LIGHTNING DIRECT EFFECTS ON ANISOTROPIC MATERIALS FROM ELECTRO-THERMAL SIMULATION

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1 Abstract

Mitigating lightning Direct Effects (DE) damage on aerospace vehicles is an important engineering challenge and is directly related to safety of flight. Depending on the threat level and materials involved, vehicle surfaces and other design features may need to be protected to help mitigate damage. Numerical simulation can provide insight into the amount of damage likely to occur during a lightning strike and can reduce the costs associated with an expensive testing program. We here present a new simulation tool for such analyses that we believe provides unique capabilities especially well-suited for the protection of aerospace platforms, and we apply this new tool to the analysis of lightning DE on an anisotropic composite surface. Our simulation tool is the combined framework of EMA3D and the Elmer thermal physics solver. This new analysis platform allows for the correct description of anisotropic materials at both the electrical and thermal level. By implementing DE analysis capabilities in EMA3D we find a comprehensive avenue through which to analyse a wide range of E3 concerns for an entire aerospace vehicle.

2 Introduction

Thermal effects caused by large currents during a lightning strike are one of the primary causes of Direct Effects (DE) damage to aerospace vehicles and other structures [1]. The physics of DE damage due to Joule heating is governed by the heat equation. For solids the heat equation has the form

$$\rho\, c_p \frac{\partial T}{\partial t} - \nabla(\overleftrightarrow{k}\, \nabla T) = \rho\, h \qquad (1)$$

In this equation h is the heat source, T is the temperature, c_p is the heat capacity, ρ is the density, t is time, and k is the anisotropic heat conductivity tensor. For many modern heating applications it is important to account for the anisotropic nature of certain materials and we will come back to this point. For isotropic materials, k is a scalar quantity, and if we allow uniform current density the heat source, h, has a compact proportionality:

$$h \sim I^2 R \qquad (2)$$

where I is the total current and R is the resistance of the material. From the form of relation (2) it is clear that regions with large induced current densities during a lightning strike tend to be more vulnerable for DE damage. Naturally, the point of lightning attachment or detachment on the surface of a structure may be a region of high current density, and it is by now well known that aircraft with composite skins are particularly vulnerable to DE damage at the point of attachment [2].

DE thermal effects are not limited to the surface of aerospace vehicles. Regions of the vehicle where wires or other design features are forced to carry large currents may also be vulnerable. On many spacecraft with multi-stage designs, the protection of explosive ordnances from excessive thermal heating is a mission critical objective.

From an engineering standpoint, simulation provides a powerful and cost effective way to investigate the lightning hazard to aerospace platforms, and this is true for the DE due to Joule heating. While electro-thermal simulation of lightning DE is not new [3], we here present a new simulation tool for such analyses that we believe provides unique capabilities especially well-suited for the protection of aerospace platforms, and we apply this new tool to the analysis of lightning DE on a composite surface.

3 Simulation Method

Our simulation approach in this paper is to use EMA3D combined with Elmer to extract the thermal effects of a lightning strike to a carbon fiber composite (CFC) surface. We outline our approach and the advantages of this method in what follows.

EMA3D is a three-dimensional full wave finite-difference time-domain (FDTD) numerical solution to Maxwell's equations [4]. EMA3D has been optimized for system level electromagnetic environmental effects (E3) and has been in development since 1978. EMA3D is regularly used for the analysis of many E3 problems including lightning indirect effects, lightning zoning, electrostatic charging, and high intensity radiated fields. It has been used extensively in the analysis of lightning effects on aerospace platforms and is well-suited for performing lightning simulations on entire aerospace vehicles. Such a comprehensive platform is an excellent avenue through which to analyse thermal DE since during the simulation of an entire aerospace vehicle, regions of concern can be pinpointed to examine any vulnerability and users do not have to learn different software tools through which to perform their various E3 analyses.

Elmer is an open-source multi-physics solver that has many physical models including the heat equation [5]. One of the primary utilities of Elmer is that users can precisely control aspects of their simulation by supplying User Defined Functions (UDF) which are compiled as dynamically linked libraries to be accessed at runtime. For example, the heating source, *h*, of equation (1), may be a complicated function of both time and space that must be read and interpolated from an existing database during the simulation. The UDF capability in Elmer allows the user to overcome this challenge.

3.1 EMA/Elmer Framework

Recently, the capabilities of EMA3D have been extended to include a thermal probe output which generates the heating source, *h*, of equation (1) for both isotropic and anisotropic materials including the full time and spatial dependence. Additionally, Elmer UDF's have been created to read this source into the simulation providing a powerful basis for thermal modelling of a full aerospace platform. The EMA3D GUI utilities also allow a user to export the meshed geometry for simulation in Elmer. That is, the same geometry (or subset thereof) that is used for the electromagnetic simulation is exported directly for use in Elmer, which combined with the source *h* is then used for a complete lightning DE analysis. We will refer to this combined framework as EMA3D/Elmer.

