Validation of Numerical Simulation Approach for Lightning Transient Analysis of a Transport Category Aircraft

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1 Abstract

Lightning strikes to aircraft can cause physical damage to structures and components, but the lightning currents can also couple to electronics cables potentially upsetting or damaging critical electronics systems. Because the coupling of lightning currents to system electronics cables and boxes does not usually cause direct physical damage, it is known as indirect effects of lightning (IEL). The certification requirements of 14 CFR 25.1316, for electrical and electronic system lightning protection, ensure transport category aircraft electronic systems can function appropriately, depending on criticality, through the expected lightning environments for that system. One of the critical steps in the certification process is determining the lightning transient environment that will appear at equipment interface circuits for all identified systems requiring lightning assessment. The certification guidance material in AC 20-136B [1] identifies EM simulation as a possible means to establish the aircraft lightning transient environment. Complex analyses using computational electromagnetics (CEM) simulation software can determine aircraft actual transient levels (ATLs) in a manner that is similar to traditional full vehicle lightning transient analysis (LTA) tests. This paper reviews certification guidelines and presents a computer simulation approach to determine ATLs for a transport category airplane. The simulation ATL results were compared to the measured results from a traditional full vehicle LTA test to validate the simulation results. A proposed method for margin development is presented as well as an argument to evaluate the overall uncertainty in the verification process based on a combination of aircraft test and analysis.

2 Guidance Material Review

When certifying aircraft electronics to lightning indirect effects, AC 20-136B provides guidance about how aircraft manufacturers can comply with 14 CFR 25.1316. There are seven primary steps to be performed when evaluating IEL transient effects on aircraft electronics equipment [1]:

1. Identify the systems to be assessed.
2. Determine the lightning strike zones for the aircraft.
3. Establish the aircraft lightning environment for each zone.
4. **Determine the lightning transient environment associated with the systems.**
5. **Establish equipment transient design levels (ETDLs) and aircraft actual transient levels (ATLs).**
6. Verify compliance to the requirements.
7. Take corrective measures, if needed.

Steps four and five are highlighted above because they are the primary topics of this paper. The AC identifies the lightning environment for this assessment to be voltages and currents produced by lightning current flowing through the aircraft. These voltages and currents at electronic interfaces result from aperture coupling, structural voltages or conducted currents resulting from direct attachments to equipment and sensors. The lightning ATLs, waveforms and amplitudes, that appear at electronic equipment interfaces for all appropriate systems should be determined. The three primary techniques for determining ATLs are by testing, analysis or similarity arguments. When using complex numerical simulation tools to determine aircraft ATLs, the user should reference ARP 5415A [2]. For analysis used to determine aircraft transients, a typical analysis plan is provided and includes the following steps:

a. The analysis technique(s) proposed,
b. Key analytical model input data required,
c. Source of the model input data,
d. Validation approach for the model,
e. Validation approach for the analysis technique,
f. Sensitivity of the model and technique to input variations, and
g. TCL, ATL and ETDL margins required to account for model sensitivity and input variations.

The focus of this paper is on steps of the analysis approach, validation of the model and the margin development.

3 Analysis Technique

The aircraft model simulations were performed using a full wave finite-difference time-domain (FDTD) code with an integrated multi-conductor transmission line (TL) algorithm. The simulation software, EMA3D with integrated MHARNESS, uses an analytical approach recognized in ARP5415 and the Lightning Protection of Aircraft Handbook [3] for performing lightning simulations on aircraft. There is a long validation history within the aerospace industry for when using this analysis approach to determine aircraft level lightning response [4-9].

Most state of the art CEM software today utilize various speedup techniques to complete simulations with greater efficiency. All simulations were completed using parallel processing on cluster computers to greatly speed up computation time. Another speedup technique applicable to quasi-magnetostatic problems such as lightning was utilized. The magnetostatic time step (or gradual permittivity scaling formalism) is a standard feature of EMA3D [10] that can increase the permittivity throughout the problem space once the higher frequency content of the lightning pulse has exhausted; thereby allowing an increased time stepping for the problem. Increasing the FDTD step time can greatly reduce the total number of steps needed to complete a simulation.

