

On the Simulation of the Lightning Strikes to Complex Grounded Structures

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Abstract: This paper presents the implementation of a self-consistent lightning attachment model by using the COMSOL Multiphysics 3.5 programming language in MATLAB. This model simulates the interaction of lightning flashes to grounded structures considering the time-varying electric field during thunderstorms. The general details and experiences gained on the implementation of the model to evaluate the attachment of lightning flashes to any practical structure (e.g. a wind mill, a nuclear power station or any building with complex structure) are here presented. Particular attention is paid to describe the approach used to avoid the intrinsic meshing and solving errors mainly caused by the disproportion in size between the different components of this problem (e.g. the structure geometry, the lightning rods and conductors, the descending and ascending discharges, the thundercloud, etc).

Keywords: Lightning attachment, Lightning protection, Leader discharges, Complex structures

1. Introduction

There is a considerable world-wide interest among lightning protection engineers and designers on the improvement of the standard procedures to assess the location of the most vulnerable places on complex structures to be struck by lightning. For this reason, physical numerical models have been suggested as a valuable tool to properly assess the interaction of lightning flashes with ground-based objects [1]. However, these models have mostly been applied to analyse the lightning interception process of simple structures such as lightning rods, tall masts, horizontal conductors, etc. For this reason, the models have to be further improved to simulate complex structures (e.g. a wind mills, a nuclear power stations, historic value buildings, etc) with a reasonable computational effort (resources and time) and with a high application level [1]. Moreover,

such models need to be implemented with a user-friendly and computationally efficient solution algorithm.

Recently, a state-of-the-art, self-consistent physical model (called –SLIM–) has been proposed to simulate the physics of the initiation and propagation of upward connecting leaders prior to a lightning strike [2]. These upward leader discharges are initiated due to the high electric field produced by a descending lightning leader discharge (referred to as the stepped downward leader) started from a thundercloud. It is believed that a lightning strike takes place when an upward connecting leader successfully attaches the downward leader [3].

SLIM computes continuously the properties of an upward connecting leader propagating under the influence of the electric field produced by a descending stepped leader and a thundercloud [2]. Hence, the charge per unit length, potential gradient, channel radius, injected current and propagation velocity of the upward leader are self-consistently simulated as it propagates towards the downward leader. By following the propagation of both the upward and the downward leaders, the model evaluates the possibility of leader initiation and successful lightning attachment to different vulnerable places on complex structures.

The most demanding step for the implementation of SLIM is the three dimensional solution of the Poisson equation for the geometry of the analysed object including its protecting elements (e.g. lightning rods, conductors, etc.). This solution has to be updated for every simulation step in order to properly represent the electrostatic conditions during the descent of the stepped leader. Since the simulation of the propagation of both leaders from different points on a structure require of several thousand simulation steps, a computationally efficient and reliable electrostatic calculation is a must.

Due to its flexibility, COMSOL Multiphysics has been here used to calculate

the electrostatic conditions around complex grounded structures. However, the implementation of such three dimensional calculation is still challenging despite of the powerful desktop computers available today and the continuous improvements in the software. This is because the modeling of this problem leads to several challenges in meshing and solving due to the disproportion in size between the different elements of the geometry. For instance, while the radius of the lightning rods and conductors is in the order of several millimeters, the downward stepped leader length can reach several kilometers. Thus, careful and educated simplifications of the geometries are required in order to successfully compute the Poisson equation with COMSOL Multiphysics. Thus, providing fast, accurate and reliable input to the upward leader calculation in SLIM.

This paper presents the general details and experiences gained on the stage of design of the COMSOL Multiphysics model to be analysed with SLIM. Furthermore, the approach followed for the reliable and accurate implementation of SLIM in the COMSOL 3.5 programming language (in MATLAB) is also presented.

2. General description of SLIM

SLIM is a state-of-the-art physical model to simulate the initiation and propagation of upward leaders under the influence of downward lightning stepped leaders. The model considers the time variation of the electric field produced by the descent of the downward leader, as well as the space charge created by streamers and aborted leaders. The simulation is performed through an iterative analysis of the electric field and potential distribution in front of a point $P_i(x_i, y_i, z_i)$ on the analysed structure. The analysis is performed considering the approach of a downward leader (whose tip is located at $(x_{down}, y_{down}, z_{down}(t))$ moving with a velocity v_{down} from the cloud base z_{cloud} .