As alluded to earlier, a complete thermal DE framework should have the ability to accurately model anisotropic materials, if only to account for the vulnerability of composite materials in many modern aircraft. EMA3D/Elmer includes the ability to model anisotropic materials in both the electromagnetic and thermal simulations. In an anisotropic medium, the average heating source of equation (1) within some volume *dV* can be written as [6]

$$h \sim \int \mathbf{E} \cdot [\overleftrightarrow{\boldsymbol{\Sigma}} \cdot \mathbf{E}] dV \qquad (3)$$

where **E** is the local electric field and $\sum$ is the electrical conductivity tensor. In addition to the electrical conductivity tensor, many anisotropic materials are characterized by thermal conductivity tensors, (see equation (1)). EMA3D/Elmer accounts for this using a UDF which allows the user to also control the spatial dependence of the tensor. This proves to be one convenient way to model composite materials as will be seen below.

The EMA3D/Elmer framework uses a weak electro-thermal coupling approximation. This means that changes to the electrical properties that occur due to heating are not accounted for in the simulation.

3.2 Anisotropic CFC Surface

We demonstrate EMA3D/Elmer on the problem of component C lightning attachment to an anisotropic CFC surface. This problem is of great interest in E3 aerospace applications. The CFC material is comprised of 16 layers, each 1.35e-04 meters thick. The layers are two repeating stacks of eight layers, as seen in Table 1. The electrical conductivity of each layer is a tensor that depends on the orientation of the fibers of each layer. Table 2 shows the conductivity in Siemens/meter where 'para' indicates the direction along the fiber direction, 'trans' is transverse to the fiber direction (but in the same plane) and 'perp' is perpendicular, or the direction between different layers. Similarly, the thermal conductivity is also anisotropic and depends on the layer orientation. Table 3 shows the thermal conductivity using the same nomenclature as in Table 2. Additionally, the heat capacity is 116 J/(kg-K) and the density is 2000 kg/m^3.

Table 1 CFC Layer Fiber Directions

CFC Layer #	Fiber Direction °
1	90
2	45
3	0
4	-45
5	-45
5	0
7	45
8	90

Table 2 Electrical conductivity values for the CFC layers

	σ para	σ trans	σ perp
Units	S/m	S/m	S/m
CFC	2.90e+04	1	0.1

Table 3 Thermal conductivity values for the CFC layers

	k para	k trans	k perp
Units	W/(m-K)	W/(m-K)	W/(m-K)
CFC	18	1.9	0.95

For the thermal analysis we use a finite-element mesh comprised of eight node quads, as see in Figure 1.

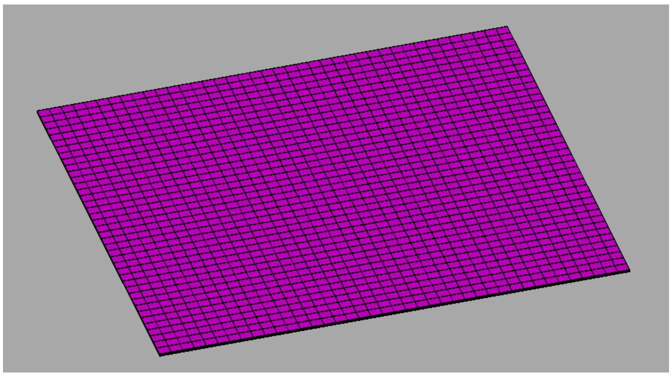

Figure 1: Finite-element mesh of the CFC surface used in our thermal simulation

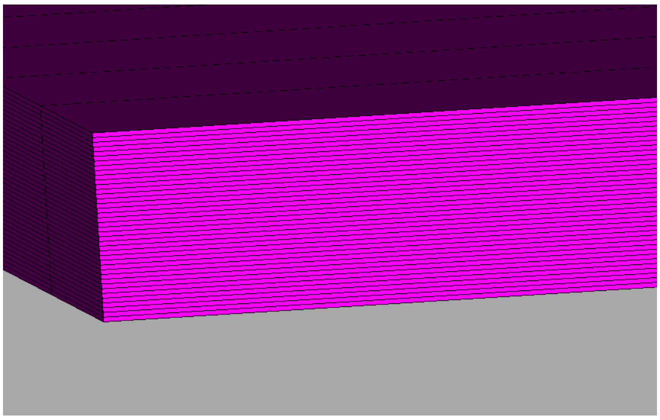

Figure 2: Side view of the mesh for our thermal analysis

The side view of our finite element mesh is seen in Figure 2.