4 Aircraft Model Development

The development process of the CEM model involves many details to represent the EM aspects of a full aircraft design. A high-level review of the model, development steps, assumptions and rationale are covered in this section. The EMA3D model developed for this validation effort was created to match the test configuration of the transport category airplane being investigated. The full CEM model with return conductor system (RCS) is represented in Figure 1. The model did not contain the RH wing to increase computational efficiency. The full vehicle test configuration, described in section 5, did not include an RCS or measurements in the RH wing. In this regard, the model reflects the test approach.

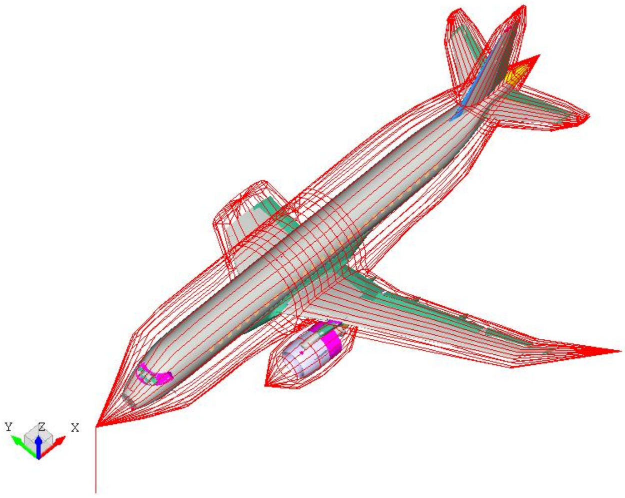

Figure 1: Full aircraft model with RCS as implemented during testing

Key Model Inputs and Source of Inputs

It is important that all numerical models are based on the actual aircraft design. The goal of CEM analysis is to capture the pertinent electromagnetic responses of a model related to aircraft resistances, inductances and capacitances. Using appropriate material assignments within the model captures the resistive portion of the EM effects.

Starting with the 3D solid body manufacturing CAD ensures model components will have accurate dimensions, shapes and locations of the aircraft being modeled which relate to the inductive and capacitive electromagnetic (EM) behavior. Furthermore, using imported CAD data allows the components of the simulation model to be directly linked to the actual aircraft design, which is useful when justifying the traceability of model inputs in the certification process.

The mesh generation approach for this effort uses surface mesh representations of the aircraft components with a 4 cm cubic cell size. This cell size allows for adequate resolution of geometrical details with acceptable computational efficiency. Although the final CAD geometry used for CEM models is derived from manufacturing CAD models but there are some very distinct differences between the two types of CAD geometries. The CEM development process requires that assumptions are made about the geometry and material properties. Some of the significant differences between manufacturing CAD and CEM CAD geometries are described in Table 1.

Table 1: Manufacturing CAD vs. CEM CAD

3D Manufacturing CAD	3D CAD for CEM
Includes all components in the design, even tiny washers, brackets and shims.	Excludes brackets and other small components that do not significantly impact EM coupling.
Components have very complex shapes, curvatures, cut-outs, and flanged sections for part definition.	Use representations of a component's shape and volume, like single meshed surfaces or lines.
Structural joints in manufacturing CAD involve overlapping components connected by fasteners, bolts, rivets, etc.	CEM CAD will link two joined components with a seam that controls the impedance between components.
Harnesses are routed as empty volumetric tubes.	Single lines used to rout cables in 3D geometry.

All of the modeling techniques listed above have been proven effective at improving modeling efficiency while still being able to capture the pertinent EM effects for lightning interaction problems. An example showing the full 3D manufacturing CAD vs. CEM representation of a fuselage section with frames is shown in Figure 2.

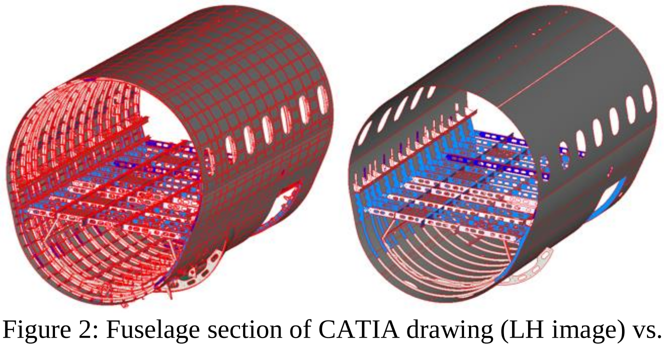

Figure 2: Fuselage section of CATIA drawing (LH image) vs. the CEM model CAD showing component simplification (RH image).

