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EVALUATION OF LIGHTNING INCIDENCE TO ELEMENTS OF A COMPLEX STRUCTURE: A MONTE CARLO APPROACH

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Abstract - There are complex structures for which the installation and positioning of the lightning protection system (LPS) cannot be done using the lightning protection standard guidelines. As a result, there are some "unprotected" or "exposed" areas. In an effort to quantify the lightning threat to these areas, a Monte Carlo statistical tool has been developed. This statistical tool uses two random number generators: a uniform distribution to generate origins of downward propagating leaders and a lognormal distribution to generate returns stroke peak currents. Downward leaders propagate vertically downward and their striking distances are defined by the polarity and peak current. Following the electrogeometrical concept, we assume that the leader attaches to the closest object within its striking distance. The statistical analysis is run for 10,000 years with an assumed ground flash density and peak current distributions, and the output of the program is the probability of direct attachment to objects of interest with its corresponding peak current distribution.

1 - INTRODUCTION

It is not very often that an engineer is challenged to design a lightning protection system for a complex structure that does not resemble those represented in the lightning protection standards. Furthermore, some of these complex structures do not permit the use of air terminals (lightning rods or catenary wires) as recommended by the standards. This is the case for the new lightning protection system for Launch Complex 39B at the Kennedy Space Center, Florida, to be used for the Constellation Program. The design of this lightning protection system presented many challenges, such as minimizing the likelihood of a direct attachment to the space craft while providing enough clearance required by the expected drifts during launch. Spacecrafts require what is known as a flight out hole, which is an opening in the lightning protection system for the vehicle to go through. The problem is that providing this clearance increases the possibility of sneak through strikes (shielding failures) that could potentially impact the vehicle or ground support equipment.

The problem becomes more complicated when the location of lightning protection towers and downlead anchoring points is dictated by existing infrastructure that cannot be removed or relocated, such as underground tunnels, utilities, etc.

All these unique challenges prompted the refinement of a Monte Carlo statistical tool that was originally developed in 2006 by ASRC Aerospace to evaluate the lightning protection system of the Space Shuttle. The first version of this tool had some limitations that were overcome by the new development used to design and evaluate the new lightning protection system for Launch Pad 39B. The new version of this tool allows for the simulation of both negative and positive strikes, while providing the user with the probability of a direct attachment to any object of interest and the current distribution. With this tool, it is possible to quantify the exposure of certain objects or likelihood of direct lightning attachments.

The assumptions of this tool are presented in Section 2. Two case studies, that of vertical conductors of different height and the Launch Complex 39B at the Kennedy Space Center, FL are presented in Section 3. The results are discussed in Section 4 and the conclusions are presented in Section 5.

2 – MONTE CARLO SIMULATION ASSUMPTIONS

The following assumptions are made by the Monte Carlo procedure:

- Peak current (*I*, in kiloamperes) and striking distance (*d*, in meters) are related by the following equations: $d=10xI^{0.65}$ [1] (negative strikes) and $d=10xI^{0.47}$ [2,3] (positive strikes).
- The leaders travel vertically downward with computational steps equal to 5% of their striking distance and with an imaginary sphere, whose radius is equal to the striking distance, centered at the leader tip.
- The leader will attach to any point that first comes in contact with the surface of the sphere as it travels downward. So, the bottom section of the leader channel (whose length is equal to the striking distance) can be in any direction.
- Ground flash density is assumed to be 10 flashes/km^2/year with a correction factor of 1.7 [1] (to account for multiple ground terminations that the existing KSC lightning detection system cannot detect), or 17 flashes/km^2/year.
- Positive strikes are assumed to be 5% of all strikes (0.85 flashes/km^2/year).
- The peak current distributions for positive and negative strikes (first strokes in the absence of strike object) are defined by lognormal distributions with μ=35 kA, σ=1.2 and μ=31.1 kA, σ=0.484, respectively, where μ and σ are the logarithmic mean and standard deviation, respectively. Strokes with peak currents less than 2 kA are not considered in the simulation.