Since a detailed description of the model is presented in [2], only the major features of the model related to COMSOL are introduced in this section. The main steps in SLIM that need the direct input of the electrostatic calculations are related to the initiation of the first and subsequent streamers and the calculation of the streamer charge in front of the leader channel. The former uses the electric field in front of the analysis point in order to evaluate the well-known streamer criterion:

$$N_{crit} \leq e^{\int \bar{\alpha}(E,p) \cdot dx} \quad (1)$$

where $\bar{\alpha}$ is the effective ionization coefficient which is a function of the electric field E and the pressure p , and N_{crit} is a critical number of ions in the avalanche head [2]. This condition is evaluated to determine the height of the downward leader tip $z_{down}(t^{str})$ at which streamers are initiated from P_i . The later step uses the potential distribution U_1 along a fictitious line l between the analysis point and the downward leader tip at the simulation time t . Then, the total corona charge ΔQ is determined from the difference between the geometrical potential distribution U_1 computed with COMSOL and the potential distribution after the corona formation U_2 (Figure 1):

$$\Delta Q(t) = K_Q \cdot \int_{l_L}^{l_S} (U_1(l(t)) - U_2(l(t))) \cdot dl \quad (2)$$

where K_Q is a constant geometrical factor that takes into account the effect of all of the streamers on the total charge. The potential distribution U_2 after the corona formation is computed as:

$$U_2(l(t)) = \sum_{k=1}^{n(t)} E_L^{(k)} \cdot l_L^{(k)} + E_{str} \cdot l(t) \quad (3)$$

where $E_L^{(k)}$ and $l_L^{(k)}$ are the electric field and the length of the k^{th} upward leader segment, and E_{str} is the average streamer propagation electric field.

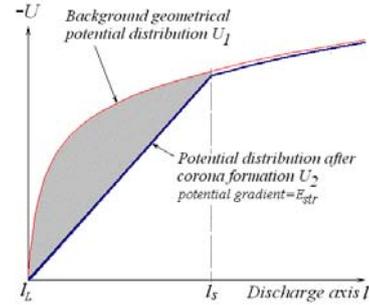


Figure 1. Potential distribution before and after corona formation in front of the leader tip.

3. Use of COMSOL Multiphysics

3.1 Governing equations

For the implementation of SLIM, one electrostatics module is used to solve the Poisson's equation for potential Φ :

$$\nabla \cdot \bar{E} = -\nabla^2 \Phi = \frac{e \cdot n_+}{\epsilon_0} \quad (3)$$

where E is the electric field, e is the elementary charge and ϵ_0 is the dielectric permittivity. The term n_+ is the density of small ions produced by glow corona at the analysis point or generated on the ground surface. This term is considered in the simulation when the effect of glow corona is taken into account. Otherwise, equation (3) turns into the Laplace equation. The electrostatic calculation is first solved in COMSOL Multiphysics during the design stage. During the execution stage of SLIM, equation (3) is iteratively solved in Matlab through the COMSOL 3.5 programming language.

3.2 Geometric objects

One of the most important steps in the design stage of a model to be analysed with SLIM is the creation of the geometry objects in COMSOL Multiphysics. In this step, a single, three dimensional geometry object of the analysed structure needs to be successfully composed. Observe that this geometry object can be directly drawn in COMSOL or it can be imported from any CAD program (Figure 2). One major consideration during the drawing step is the simplification of the analysed structure. Due to the complexity of the geometry of real structures, it is necessary to disregard any feature irrelevant to the lightning attachment process. Particularly, decoration features, frames of windows and doors, and any other feature that does not interact with lightning ought to be discarded. This is because they increase unnecessarily the number of mesh points, making the solution slower and less stable.

In addition, the geometry object should not include any thin element such as lightning rods, metal pipes, metallic roof parapets, air termination studs, conductors or any other bar-like feature likely to be struck by lightning (Figure 3.a). These elements are later represented by lines when the SLIM code is executed in Matlab, based on a matrix of coordinates introduced as input by the user. This simplification avoids the meshing problems that otherwise would occur when these features of small dimensions are drawn as a volume geometry objects.

Since the considered electrostatic problem involves open boundaries, the structure geometry object is placed inside a finite analysis volume (Figure 3.b). In order to keep a reasonable number of mesh points, the height of this volume does not extend up to the cloud

base (normally assumed to be 4000 m above ground). Numerical experiments have shown that the minimum height of the analysis volume is 600 m for structure objects shorter than 60 m. The minimum analysis volume height for taller structures should be at least ten times the height of the structure geometry object. In a similar way, the width and breadth of the analysis volume is set large enough to guarantee the proper evaluation of the open boundaries at the side faces. This condition is generally satisfied when the lateral dimensions of the analysis volume are several times larger than the dimensions of the structure object [4].

