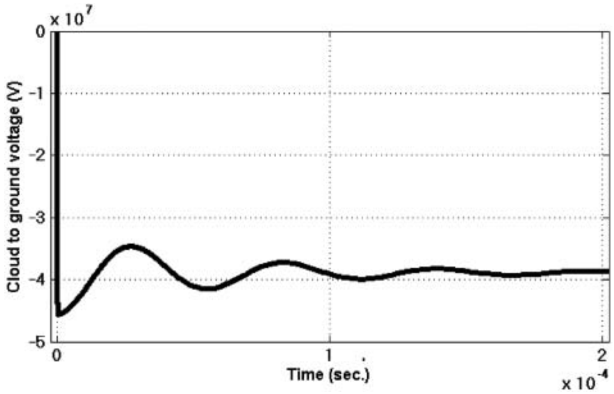

Figure 6: Cloud to aircraft-lightning channel voltage.

the cloud and aircraft channel reached a minimum of about −45 MV before settling to a steady-state value of −.3MV within 200 μs as shown in Figure 6. The aircraft-to-ground voltage reaches a minimum of −63 MV and settles to a steady-state value of −40 MV (Figure 7) in 200 μs. The difference in the minima and the steady-state values of the voltages waveforms is due to the lightning path resistance. That is, the channel from cloud-to-stroke point is 800 m long with a total channel resistance of 800 Ω while the lightning channel from aircraft-to-ground is 200 m with a channel resistance of 200 Ω. This is based on the lightning channel resistance of 1Ω/m. Furthermore, it can be noted from the voltage waveforms that the voltages reached minima at different times with the cloud-to-aircraft channel reaching minima took about 40 ns while the aircraft-to-ground channel reaching minima in about 4 μs. The times at which the voltages reach minima for the two voltage waveforms differ due to the time taken for the transient pulse to travel from the stroke point. The pulse from the return stroke point to the cloud is faster due to one pi section of the transmission line while that from the stroke point to ground travelled through two pi sections of the lines, that is, the aircraft and the lightning channel to ground thus different medium of propagation reducing the propagation velocity.

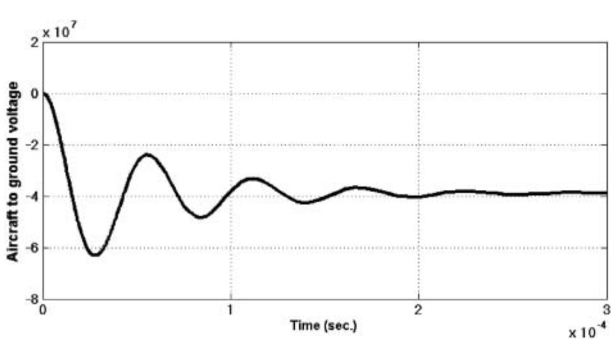

Figure 7: Aircraft to ground channel voltage.

The lightning voltage is not a major problem at present for aircraft with aluminium airframes unless with climate changes the severity of lightning flashes increases. However, today's modern aircraft coming off the assembly lines are making extensive use of composite materials to reduce aircraft weight significantly and, thereby, effect fuel consumption reduction. Unlike aluminium, composite materials often do not conduct and dissipate electricity. Airframes of electrically insulated carbon fibre/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 observed magnitudes of peak current and voltage are capable of inducing a higher electric field along the aircraft surface since the time transient is short; this can have severe effects on an aircraft's electrical and electronics systems.

7. CONCLUSIONS

In this paper we have presented an important extension of the dipole-based electric circuit model for aircraft-lightning electrodynamics during the return stroke phase. The electrostatic state of the aircraft prior to the lightning strike is modelled by a matrix formulation of the cloud-aircraft-ground systems to determine the capacitive element that significantly contributes to the transient characteristics of the return stroke currents and voltages along the aircraft surface. The capacitive elements determined from the dipole electric charges significantly determine the nanosecond variations of current transients. 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). Although this study has been done for one particular kind of aircraft, the methodology may be applied to any aircraft at any height under any size of cloud. Such a design strategy is necessary to mitigate adverse lightning effects on aircraft. The results obtained can be used for further analysis of direct and indirect effects to aircraft and avionics installed within the aircraft. We note that it is such lightning induced surface currents on the fuselage that enter the navigational computers and cause low-flying aircraft like military jets to crash regularly.

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