Kalenderli, Ö., Bolat, S., "Analysis of Lightning Strike to Airplane by Finite Element Method", Electrostatics 2013 International Conference on Electrostatics, Budapest, Hungary, April 17-19, 2013.

Analysis of Lightning Strike to Airplane by Finite Element Method

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***Abstract*- In this study, lightning strike phenomena is investigated using electric field and potential distribution calculations considering conductor object approach in a uniform field by Finite Element Method. Various taking off and landing positions of a plane are taken into consideration in the calculations in addition to normal flying position. It has been observed that, electric field strength has higher magnitudes on places which have small curvature radii such as, wings, tail and nose and those parts of airplane lead the lightning and lightning strike, electric field and strike conditions change according to the flying position of the airplane.**

I. Introduction

Lightning is a discharge phenomenon which is distinguished by its light, sound and electrical effects, occurring between cloud to ground, within clouds or between clouds [1]. This fast and massive electrostatic discharge can have voltages up to 100 MV, carry up to 200 kA and MW of power, however its energy is small, i.e. level of Js. Lightning may cause damages by the current they carry when they strike to an object. Lightning clouds which causes lightning strike are air masses having a diameter of approximately 5-10 km and a height of 10-15 km. 70-90% of lightning have negative polarity, while remaining have positive polarity. Therefore, most of the time clouds have positive charges at the top, negative charges at the bottom which makes the part of ground facing the cloud is positively charged. By considering lightning clouds are 1-3 km (approximately 2 km) above the ground, the electrical configuration can be represented by a plane-plane electrode system, having a 2 km electrode separation with a uniform field distribution where the cloud is the top electrode, ground is the bottom electrode. In this electrode configuration, discharge channels namely leaders, move from the cloud towards the ground by 50-80 m long steps; they recombine with the points suitable with regard to potential and electric field and they eventually reach to the ground. Aircrafts and airplanes which are either the trigger of the discharge or the target of the discharge are affected by this incident.

In this study, lightning strike phenomena is investigated using electric field and potential distribution calculations considering conductor object approach in a uniform field by Finite Element Method. Various taking off and landing positions of an airplane are taken into consideration in the calculations in addition to normal flying position. There are numerous studies in the literature which has been carried out by numerical methods [2-5]. In all of the calculations, airplane is considered to be a chargeless conductor object and maximum electric field points, magnitudes and change with outer field have been calculated. All these calculations have been carried out for the cases lightning leader approaching the plane and plane approaching to the lightning leader. Therefore, it is possible to evaluate cases regarding an airplane approaching to lightning and lightning approaching to an airplane, and striking to an airplane by determining maximum field change on the airplane in time and space domains.

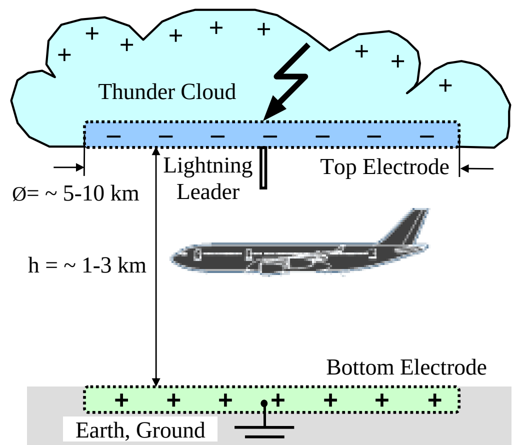

Fig. 1. The model

II. Finite Element Method

In order to solve the static electric field problem in the study, a second degree homogenous differential equation called Laplace's equation;

$$\Delta V = \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = 0 \qquad (1)$$

needs to be solved. V = V(x,y,z) is electric potential.
In finite element method, Laplace's equation is solved by minimizing the electrical energy equation

$$W = z\iint \left\{ \frac{1}{2} \left[\varepsilon_x \left(\frac{\partial V}{\partial x} \right)^2 + \varepsilon_y \left(\frac{\partial V}{\partial y} \right)^2 \right] \right\} dx.dy \qquad (2)$$

in the solution region. The solution by this minimization is also the desired solution of Laplace's equation.