Once the structure geometry object and the analysis volume are available in the COMSOL GUI, they should be composed as a single geometry object named *COI*. For this, a difference operation is performed between the analysis volume and the structure geometry object. In this way, only the outer surface of the analysed structure is considered for the electrostatic calculation. Then, the descending leader is included as one line segment drawn inside the final composed geometry object *COI*. Observe that only the lower section of the downward leader inside the analysis volume is then included. Last, the final geometry object *COI* is exported to Matlab from the COMSOL Multiphysics GUI.

During execution time, SLIM takes the exported geometry object *COI* during every simulation step, add lines for the thin lightning exposed objects and updates the location of the lower end of the line representing the downward leader. In addition, lines representing each segment of the propagating upward leader are added to the geometry after the leader inception condition has been reached.

3.3 Meshing

In order to obtain the proper solution of the 3D geometry, it is necessary to use an adequate mesh. Hence, the meshing of the geometry should be first performed in COMSOL Multiphysics GUI during the design stage to detect possible mesh errors and to identify features causing those errors. Generally, a normal mesh with maximum element size scaling factor, element growth rate, curvature factor and mesh curvature cut off equal to 1, 1.4, 0.4 and 0.01 can be used at first. Notice that if the meshing of the geometry is not successful, the structure geometry object should be modified accordingly until meshing is possible.

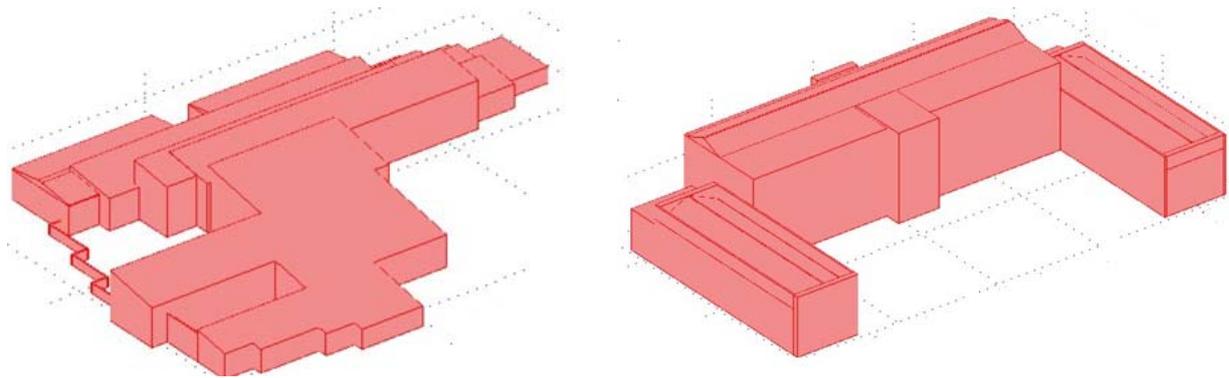


Figure 2. Examples of real buildings modeled with COMSOL Multiphysics

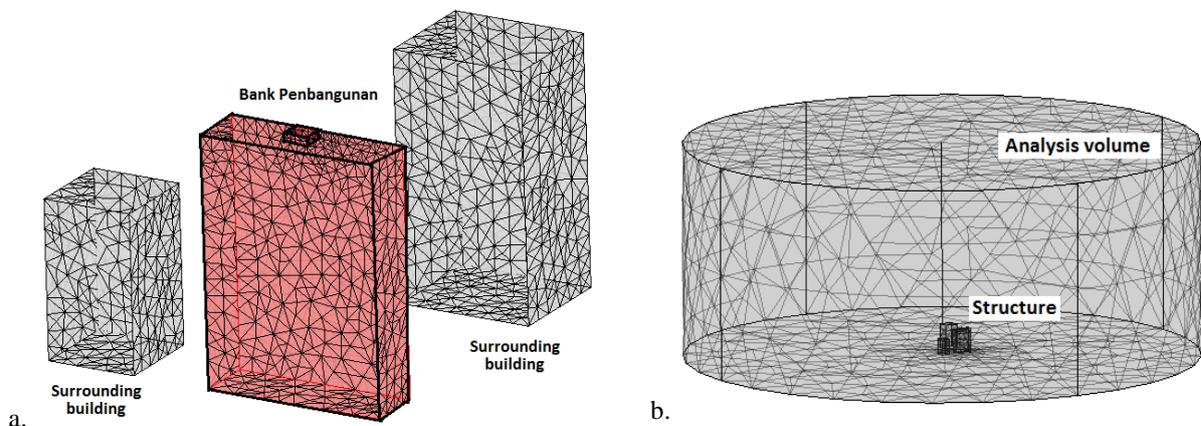


Figure 3. Example of the meshing of a building (Bank Pembangunan) in Malaysia. *a)* details of the analysed structure, *b)* the structure and the analysis volume. Notice that the lightning rods on top of the building are not drawn.