3.3 Simulation Environment

Our lightning environment is 400 Amp component C applied for 0.5 seconds. The lightning waveform applied during the simulation has a rise-time of about 50 nanoseconds. The attachment occurs on the top and middle of the surface. Detachment occurs on electrical grounds on two edges in the 0 degree direction.

4 Results

We begin analyzing our results by looking at the surface current density on the top of the CFC at 2.0e-007 seconds shown in Figure 3.

Although the grounding planes are in the zero degree direction (left and right of the Figure), the current preferentially flows up and down, along the top layer's fiber orientation. This makes sense as the 'para' conductivity is so much higher than in any other direction, as the reader may recall from Table 2.

In the thermal simulation, the two edges at the electrical ground are kept at temperature T = 0 as a boundary condition. The initial condition for the simulation is T = 0 everywhere, and all temperatures reported here should be interpreted as a change in temperature.

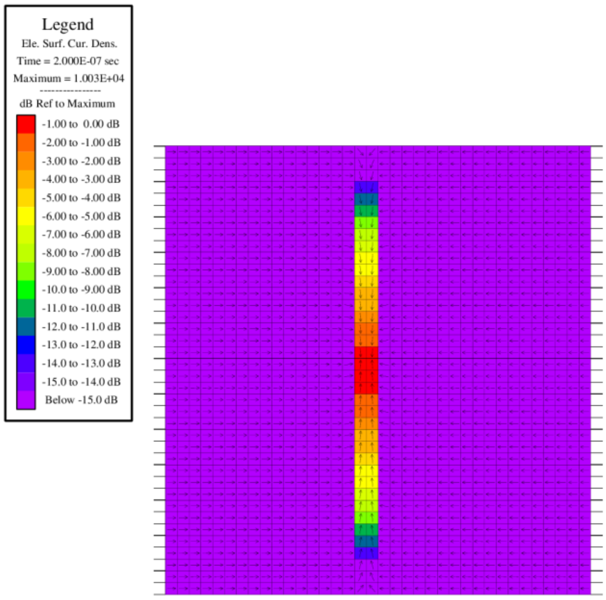

Figure 3: Surface current density at early times in the simulation in Amperes/m^2

We also point out that in our simulation there is no phase change explicitly present. Rather, we report a change in temperature and the interpretation is that above a certain temperature change the material is likely to be damaged or even destroyed. For instance, many CFC materials will begin to delaminate at temperature gains of a few hundred Kelvin [3]. In this paper, we will assume delamination to occur in any region where there is a temperature gain of 1000 Kelvin or higher.

Thus, the correct interpretation for this analysis is that regions subjected to a certain temperature gain or higher will likely be damaged in the real testing or lightning strike environment. Indeed, the maximum observed temperature in this analysis is likely artificially high, since the attachment location is relegated to a very narrow line in space. Further, the properties of the CFC will change and it will likely even melt at high enough temperatures. However, the reader should consider the results here as predicting the size and shape of a region likely to be damaged during a lightning component C event.

Our results are presented in Figure 4, Figure 5 and Figure 6. Figure 4 shows a 3D plot of the temperature profile of the top panel at the end of the simulation. The detach channels are on the forward and back side (or top and bottom in the 2D projection) and there the boundary is kept at T = 0. Elmer PostProcessor allows for full time animation of the simulation results including with material opacity less than one. As alluded to above, the max temperature gain at the point of attachment is quite large, and then dies off quickly. In light of the discussion above, we interpret this as a region near the attachment is likely to be severely damaged from this event.

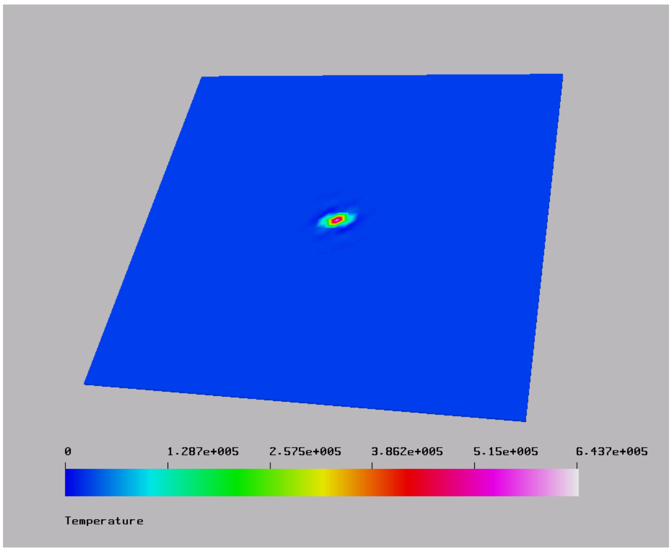

Figure 4: 3D Elmer plot of the temperature profile of the CFC surface at the end of the lightning simulation. The heating is centered near the point of attachment.

