INITIAL VALIDATION OF GEMACS FOR AIRCRAFT LIGHTNING INTERACTION ANALYSIS

Randy J. Jost
Frank G. Tomko
Air Force Institute of Technology
Department of Electrical and Computer Engineering
Wright-Patterson AFB, Ohio 45433-6583

James L. Hebert
Air Force Wright Aeronautical Laboratories
Wright-Patterson AFB, Ohio 45433

Abstract

Initial validation of an Air Force owned general purpose electromagnetic code, the "General Electromagnetic Model for the Analysis of Complex Systems" (GEMACS), for the analysis of lightning's interaction is presented. Results from this analysis are compared with previous studies performed with a time-domain three-dimensional finite difference code (T3DFD) and with data recorded on a specially instrumented FAA CV-580 aircraft during an actual lightning strike. Results show that GEMACS adequately predicts the electromagnetic interaction of lightning with the aircraft and in some cases provides more information, more efficiently, than the T3DFD code.

Introduction

Lightning presents a formidable threat to present and future air vehicles. Lightning produces two types of effects when it interacts with an aircraft: direct effects and indirect effects. Direct effects include those associated with pitting and burning which can cause loss of structural integrity or catastrophic fuel tank explosions. Indirect effects include those which are electro-magnetically induced such as voltage and current transients on flight critical avionics electrical circuits.

Two general trends in aircraft construction have increased the interest in protection from lightning's indirect effects. The increased use of weight saving composites, which do not offer the inherent shielding protection afforded by all metal aircraft, increases the avenues through which lightning's energy may couple into the aircraft's interior. At the same time, the development of highly critical, low voltage digital electronics, such as digital fly-by-wire flight control systems, has made protection against lightning's indirect effects vital to an aircraft's survivability in a lightning strike.

Increased demands for high performance require that lightning protection be added at the minimum of cost in terms of dollars, weight and maintenance. The most effective time to design in this protection is while the aircraft is still on the drawing board and requires accurate electromagnetic models of the current distributions which develop on the aircraft as a result of a lightning strike. While many models exist and have been used for this purpose, very few have been validated using actual in-flight measured lightning data.

Initial efforts to validate a time-domain three-dimensional finite difference code (T3DFD) were quite successful [1,2] and greatly helped to understand the significance of such parameters as lightning channel orientation and channel physics. The time domain current distributions were converted to the frequency domain by Fast Fourier Transforms (FFT). While successful, this code has several drawbacks, primarily with CPU time requirements and in predicting the low frequency transfer functions for the aircraft/lightning interaction. GEMACS was used to see if similar results could be obtained using a frequency domain, method of moments based analysis.

A wire grid model of the CV-580 aircraft and associated lightning channels was constructed. Predicted segment currents were used to derive aircraft wire grid transfer functions for selected frequencies. The predicted transfer functions were compared to transfer functions derived from in-flight lightning measurements and from T3DFD predictions. The GEMACS analysis provides more information at low frequencies where lightning's energy is highest and also enables the user to calculate selected portions of the frequency response such as at resonance peaks. Because of this increased flexibility, GEMACS gives results that are comparable to T3DFD and does so at a substantial savings in CPU time.

The Analysis of Coupling

Aircraft skin currents caused by lightning strikes induce EM fields on and within the aircraft [2,3,4]. To analyze and understand the EM interaction of lightning with aerospace vehicles, it is necessary to understand how the current and charge induced by lightning are distributed on the vehicle's surfaces [5,6]. This information is used to make predictions of how the induced fields couple into the aircraft through joints, gaps and other apertures. Finally, a knowledge of the fields inside the aircraft is used to analyze the potential vulnerability of the aircraft to the electromagnetic threat.

One method used to simplify the complicated EM analysis consists of dividing the interaction process into external and internal interactions [7,8]. The external interaction consists of the lightning's current and voltage distributions on the aircraft's surface. The internal interaction consists of the coupling, penetration and propagation of this energy into the internal system circuits. Theoretically, these two
processes are not independent, especially when apertures are electrically larger than the wavelength of the EM threat [5, 8]. However, when the mutual coupling between the processes is weak, the internal components do not affect the external charge and current distributions. In these cases, the analysis is greatly simplified by decoupling the external and internal processes.