During the execution stage, SLIM automatically chooses the mesh type by compromising quality, meshing stability and number of elements. Particularly, SLIM sets the maximum element size for the lines representing the lightning protection elements according to the user input. For the lines representing the downward leader and the upward leader segments, the maximum element size of 4 and 0.2 meter respectively is set by default.

Unfortunately meshing errors can occur after the location of the descending leader tip is automatically updated in the geometry by SLIM. In such cases, SLIM progressively reduces the overall mesh quality of the model from a normal mesh down to a coarse one. Such approach helped to avoid meshing problems keeping the accuracy of the solution. This is because numerical experiments have shown that there are not large differences

between the results obtained with coarse and fine volume meshes [4].

If the meshing problem persisted after this, small spatial variations (in steps of ± 0.05 m) in the end location of the lines for the downward and upward leader segments are performed within an iterative loop (of up to 4 steps). During each step, meshes of different qualities are attempted. This last approach helped to reach a successful mesh in most of the cases evaluated.

3.3 Boundary conditions and other settings

The main boundary conditions for the model must be set during design stage by the user. Since the upper and side faces of the geometry represent open borders, they are set as insulation boundaries. Naturally, the bottom boundary is set as ground. Regarding the boundaries representing the outer surface of the analysed structure, they are set as ground. Notice that the potential of the surface of

complex structures can be assumed to be zero due to the usage of reinforced concrete, metallic pipes and other metallic elements connected to the grounding system.

One important setting during design stage is the definition of the line that represents the downward leader as a line charge density. This must be done in edge settings by attributing the charge density to q_z . The charge distribution of such line is defined as a scalar expression q_z which is a function of the downward leader height above ground, the cloud height and the prospective return stroke peak current [1]. The values of these parameters are defined in the constants of the model. For sake of simplicity, both the constants and the scalar expressions can be uploaded by the user from the corresponding text files in SLIM.

3.4 Solution

It is a good practice to solve the electrostatic problem in COMSOL Multiphysics model before exporting the fem structure to Matlab. This allows the user to crosscheck that the boundary conditions and the settings of the model are right. In addition, the user can test different solvers in order to find the most

suitable (in terms of required memory and computation time) considering the available computer resources. Observe that optimum and fastest solver (and preconditioners) depends upon the type of the problem and the available computational resources. In our case, the best performance is obtained by using the conjugate gradients iterative solver with algebraic multigrid preconditioner [5]. Once the model design by the user has been successfully composed, meshed, set and solved, the complete fem structure is exported to Matlab.

4. Results: a study case

In this paper, the lightning attachment to an actual structure (the Pembangunan bank in Kuala Lumpur, Malaysia) is calculated with SLIM and COMSOL Multiphysics. This 110 m tall building is separated by about 60 m from another structure of similar height and 30m from a shorter building (80 m tall). During the period of analysis of lightning strikes, there was an air terminal at the center of the building whose tip is located 115 m above ground.