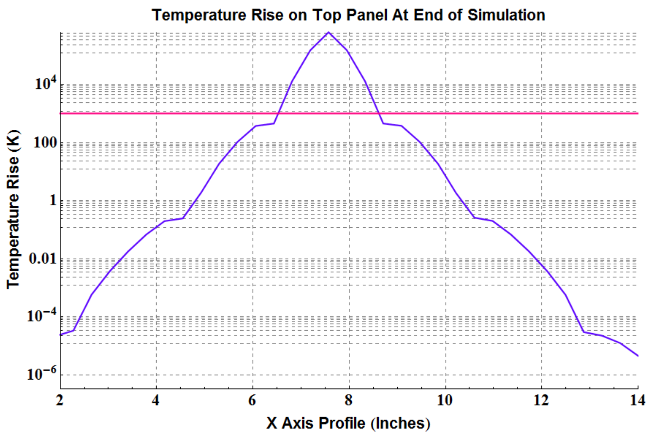

Figure 5: Temperature profile along the x axis on the top panel at the end of simulation. The profile is in middle of the panel in the y-axis.

We can begin to quantify the likely spatial extent of damage by plotting the cross sectional view of the temperature gain across the top layer and through the material, which we will do in the next two figures.

Figure 5 shows the temperature profile along the x-axis on the top panel of the CFC surface. The profile is located in the middle of the panel in the y-axis. The Figure shows that across a region of about 2 inches on the top surface the temperature gain is above 1000 Kelvin, our threshold at which we expect significant damage to occur to the CFC sheet. Practically, we may expect a region with diameter of about 2 inches to show delamination at the top surface of the CFC panel.

We can take this analysis one step further by examining a two-dimensional contour plot of a cross-sectional through the center of the panel, as seen in Figure 6. This figure shows the distribution of the expected temperature rise distributed in the middle of the sheet, similar to Figure 5, but with the extent in the perpendicular (z) direction as well. The high temperature region in the center indicates the region closest to the attachment point and shows an expected region of damage extending all the way through the panel, with a diameter of about 2 inches at the top which narrows to about 1 inch at the bottom. From this result, we may expect significant damage to the CFC panel with spatial extent ranging from about 1-2 inches in diameter near the point of attachment.

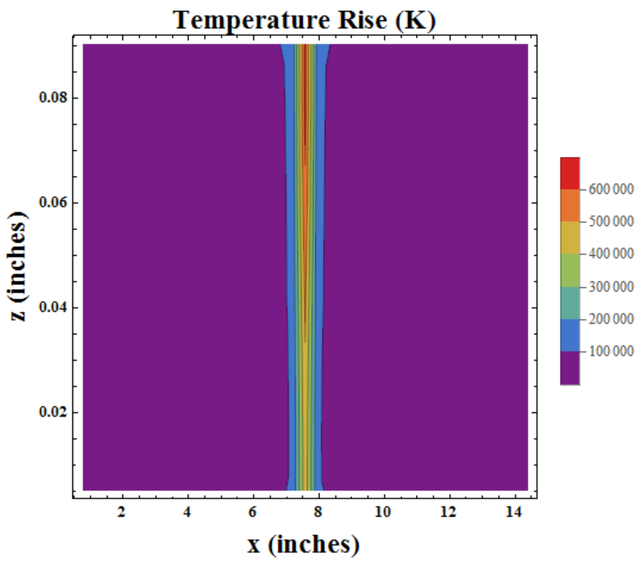

Figure 6: Cross sectional view of the composite surface heating. The view is centered in the middle of the x axis.

5 Conclusions and Outlook

We have presented a new simulation platform for investigating thermal DE of lightning. The new platform, EMA3D/Elmer, combines the comprehensive E3 software capabilities of EMA3D with the open-source, user-friendly multi-physics package of Elmer.

We applied this new platform to the investigation of thermal heating on a CFC surface subject to lightning component C and presented our results. We found results consistent with intuition: namely, that unprotected CFC is vulnerable to DE damage in a lightning environment. For a 400 Amp component C attachment, we found an expected region of about 1-2 inches will likely have significant damage for the CFC panel analyzed here.

Future investigations will include adding conductive protective layers to the CFC surface and performing full vehicle simulation with target areas for thermal analysis. We believe this latter capability sets EMA3D/Elmer apart as a unique simulation tool in DE analysis. Future investigations will also be extended to consider component A lightning strikes as well. Although the time scale for heat diffusion is quite small during a component A event, the heating source for anisotropic materials is still most accurately handled with a full simulation platform capturing both the electric and thermal dynamics.

6 Acknowledgements

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7 References

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