The idea of finite elements is to break the problem down into large number of regions, each with a simple geometry. This process is called discretization. Through the discretization process, usually triangular elements are used. After breaking the insulating region down into triangles, the true solution for the desired potential is approximated by very simple function using boundary conditions, known potentials and material properties. The approximation functions written for each triangle constitute a linear equation system in the form of a sparse matrix. This linear system is solved by a numerical method iteratively and potentials at the nodes of each triangle can be calculated. Potential approximation functions, electric potential and electric field strength of any point can be determined with respect to potential magnitudes at the triangle's corners.

If enough small regions are used, the approximate potential closely matches the exact solution. The advantage of breaking the domain down into a number of small elements is that the problem becomes transformed from a small but difficult to solve problem into a big but relatively easy to solve problem. a linear algebra problem is formed with perhaps tens of thousands of unknowns. However, algorithms exist that allow the resulting linear algebra problem to be solved, usually in a short amount of time [5-7].

In this study, the electric field data is determined by FEMM 4.0 packet program of finite element method [8].

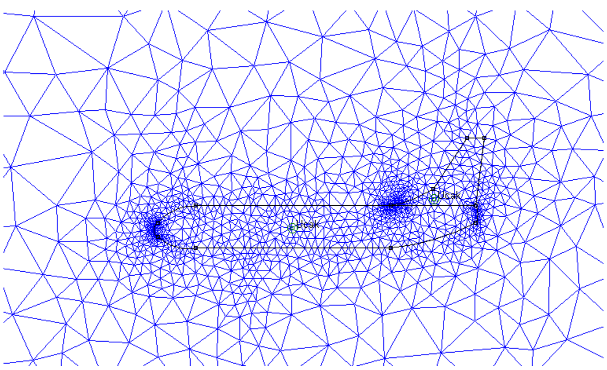

Fig. 2. A finite element mesh used in this study

III. Case Studies

The purpose of this study is analyzing the change in maximum electric field strength on an airplane while airplane changes its location with respect to the lightning, lightning leader and lightning cloud. Potential distribution around the airplane and maximum electric field strength on the airplane can determined and observed by finite element method. By this analysis, it has been thought that, the information about electric field strength on an airplane will help not only to predict the distance of the lightning leader but also determine the conditions which direct the lightning leader to the airplane.

A. Airplane Approaches to Lightning

In this case, maximum electric field on an airplane approaching to the lightning leader is examined with respect to the thunder cloud potential. The lightning leader is considered to be initiated in the middle of the cloud having the radius of approximately 10 km and reached to the middle of the distance between the cloud and the ground. Cloud potential is changed from 10 MV to 100 MV to see the effect of potential and current on electric field. These values are compatible with measurements in the literature. The results are shown in the Figure 3.

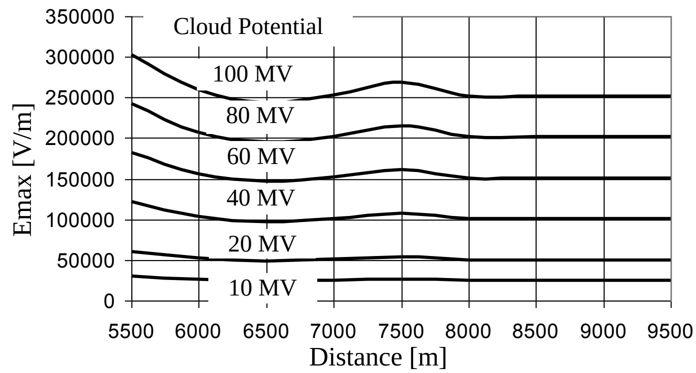

Fig. 3. Change in Emax with the horizontal distance for different cloud potentials

As seen in the Figure 3 above, when the airplane approaches to the lightning leader, maximum electric field on it increases. This increase is also approximately proportional to the cloud potential. When the airplane flies away from the lightning, electrostatic effect of the leader on decays and electric field on the airplane only depends on the cloud potential. When the charge, hence potential of the cloud is high, electric field on the airplane gets higher which is important because lightning may be initiated by the airplane and propagates towards the points having high electric field. Electrical ionization, which starts at the points with high electric field, forms channel to lightning and directs the lightning towards those points.