Material Property Selection

An essential step to using CEM simulations as part of a certification program is to quantify all material properties and interfaces in the presence of lightning transients. Many of the metallic materials used on aircraft have well established electrical properties that can be identified in specification sheets. However, it may be necessary to perform a material property measurement program to identify key EM properties associated with composite materials and contact resistances associated with critical aircraft structural joints.

The aircraft parameters in this model are primarily aluminium with composite belly fairing, flooring, flaps, spoilers, ailerons, elevators and rudders. A detailed list of aircraft model components, material properties and assumptions are recorded in the model tracking document. When using a surface mesh technique for FDTD lightning simulations, it is common to implement a low frequency modeling approach where the conductivities of model cells are adjusted based on the actual thickness of the component being modelled. This conductivity adjustment is used in this model and is represented in equation ,1 where σ is conductivity in S/m and t is the thickness.

$$(1) \quad \sigma_{model} = \sigma_{actual} \cdot \frac{t_{actual}}{t_{model}}$$

Harness Modelling

Many simulation techniques exist to evaluate aircraft lightning coupling characteristics. Some of these approaches rely on simplified analysis to estimate cable transients [11,12] or determine the electromagnetic fields where cables exist and drive a separate numerical harness model with the 3D levels [13]. Sub-modeling approaches are particularly useful early in a design process or for deeper problem understanding and can serve a valuable purpose. However, when trying to determine ATLs on complex cables that route through multiple regions of the aircraft and interact with cables coming from other exposed regions, the authors have found it necessary to include many aspects of the cable routing and branches in the model. This model utilizes complex harness definitions with cable sections that route through multiple regions of the aircraft. This type of full vehicle, complex harness representation has been implemented on other aircraft certification programs [14,15] and is becoming more commonplace in today's analysis driven approach to compliance.

The wire harness bundles were modeled using the software integrated transmission line solver, MHARNESS. This feature allows the discretization and connectivity of individual conductors in a bundle to be resolved within the FDTD problem space. Although the exact position of certain cables is typically not controlled in the harness assembly, the routing and spatial positioning of each wire in the model can reproduce the aircraft cables with acceptable approximations. Termination resistances and transfer impedances for the connectors to electronic boxes are also considered in the MHARNESS definition.

The full aircraft model with harness representation is shown in Figure 3. The exterior surfaces of this images have been shaded to show the black lines representing the harness routing.

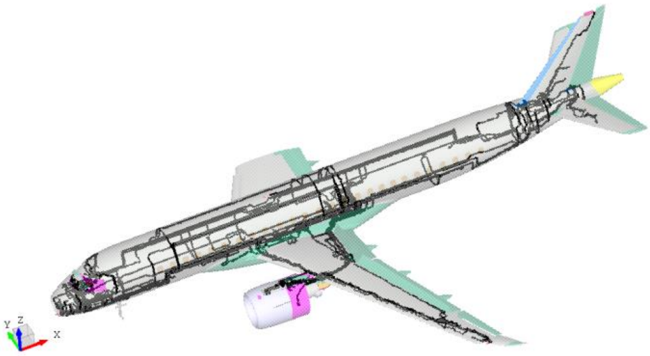

Figure 3. Transport category aircraft CEM model developed for lightning ATL simulations. Exterior surfaces are shaded to show interior cable routing.

This simulation model included all the necessary wires and harnessing assessed for the full vehicle test campaign. The process of collecting all cable routing, box connectivity, wire types and shielding levels is slow, but straight forward. The primary means to collect and implement the harness details involved 3D routing CAD, wiring diagrams and box connectivity spreadsheets, as show in Figure 4. The box connectivity is built up cable by cable and harness segments become packed with many conductors as shown in Figure 5.

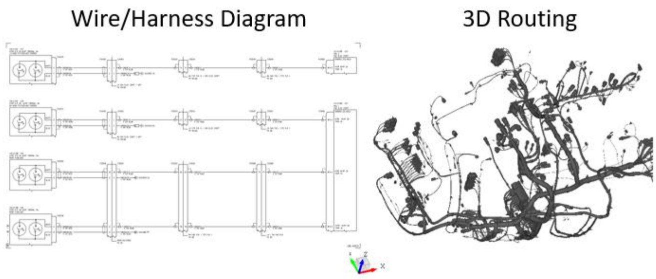

Figure 4: Traditional wire harness diagram and 3D cable routing model that provide the information needed for EMA3D model development.