**T3DFD**

In an earlier study, a T3DFD program was implemented for the analysis of lightning's EM interaction with a CV-580 aircraft [2]. The time-domain results were transformed into the frequency domain to compare T3DFD predicted surface currents to in-flight lightning measurements. During this and a subsequent investigation using a similar time-domain finite difference code [1] it was found that these codes are able to accurately predict lightning's current distributions on the aircraft. However, these codes require substantial CPU times as they must calculate six separate time varying field quantities each time step at many points within a decentralizing grid. The grid used to model the CV-580 had 90,000 points and the time steps were less than one nanosecond. The time step size was limited to one-half of the time necessary for the energy to travel the shortest distance between two grid points. The solution for the time-domain formulation was found to remain stable for approximately 3000 time steps and accurately predicted the lightning's interaction for approximately 3 micro seconds. GEMACS was then used to see if similar accuracy could be obtained while gaining benefits such as increased flexibility in geometry input and the solution only of regions of interest at a saving in CPU time.

**GEMACS**

The program General Electromagnetic Model for the Analysis of Complex Systems (GEMACS) is a general purpose code for modeling structures and calculating electromagnetic quantities associated with the interaction of electromagnetic fields with the modeled body [9, 10]. Unlike many other codes, it is suitable for analyzing many types of electromagnetic problems. These problems include radar cross section calculations, EMI/RFI problems, or in this case, lightning interaction with an aircraft.

While T3DFD is a time-domain code, GEMACS is a frequency-domain code. GEMACS consists of a series of modules which may be called up individually or sequentially. These modules include a method of moments (MOM) and a geometrical theory of diffraction (GTD) implementation. Other modules of the program include a geometry processor for constructing the object of interest, and a banded matrix iteration (BMI) technique for speeding up calculations involving large matrices. In addition, the MOM and GTD modules can be combined to run a hybrid solution to the problem. Finally, several other modules perform system functions, such as tracking CPU time used or outputting results. Planned upgrades include modification of the program to handle cavities and the implementation of a finite difference module.

For this problem, GEMACS was used to predict the current distribution on the surface of a CV-580 aircraft. The predicted segment currents were used to derive wire grid transfer functions which were then compared to actual aircraft transfer functions. The normalization process consisted of dividing the predicted current response by the entry segment current for a given frequency in the same manner as was performed during the T3DFD analysis.

During the modeling process, there were two major modeling considerations. First, the structure of the aircraft had to be accurately modeled. Second, the lightning channel had to be modeled with sufficient detail to represent the situation measured in the actual airborne event.

To address the first concern, care was taken to insure that the geometrical representation of the aircraft resulted in a stable electromagnetic description of the problem according to the rules outlined in the GEMACS manuals. The resultant structure consisted of 161 segments, joined at 74 points, with a maximum segment length of 6 meters.

The lightning channel was modeled as two long wires, 20 times longer than the longest dimension of the CV-580, in orientations identical to that photographically recorded during the lightning strike to the CV-580 and identical to that used during the T3DFD analysis. The channel approaches the aircraft from directly above the right wing tip and exits out the left wing tip towards the rear of the aircraft. The channel was terminated into an infinite ground plane, representing the earth, located at z = 0. The segment representing the top of the lightning channel was excited with a delta-gap voltage source of 1.0 volt. The segment where the channel entered the aircraft was recorded and used with the responses on selected segments to form transfer functions.

After the modeling process was completed, the resultant system consisted of 384 wire segments. Figure 1. shows the modeled structure and environment with selected segments which best represented the actual aircraft skin current sensor locations. The acronyms AP, FF, LW, and RW refer to sensors located on the aft fuselage, forward fuselage, left wing, and right wing respectively. The program was operated for a total of ten frequencies, from 0.5 MHz to 5.0 MHz, in 0.5 MHz increments. A MOM solution technique was used to find the current on the segments of the structure. These currents were then compared with those predicted by the T3DFD program and measured during the CV-580 airborne program.

Many observations can be made by inspecting the resulting transfer functions graphed in Figure 2. In all cases, natural half-wavelength resonances due purely to the aircraft dimensions were noted. The lengths of various aircraft wire grid dimensions were responsible for many of the half-wavelength
resonant spikes found in the transfer functions.

The AF and FF transfer functions both have resonances at 3.5 MHz, which corresponds to a half-wavelength of 1688 inches or very close to the combination of the fuselage and aft stabilizers' lengths. The RW transfer function, exhibits a resonance at 4.5 MHz, equal to a half-wavelength of 1312 inches or about 36 inches (approximately 3%) short of the wing span.