- The Monte Carlo simulation runs for a period of 10,000 years, and the results are used to compute the annual lightning incidence. The number of years of simulation can be changed by the user.
- Only downward propagating leaders are considered regardless of the height of the structures.
- Structures and vehicles being protected are assumed to be at the pad for 365 days per year. In practice, they are at the pad for a fraction of that time.

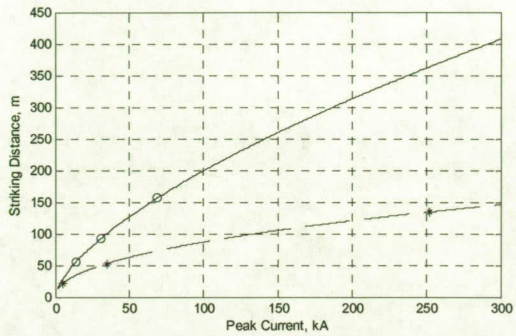

Figure 1 – Striking distance as a function of stroke peak current. Note that the 5, 50, and 95% points are marked with circles and asterisks for negatives and positives strokes, respectively.

The ground flash density and percent of positive strikes are based on actual data collected at KSC. The cumulative peak current distributions were obtained by performing a curve fit to 95%, 50%, and 5% values [1] (see Table 1 and Figure 2). Figure 2 shows the lognormal cumulative distribution function that indicates the probability of a stroke peak current of being less than the tabulated values.

Peak Current (min 2 kA)	Percent of cases exceeding tabulated value		
	95%	50%	5%
Negative 1st Strokes (kA)	14	31	80
	(14)	(31)	(70)
Positive 1st Strokes (kA)	4.6	35	250
	(4.8)	(35)	(252)

Table 1 – Lightning peak current statistics [1]. The values in parentheses are those that the lognormal distributions used by the Monte Carlo model yields (See Figure 1).

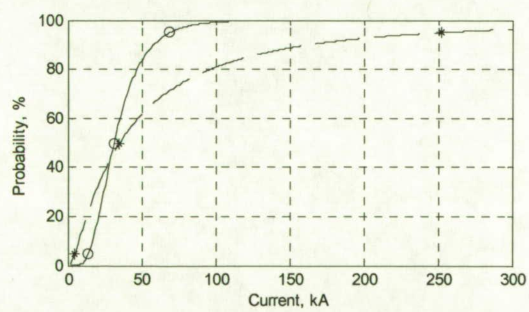

Figure 2 – Lognormal cumulative distribution function of the first stroke peak current parameters in Table 1. Note that the 5, 50, and 95% values are shown with circle markers and asterisks for the negative and positive strokes, respectively.

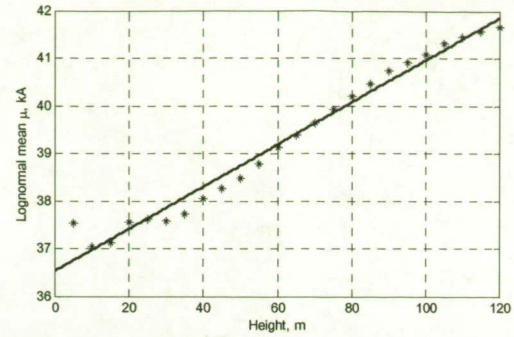

Figure 3 – Geometric mean peak current as a function of the height of the vertical conductor.

3 – CASE STUDIES

To demonstrate the capabilities of the presented method, two case studies are presented. The first case study is a vertical conductor in the open field (Section 3.1) and the second case is the new lightning protection system for Launch Complex 39B at the Kennedy Space Center (Section 3.2). Note that the estimation of the current distributions for both cases has been carried considering only the negative strokes.