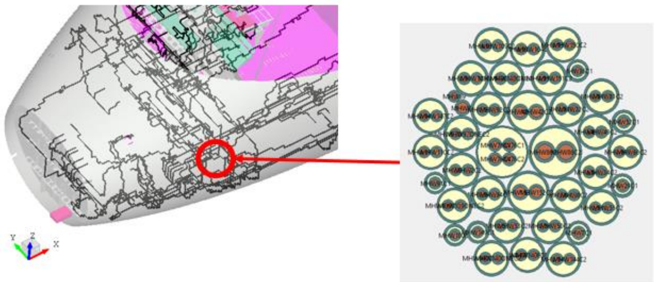

Figure 5: Cable packing example configuration for forward electronics bay harness.

5 Full Aircraft Lightning Tests

Traditional full aircraft LTA tests were performed on a transport category aircraft to establish ATLs and ETDLs. The wires selected for measurement were representative of regions of the aircraft including cockpit, avionics bays, engine, wing, landing gear, fuel systems and empennage sections. The focus was on flight critical and essential equipment but cables routing to all aircraft regions were investigated. Considerations for each line replaceable unit (LRU), wire type, routing, length and exposure to electromagnetic environment were also used during the measurement selection process. The general methodology for selecting electronics pins for measurement is shown in Figure 6. In addition to Level A systems, some Level B systems with wiring exposed to severe electromagnetic environments were also considered. The list of pins selected for measurement, resulting from the flowchart below, was reduced to a feasible quantity for test by a similarity analysis.

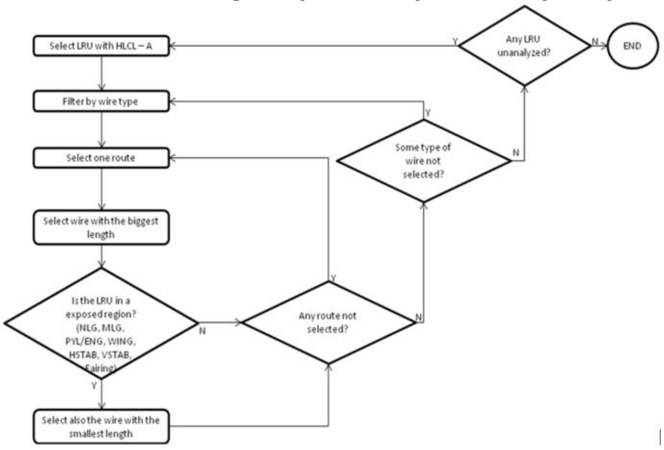

Figure 6: Pin measurement selection methodology

This aircraft is nearly symmetric in for all equipment and wiring in the wings and empennage. Therefore, only wiring from the LH wing and LH empennage is considered, and not the RH sides. The test return array was configured to exclude the RH side of the aircraft as shown in Figure 7.

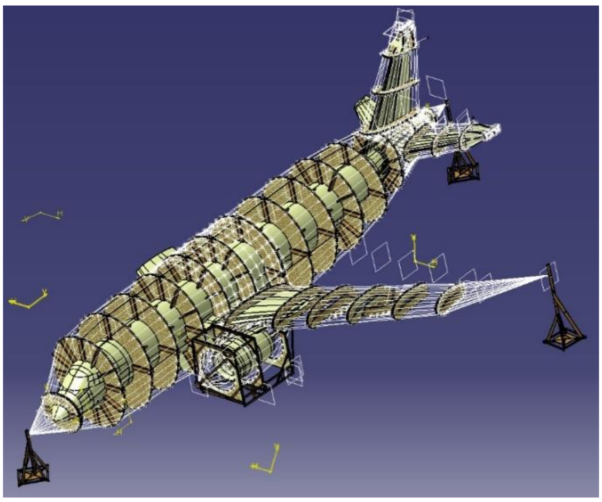

Figure 7: RCS developed for full vehicle testing that excludes RH wing and horizontal stabilizer because of symmetry.