The four transfer functions also yield other resonances at lower frequencies which probably do not relate to natural aircraft half-wavelengths. Predicted transfer function spikes at frequencies of 1.0 MHz to 2.5 MHz are due to a variety of reasons. The AF transfer function has many prominent peaks which are likely a result of mutual coupling phenomena taking place between the aft fuselage and the exiting lightning channel.

The large spike found on the RW and LW transfer functions is not a result of mutual coupling, but rather illustrates a different phenomenon. The right and left wing are in the direct line of entering and exiting energy. As such, near DC, at the relatively low frequency of 1.0 MHz, the current flows in a more direct path and the result approaches a static current distribution. In other words, the aircraft wings' current response more closely resembles the input current surge. The noticeable similarity between the RW and LW transfer functions is a direct result of the symmetry inherent to the winged portion of the aircraft wire grid model.

**Airborne Data**

During 1984 and 1985, a CV-580 aircraft was supplied by the FAA and instrumented by AFVAL/FIESL, and the electromagnetic fields and skin current distributions on the aircraft due to direct lightning attachments were measured and recorded [6,11]. Lightning currents were measured at the base of booms equipped with current shunts installed at the wing tips. The shunts were oriented to produce a negative polarity waveform when conventional current flowed onto the aircraft. Time-domain skin current distributions were measured on the CV-580 for 50 lightning strikes. The current distributions were measured by four Multi-Gap Loop (MGL) derivative magnetic field sensors which were located under each wing between the engine and the fuselage, on the top forward fuselage, and on the top aft fuselage. Fast Fourier Transforms (FFT) were applied to the airborne data to derive aircraft frequency-domain transfer functions.

**Comparison of Results**

**GEMACS vs. Airborne.**

The predicted versus actual transfer function comparisons were qualitative in nature. That is, only shapes of the curves and locations of resonances were compared with no regard to peak magnitudes. The GEMACS predictions closely resembled the actual data for one of the transfer functions. In other cases, many of the actual aircraft transfer function spikes were not evident in the predicted aircraft transfer functions. Figure 3 shows the actual and predicted transfer functions side-by-side for easy comparisons.

The predicted AF transfer function was an excellent representation of the actual aft fuselage transfer function, while all other predictions were adequate representations. The GEMACS AF transfer function and the actual AF waveform show resonances at 1.5 MHz, 2.5 MHz, 3.5 MHz, and 5 MHz. However, the actual AF waveform shows additional spikes at frequencies not used in this analysis. The GEMACS AF transfer function closely resembles a skewed version of the actual AF waveform in that a prominent spike is not observed on the actual AF waveform occurs at 4.5 MHz. The spikes found on the GEMACS LM and RW transfer functions are also observed on the actual LM and RW transfer functions. However, many more resonances exist on the actual RW and LM waveforms.

The differences found in the predicted and actual transfer functions may be attributed to three different aspects of the modeling employed in this analysis. First, the 162 segment aircraft wire grid model allowed the AF and FF transfer functions to be more representative of the actual waveforms than the RW and LW predictions. Of the total 161 segments, only 40 segments were used to grid both wings and engine mounts, leaving 141 segments for the remaining portion of the aircraft. Of these 141 segments, 130 wire grid segments represent the fuselage. As such, this portion of the wire grid model more closely resembles the actual aircraft fuselage. Had more segments been used to model the aircraft wings, the RW and LW transfer functions would probably have yielded more information.

Second, although the analysis frequency bandwidth was justified, additional frequencies in the bandwidth would have provided more transfer function resonances at higher frequencies, as suggested by the actual waveforms.

Third, the aircraft/lightning channel was assumed to be perfectly conducting and modeled as such. GEMACS offers the user the option of loading some or all of the segments and to choose the conductivities of those loads. Although this feature was not used in this effort, the addition of resistive, inductive, or capacitive loadings on the wire segments would have influenced the predicted transfer functions to show a more complex interaction between the channel and aircraft. These additional predicted resonances may account for the additional resonances found in the aircraft transfer functions. Overall, the predicted waveforms were adequate representations of the actual waveforms, given the constraints explained above.

**GEMACS vs. T3DFD.**

Figure 4 shows typical results obtained from the T3DFD program as well as the process employed to yield the transfer function of the lightning data. When the FFT of these
responses was taken and divided by the frequency-domain transformed input they produced transfer functions which provided very little information at low frequencies.