3.1 – VERTICAL CONDUCTORS

A vertical conductor with a variable height varying from 5 to 120 meters in increments of 5 meters was modeled and the Monte Carlo Statistical Tool was run for each one of the different heights to evaluate the peak current distributions as a function of the height of the vertical conductor. The results of the simulation seem to indicate that the current distribution geometric mean increases almost linearly with the height of the vertical conductor (See Figure 3). In this case, a least square curve fitting is given by (1):

$$\mu \approx 0.0444 \times h + 36.5 \quad (1)$$

The standard deviation of the current distributions of those strokes that attach to the vertical conductor is shown in Figure 3.

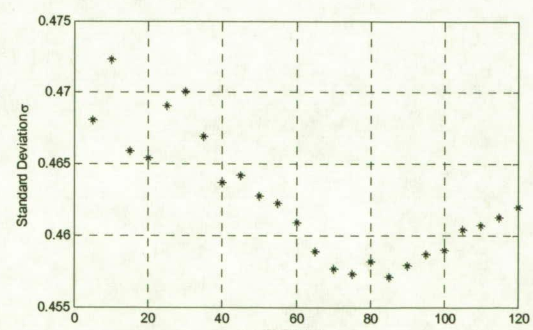

Figure 4 – Standard Deviation as a function of the height of the vertical conductor.

Note that the number of strikes to the vertical conductor increases as a function of height, therefore, the curve fitting for the current distributions at higher heights is better resolved because of the increased samples or number of direct strikes to the vertical conductor (See Figure 5). The number of direct strikes to the vertical conductor seems to reach a plateau at about 120m. This is expected since the striking distances have finite values and are defined by the lognormal distribution of the peak currents.

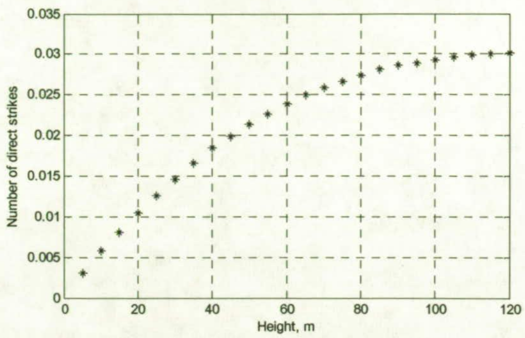

Figure 5 – Normalized number of direct strikes to the vertical conductor per year for Ng=1 as a function of height (only negative strokes are considered).

These results seem to indicate that as the height of the vertical conductor increases, so does the probability of larger peak currents.

3.2 – LC39B LIGHTNING PROTECTION SYSTEM

This lightning protection system consists of three towers and nine downleads, as shown on Figure 6. The towers are about 161 meters height with insulators of about 22 meters mounted on top, for an overall height of about 183 meters. A catenary wire system rests on top of the insulators. The outer triangle is formed by the catenary wires that connect towers 1, 2, and 3. The flight out hole has the shape of a pentagon and the space craft is centered underneath it.

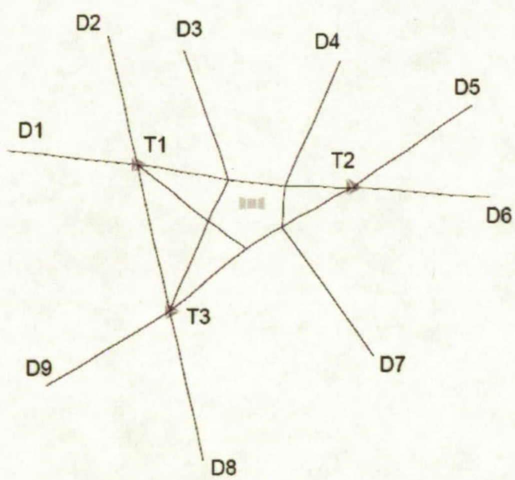

Figure 6. Plan view of the lightning protection system of LC39B at the Kennedy Space Center, FL.

An isometric view of the lightning protection system, showing the towers, the catenary wire system, and the downleads is shown in Figure 7. The model used by the Monte Carlo Simulation tool is derived from the CAD model of the system. Therefore, sag information is taken into consideration.