6 Simulation and Validation Results

Three attach/detach cases from the full vehicle LTA testing were selected for simulation validation. These cases concentrate maximum currents in high coupling aircraft regions that are commonly the most severe for ATL determination. These simulation configurations included:

1. Nose attach – LH horizontal stabilizer detach
2. Nose attach – LH Wingtip detach
3. Nose attach – Engine exhaust detach

While many measurements were taken in the engine, wing and stabilizer regions associated with the detachments, other measurements on cables spanning the forward avionics bay, cockpit, mid avionics bay, LG bays, control surfaces and tail region were included in the measurements. All major aircraft regions containing level A systems were considered as part of the measurements for validation. All the simulations presented here used an injection source of idealized lightning waveform Component A from ARP 5412B [16].

A critical step in this analysis approach is to demonstrate the ability of the simulation model to accurately reproduce the lightning coupling results for the aircraft in question. A validation effort comparing simulation and experimental results is traditionally used to establish acceptable margins for all simulation results. There is not one single accepted approach for validating simulated lightning coupling results, but several approaches have been successfully used. A correlation technique that compares peak values and a qualitative waveform inspection has been successfully utilized in lightning simulation projects for indirect effects certification programs [8].

For this ATL analysis open circuit pin voltages (V_{OC}), short circuit pin currents (I_{SC}) and bundle currents (I_{BC}), were measured and simulated. Typical comparisons for ATLs are provided Figures 8-11.

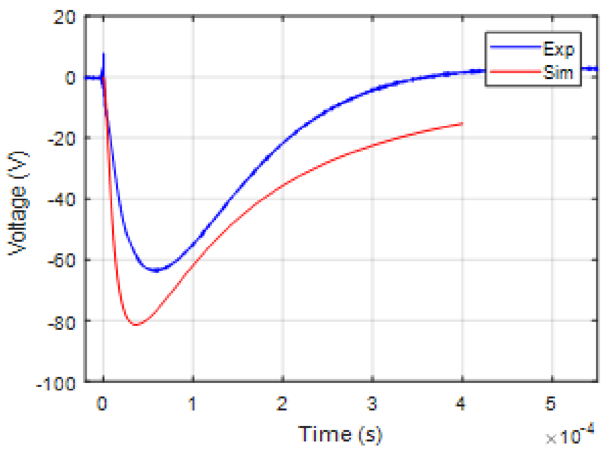

Figure 8: Example open circuit pin voltage, V_{OC}, measurement comparison.

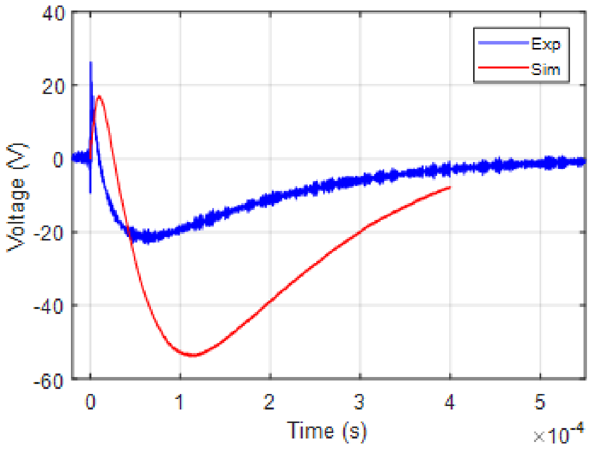

Figure 9: Sample open circuit pin voltage, V_{OC}, measurement comparison.

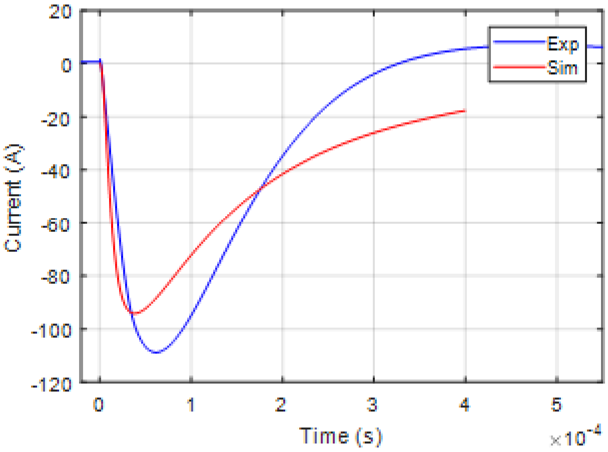

Figure 10: Sample short circuit pin current, I_{SC}, measurement comparison.