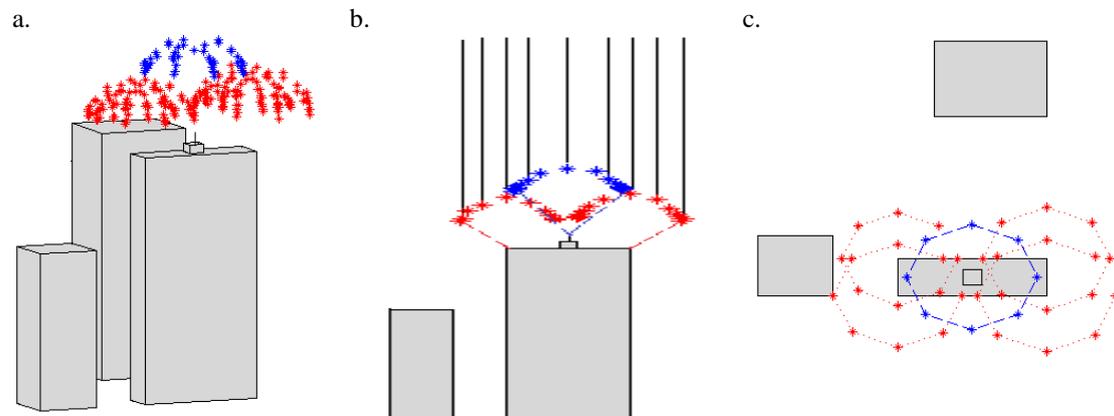


Figure 4. Lightning attachment points (where the downward leader is intercepted by the upward connecting leader) of the Pembangunan Bank computed with SLIM and COMSOL Multiphysics: *a*) 3D view, *b*) side view, *c*) top view. The asterisk in the top view show the critical positions for the downward leader at which lightning interception takes place.

For this simulation, the lightning attachment to the corners, as well as to the lightning rod on the building is simulated. For each analysed point, the location of the downward leader in the horizontal plane (x_{down}, y_{down}) is changed in order to evaluate the influence of its position on the interception process. The simulation is performed along eight radial directions (spaced 45 degrees) from the position of the analysed

point (x_i, y_i). For each direction, the maximum (critical) lateral distance at which the downward leader can be intercepted by an upward leader from the analysed point is evaluated with the bisection method.

A cylindrical analysis volume with radius of 1200 m and height of 1000 m is used. The prospective return stroke current assumed for the calculations is 16 kA. As it can be seen in

Figure 4, SLIM in combination with COMSOL Multiphysics can be used to compute the interaction of the downward lightning leaders with the simulated structure. Notice that the simulation shows that the lightning rod on top of the building cannot protect the entire building. Moreover, it shows that upward leaders initiated from the corners can readily intercept downward leaders in areas not protected by the lightning rod. This result agrees with field observations that show that this building has been struck by lightning several times at the corners, despite of the presence of the lightning rod.

For the case shown in Figure 4, seventy eight different lateral positions of the downward are simulated to estimate the lightning interception zone for the corners and the lightning rod of the building. An average time of 300 s are required to simulate the descent and interception of the downward leader for each case. A workstation with 2 processors 2.15 GHz and 16 Gb of RAM is used for the calculations. Figure 5 shows an example of the electrostatic calculation for one of the steps during the simulation at a given lateral location of the downward leader.

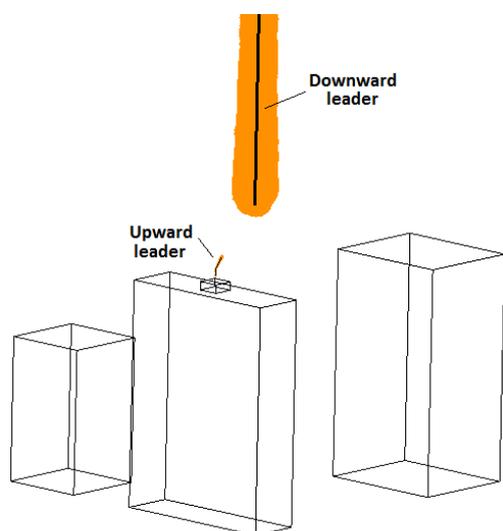


Figure 5. Isosurface plot of the normal electric field (equal to 0.6 MV/m) computed one step before the interception of the downward leader for that case.

5. Conclusions

This paper presents the strategy followed in order to implement a self-consistent lightning simulation model in Matlab by using the COMSOL Multiphysics 3.5 GUI and its programming language. Guidelines for the

successful implementation of the model to evaluate complex structures have been presented. The results of the paper show that the physical analysis of the interception of lightning flashes to complex structures is possible with reasonable computational effort and with a high application level.

6. Open code

The code of SLIM implemented with the COMSOL Multiphysics 3.5 programming language can be requested for research purposes by email to the author.

7. References

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Cloud-to-ground lightning comes from the sky down, but the part you see comes from the ground up. A typical cloud-to-ground flash lowers a path of negative electricity (that we cannot see) towards the ground in a series of spurts. Objects on the ground generally have a positive charge. Since opposites attract, an upward streamer is sent out from the object about to be struck. I'm pretty sure that lightning can go either way. We did the calculation in physics class, a bit of a back of the envelope calculation to be sure, but we came out with an electric field of 300,000 V/m being the electric field needed for lightning to form. What that means is, an electric field is created between the clouds and the ground by a build up of electrons on one of the surfaces.