Figure 7. Isometric view of the lightning protection system of LC39B at the Kennedy Space Center.

Note that the openings in the catenary wire system will result in shielding failures (sneak through strikes) that may potentially impact equipment below the lightning protection system. In this particular case, the peak currents of negative and positive strokes for events that may result in shielding failures are shown in Figures 8 and 9, respectively.

When the Monte Carlo model is run for a period of 10,000 years, the shielding failure occurs at the flight out hole about five times during this simulation period. This translates into a probability of a direct attachment to the vehicle of about 0.05% per year, assuming the vehicle is parked at the launch pad for 365 days per year.

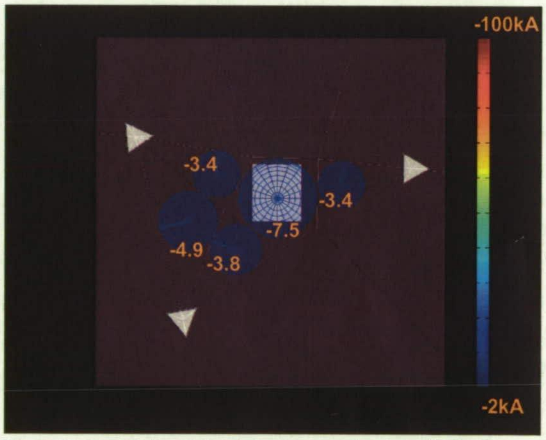

Figure 8. Sneak through peak currents for negative strikes.

The Monte Carlo model also allowed us to investigate the expected current distributions at each downlead and catenary wire section. This information was used for a flashover analysis that was performed using the ATP. This analysis will be presented on a future publication.

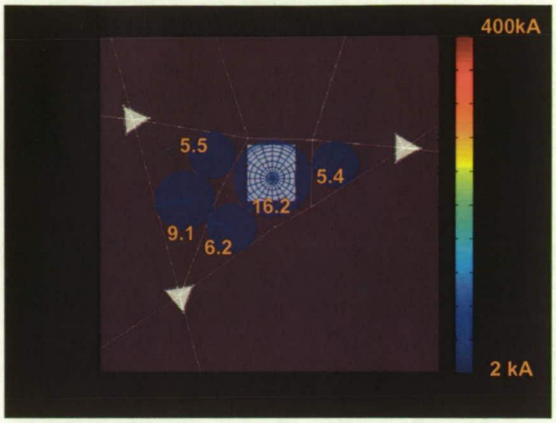

Figure 9. Sneak through peak currents for positive strikes.

4 - RESULTS

The results of the study case of the vertical conductors of different height seem to indicate that at least for the first 120 meters, the peak current geometric mean increases linearly with the conductor height. Nevertheless, the number of direct strikes or incidence level to the vertical conductor seem to reach a plateau when the height is about 120 meters, which is expected given the relationship between the striking distance and the peak current.

In the case of the lightning protection system of Launch Complex 39B, running the Monte Carlo simulation for a period of 10,000 years results on a total of five direct attachments of less than 10 kA (both positive and negative strikes) and one direct strike of more than 10 kA (a positive strike). This translates into a probability of a direct strike to the spacecraft of about 0.06% per year, assuming that the vehicle is parked at the Launch Pad 365 days a year. In reality, the vehicle is expected to be at the Lunch Pad for a week or two with about four times per year. Also, the distribution of lightning activity varies per month, with the months from June through September being the months of greatest lightning activity.

5 - CONCLUSIONS

A Monte Carlo approach to evaluate the lightning incidence to elements of complex structures and to estimate the current distributions has been presented. The approach was used to validate the design of the lightning protection system of Launch Complex 39B at the Kennedy Space Center, FL, for the Constellation program. The tool allowed the designers to move the position of the towers, within many constraints, and to design the catenary wire system to minimize the probability of direct strikes to the space craft. This tool can be used to evaluate, validate, and aid in the design of lighting protection systems, specially when the guidelines provided by lightning protection standards cannot be followed.

7 - REFERENCES

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