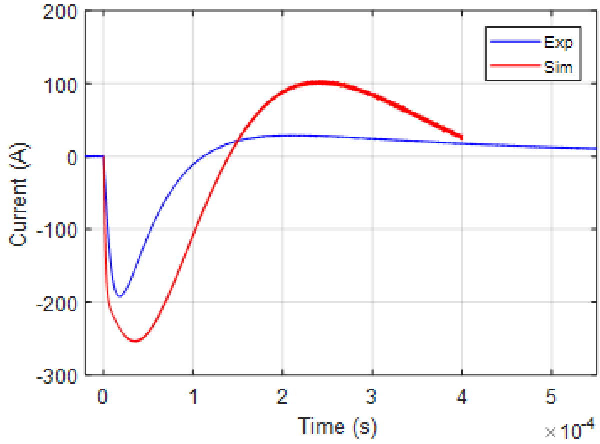

Figure 11: Sample bundle current, I_{BC}, measurement comparison.

Generally, the test data is not analyzed to provide physical explanations for the waveforms found during the campaign, which are considered as a worst case for the ETDL levels definition. However, for a validation effort it is essential to understand if the transient is the true aircraft response to lightning or due to some test artefact or simplification. To not penalize the validation effort, all test data that could not be justified by physics were excluded from the comparison. It is critical during the validation effort that both types of results are used to augment each other and help the designers achieve the full lighting coupling response needed for certification.

Amplitude Margin Development Approach

A detailed review of simulation and test results indicates that both methods give highly comparable transient amplitudes across wide amplitude ranges of ATL measurements. Peak value comparison plots were created, and it is shown in the comparative scatter plots below, Figures 12-14, that the simulation results are within 6 dB or are more severe than the test results for all measurements. It was also observed that transients at higher amplitudes tend to have closer correlation between the measured and simulated results. When establishing margin levels, it is reasonable to expect different levels of correlation depending on magnitude, coupling mechanism and component complexity. Lower amplitude correlations typically have greater number of variables contributing to the response in less severe EM regions. It is reasonable to have enveloping levels or higher margins applied to the lower transients without much concern for equipment risk. A similar approach using variable or sliding-scale margins has been implemented on other certification programs using validated simulations [17].

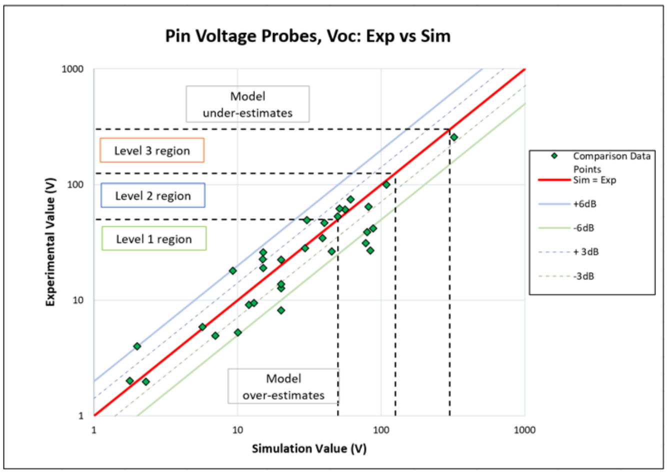

Figure 12: Scatter plot comparisons for pin voltage measurements, V_{OC}

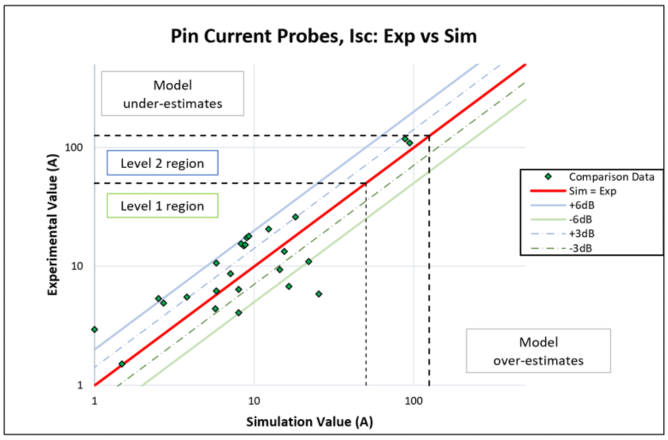

Figure 13: Scatter plot comparisons for short circuit current measurements, I_{SC}