Foreseeably, if the airplane flies away from the lightning, the electric field behavior is the opposite of the previous case (Figure 4). Hence, the maximum electric field on the aircraft decreases drastically when it moves away from the lightning leader. After 1 km, remaining electric field on the airplane is a result of charged thunder cloud. An increase in cloud potential results in an increase in electric field values as the previous case, and the change in electric field with respect to distance shows the similar characteristics.

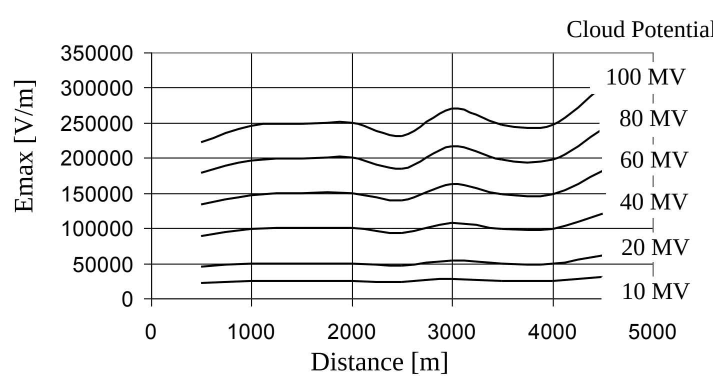

Fig. 4. Change in Emax with the horizontal distance for different cloud potentials

B. Airplane approaches to thunder cloud

In this case, the change in maximum electric field on an airplane with respect to thunder cloud potential is examined when the airplane approaches to the cloud vertically. The same thunder cloud is considered as the previous case and the airplane is assumed to be at the middle of the cloud. In this part of the analysis, the height of the thunder cloud is taken as 2 km and the altitude of the airplane is change from 300 m with 100 m steps until 200 m to the cloud. The maximum electric field calculation has been carried out for three different cloud potential the results can be seen in the Figure 5.