The GEMACS predicted FF transfer function was compared to the FF transfer function generated from the results of the T3DFD analysis. As can be seen in Figure 5, the GEMACS predicted waveform resembles the T3DFD predicted waveform in the frequency region 2 MHz to 5 MHz. The frequency-domain transform of the T3DFD data is relatively meaningless below 2 MHz due to the finite number of time-domain sampled points. For this reason, GEMACS not only predicts aircraft resonances as well as the T3DFD program, but also provides more information at lower frequencies.

A rough comparative measure of the two programs' relative efficiencies can be made based on the amount of CPU time the programs required to execute. The GEMACS program on the VAX 11/780 computer took about 9 hours and 55 minutes. The T3DFD program was run on a CDC Cyber 845 computer, which is about 1.5 times faster than the VAX. The CPU time required for one pass through the program was about 1 hour and 12 minutes. Twenty passes were needed to compute the required time-domain fields bringing the total CPU run time to about 24 hours and 7 minutes, not including the time required to convert the results to the frequency domain. Had this program been run on the VAX, the execution time would have been extended to about 36 hours. The CPU time reduction afforded by GEMACS is over 26 hours. However, it should be noted that if the GEMACS analysis had been extended to 20 MHz, the run times would have been comparable.

In terms of CPU time alone, the two programs are comparable. However, it is necessary to run the entire T3DFD program to obtain usable results. If we suspect that there are regions of interest, in terms of resonant frequencies, GEMACS allows us to solve only for those discrete portions of the frequency range of interest. This significant reduction in program execution time for selected frequency ranges demonstrates the potential benefits of the use of GEMACS in this type of application.

Conclusions

Like most research, for every question answered, five more questions are raised. However, many conclusions can be drawn from the efforts presented here. Among the many conclusions, the following stand out. First, the GEMACS code has more inherent flexibility and is easier to use. Its geometry input processor was much easier to use than the more heuristic method of entering the geometry for the T3DFD code.

It was hoped that the resonant frequencies in the aircraft transfer function would correspond to half-wavelengths equal to aircraft lengths and combinations of aircraft lengths. This was borne out by checking the calculated results with the dimensions of the aircraft. The predicted transfer functions adequately represent the actual aircraft transfer functions at most of the frequencies in the 0.5 MHz to 5.0 MHz bandwidth. The prominent peak magnitudes found in the actual aircraft transfer functions occur at frequencies related to the dimensions and combinations of the aircraft. The derived transfer functions show resonant frequencies that correspond to half-wavelengths equal to aircraft lengths and combinations of length.

Analysis of diffusion and coupling through apertures and joints has traditionally been done in the frequency domain. In using time domain codes, it is common to convert the results back to the frequency domain for analysis. The use of frequency domain codes allows the elimination of a step that potentially adds to error in the result.

The lightning/aircraft electromagnetic problem must be well-posed. Actual lightning channel entry and exit orientations strongly affect the overall interaction. With some orientations, mutual coupling between the channel and the aircraft may be possible. Plotted lightning channel current distributions at 5 MHz show that the periodic nature of the distributions is related to the length of the corresponding lightning channel model. The termination of the exiting lightning channel will also affect the validity of the results.

Some areas of follow on work include a more detailed investigation of channel modeling in GEMACS, and methods of increasing the accuracy of the results while maintaining the speed and flexibility advantages over time-domain codes.

GEMACS is a powerful, system independent, well documented, and readily available general purpose electromagnetic code. It has been demonstrated to be a useful and valid tool for lightning interaction analysis. It produces results that are comparable to codes that are more expensive to run, while demonstrating much greater flexibility and ease of use. GEMACS is a continually evolving code which is being enhanced to solve other EM problems including the external to internal coupling problem.

References

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Figure 1. Selected segments of interest.
Figure 2. Actual aircraft transfer functions.
Figure 3. Actual and GEMACS predicted transfer functions.
A. T3DFD Code Model of the CV580 Aircraft

B. Source Waveform for T3DFD Code Application

C. Response at the Forward Fuselage Surface Current Sensor to the Source in B

D. FFT of Response in C

E. Log-Log Plot of Transfer Function When Response in C is Divided by Source in B

F. Linear Plot of E from 97 kHz to 25 MHz

Figure 4. T3DFD generated results.
Figure 5. GEMACS and T3DFD Predicted Transfer Functions