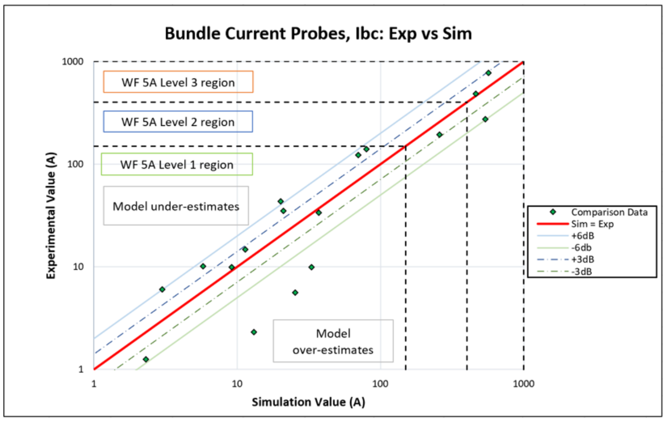

Figure 14: Scatter plot comparisons for bundle current measurements, I_{BC}

Some reviewers of simulation margin development believe multiple aspects of uncertainty should be included in the development process. When applying margins to ATLs to set ETDLs, the uncertainty associated with the method for determining ATLs is directly related to the margin in this sense. One of the typical margins may be a validation margin, M_{VAL}, that quantifies how well the analysis technique and specific model can match test results. Another margin may be expected to capture other uncertainties that aren't quantifiable from the validation effort. This second margin is related to the standard uncertainty that is typically applied to test results and will be referred to as M_{UNC}. A reasonable way to combine these types of uncertainty is to establish an overall margin that considers both aspects of uncertainty. The total margin, M_{TOT}, may be computed in a quadrature fashion as shown in equation 2.

$$(2) \qquad M_{TOT} = \sqrt{{M_{VAL}}^2 + {M_{Unc}}^2}$$

AC 20-136B paragraph (8)(i), Verify Compliance to the Requirements, discusses how margins account for uncertainties in the verification method. It also suggests that as confidence in the verification method increases, the margin can decrease. In this process, two methods were pursued for establishing aircraft ATLs, one by traditional full aircraft testing and one by full aircraft numerical simulation. The results of the validation effort provide greater confidence that each method provides an accurate response, and thereby lowers the standard uncertainty associated with each approach by itself. Therefore, a margin that is lower than the standard 6 dB may be considered for the standard uncertainty value, M_{UNC}.

Waveform Validation

In addition to amplitude comparison, some evaluation about the transient waveforms is required. Whether using full vehicle testing or simulations, all the ATL results are converted to DO-160 levels and waveforms for verification testing according to Section 22 [18]. There are 5 short circuit and bundle current waveforms: 1, 3, 5A, 5B or 6. Open circuit voltages have 6 options including: 2, 3, 4, 5A, 5B or 6. Sometimes, ATLs will be composite waveforms that have multiple coupling mechanisms contributing to the overall waveform. In this case, it is common to specify multiple amplitudes and waveforms for verification testing.

It is clear from visual inspection and comparison of peak times that the simulation and measurement results translate to nearly identical waveform specification according to DO-160. For this reason, no quantitative assessment of waveform validation is required or provided. If real doubts exist about the waveforms determined by simulation LTA analysis, worst-case levels of WF1 and WF5 at the appropriate amplitude could be specified for DO-160 verification testing. Any issues with verification testing according to these waveforms could be explored with refined analysis as needed.

Separation of Slow-rise and Oscillatory Waveforms

All of the validation and margin discussion in this section was for slower waveform transients of the WF1, WF2, WF4 and WF5A/B variety. Details were not be provided about oscillatory or noisy waveforms that were determined for unshielded cable voltage measurements. Some unjustifiable qualities of amplitude and frequency, when compared to expected aircraft resonances, were observed in test results when performing data comparisons. The authors believe there may be some real advantages to using simulated results for WF3 definition.