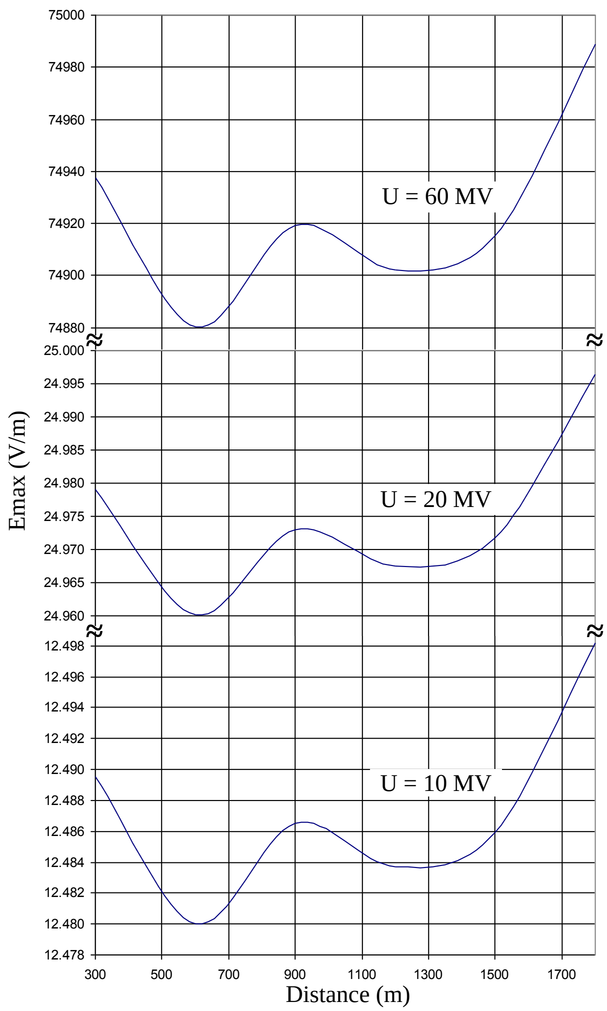

Fig. 5. Change in Emax with distance to the cloud

In the Figure 5, it is seen that, when the airplane is close to ground and especially to thunder cloud, maximum electric field on it is increasing dramatically, on the contrary, when the altitude is in between 600 m and 1200 m, since the airplane is away from both conductors, maximum field is smaller. In this zone, lightning has a low degree of probability. Similar behavior can be observed for different cloud potentials, however, the higher the cloud potential the higher the maximum electric field on the airplane. It is obvious that, the probability of a lightning strike increases when the airplane approaches to a charged cloud. Changes in the electric field can be helpful to designate a route for the airplane which has lower lightning strike possibility.

C. Lightning Approaches to Airplane

In this case, the change in maximum electric field on an airplane when a lightning leader approaches with respect to distance between the airplane and the leader is analyzed. The lightning leader is considered to be initiated at the middle of the thunder cloud and approaching to an airplane under the cloud with 100 m of steps vertically. The results can be seen in the Figure 6. When the leader is close to the airplane and caused by a higher potential cloud, electric field on the airplane increases drastically.

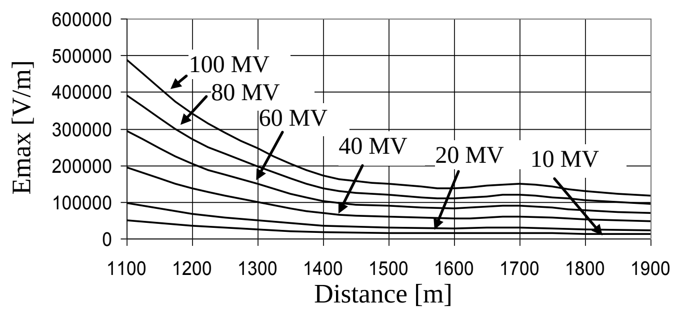

Fig. 6. Change in Emax with distance between lightning and airplane

D. Take-off

When an airplane leaves the ground and begin to flight, nose may have different angles to the horizontal. In order to investigate lightning strike possibility during take-off, nose of an airplane under thunder cloud is considered to have 15^o, 30^o and 45^o to the horizontal and maximum electric field on the airplane is calculated. In the Figure 7, potential and electric field distribution around the airplane is shown.

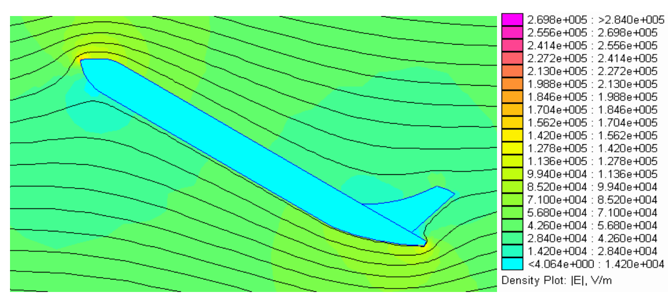

Fig. 7. Potential and electric field distribution around the airplane

In the Figure 8, the change in maximum electric field on the airplane with respect to cloud potential can be seen for three different angles. When the nose of the airplane has a bigger angle to the horizontal, the nose gets closer to the charged cloud, the electric field on the airplane, especially on the nose increases linearly.

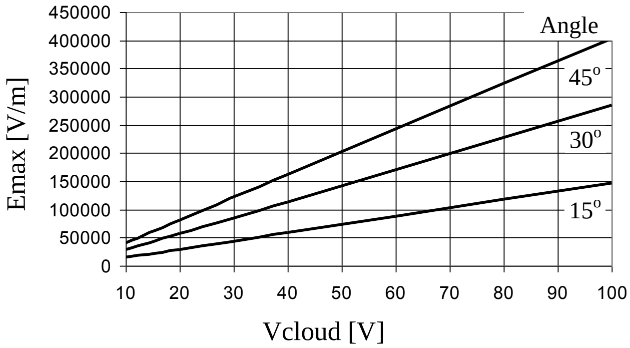

Fig. 8. The change in maximum electric field on the airplane with respect to cloud potential

E. Landing Position

During landing, an airplane's nose may be directed to the ground with different angles. When the nose is facing down to ground, the maximum electric field strength occurs on the tail. In Figure 9, potential and electric field distribution around the airplane calculated by finite element method is shown.

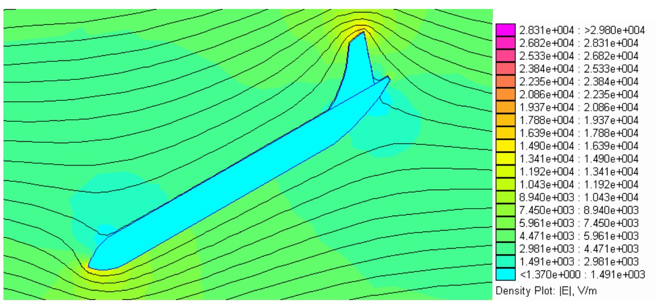

Fig. 9. The change in maximum electric field on the airplane with respect to cloud potential

In Figure 10, the change in maximum electric field on the airplane with respect to cloud potential can be seen for three different angles. In this case, similarly to the previous one, when the nose gets closer to the ground the tail will be facing the charged cloud. Therefore, electric field on the tail increases with the increase of cloud potential and angle to the horizontal.

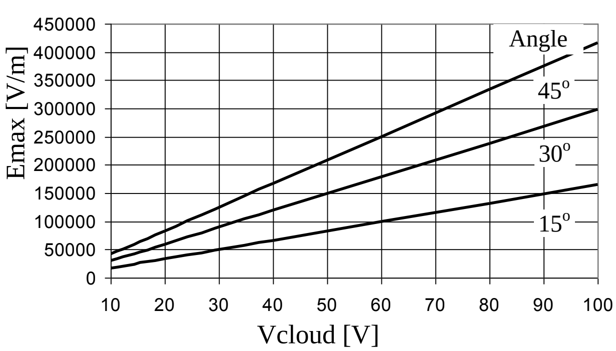

Fig. 10. The change in maximum electric field on the airplane with respect to cloud potential

The electric field at the points with small curvature radius on the airplane is higher. In order to minimize the interactions with lightning, it is important to avoid the maneuvers which put the extreme points on the airplane such as tail and nose forward.

All the models are simulated in a program of finite element method. In all the models, ground is represented by a grounded plane electrode, and the thunder cloud is represented by another plane electrode having above-mentioned potentials. The electrode separation is taken as 2 km, and the insulation material as air which has a relative dielectric constant of 1. In the simulations, real dimensions and geometry of an Airbus 340 is used which is a common commercial airplane. For accurate solution the region is divided into more than 20000 triangles for each case.

IV. Conclusion

The relationship between airplane and lightning in space has been introduced by electric field analysis when airplane approaches to or flies away from the lightning. In the other cases, when lightning approaches to airplane considering airplane location to be constant, electric field calculations give the relationship between airplane and lightning in time. In both cases, it is observed that, changes in electrical field may be informative about lightning strike possibilities. This is important in respect to lightning protection.

It is seen that, electric field strength reaches to very high intensities at the point with a small curvature radius on an airplane such as wings, tails and nose. Therefore, they are very effective on lightning strike. Lightning strike and electric field conditions change with the altitude and location of airplane.
This study and various studies in the literature show that, during a lightning strike, lightning channel may stuck to certain zones, like the wings, nose and tail.

In the future studies, lightning leader will be simulated by a space charge and will be added to this electro-static model. At the next step, the simulation will be repeated by using a time-dependent. For the same geometry, wing movements also will be taken into account.

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