Model Tuning to Match Testing

Refinement of the model was required to match test results for some specific measurements. However, nearly all of the simulation results have comparable magnitude levels and waveshapes to the test results after the first round of simulations. The initial simulation results give similar levels and waveforms to LTA test results. The amplitudes are on the same order of magnitude and waveshapes have similar peaks and duration. Being able to produce simulation results that compare well to test results after the first iteration of simulations gives confidence in modeling technique and parameter inputs.

The majority of model changes implemented after the first round of simulations were made to match experimental configurations. The original model and first round of simulation was developed to match the final design configuration of the aircraft. The types of changes that were required to tune the model to match test results were related to aircraft adjustments made for testing that included:

- Adjust RCS
- Adjust damping resistors placed between aircraft and RCS at detach locations
- Panel and equipment bay modifications that were required to incorporate test equipment
- Breakout cable configurations to make pin current and voltage measurements
- Additional shielding added to cables in severe EM regions

Comments on Margin Development

When comparing simulation and test results it is important not to develop an experimental bias and understand that test results can be wrong or misinterpreted. Neither testing nor simulation should be considered to provide the absolute truth in aircraft lightning response, which is why margin, or uncertainties are applied to the results. Both methods are good engineering approaches to understand complex aircraft lightning interactions. The guidance material suggests that margins should also be developed for test results, but this is rarely done in practice. If lightning test results look reasonable, a standard margin value of 6 dB (factor of 2) is applied to all results. Some references suggest that results from Swept Frequency Testing method and Pulse Test method may be within +/-3db correlation [19], [20]. It is the authors' opinion that simulation results, once validated, will provide an appropriate electromagnetic response that can be directly referenced without the need for complex margin development, which could unnecessarily penalize the verification process. Simulation and test results will require waveform and level grouping to derive requirements for standardized bench test according to RTCA DO-160, which typically adds additional margin.

Test results for LTA determination can be wrong or misleading. Aircraft manufacturers and authorities should review the test results and establish a certain confidence in the results to define the aircraft lightning transient environment. If some test results are questionable, there may be a need to retest or perform some additional analysis to determine the "correct" response of the aircraft in the questionable areas. In the authors' experience, a margin level of 6 dB for test results is accepted without significant explanation. Similarly, all simulation results should be reviewed for quality and questionable results should be further investigated. Some combination of analysis and similarity (or comparison to other known levels) can reasonably be expected to be as reliable as a single LTA test program on a single test flight aircraft model. The authors are not suggesting that additional testing, multiple aircraft by multiple test houses, is required to better establish the aircraft lightning environment. Rather, with the modelling ability and industry experience that exists today, analytical approaches can be viewed as favorably as full vehicle testing if the method and results are justifiable.

There is a real economic and practical justification to ease the burden of simulation validation and margin development. If reasonable justification and engineering judgement can provide evidence that simulated ATLs are similar to those acquired from testing, simulations alone will give a legitimate answer to the actual aircraft lightning environment definition. There is no present quantitative margin development approach for lightning transient phenomena provided in industry standards. The confidence level is left up to the OEM and ACO to agree on an approach. Because there is no established criteria for simulation validation margins, each authority has a different experience, or expectation of what is required for margin development and what final margins should be. Once simulation results can qualitatively be shown to provide similar results as test methods, magnitudes on the same order and generally similar waveforms, a standard 6 dB margin should be accepted by industry.

Just as no test result should be accepted without understanding the EM coupling mechanisms involved, the sensibility of all simulation results should be evaluated. However, there are some real advantages of using simulation over testing:

- Simulation can capture the aircraft in flight configuration
- No RCS, hangar or ground effects
- No adjusting aircraft components to include test equipment
- No interference from test equipment
- No noise from test generator
- No data acquisition limits in time or scope range
- If design changes occur or a faulty test results are identified later in the program, simulation models can efficiently be updated to evaluate the effects

The above points do not necessarily imply that more simulation analysis should be performed than what is required from testing.

If the aircraft is of a new design, establishing ATLs may be more involved than for aircraft that similar designs to previously certified aircraft. Some level of large-scale testing may be valuable. However, the authors believe that the systematic model development approach implemented in this program can be applied to new aircraft without the need for full scale validation. It may be necessary to quantify important material parameters for structural resistivity or joint resistance. This is especially true for new composite materials with lightning strike protection (LSP) or other materials.

7 Conclusions

This paper demonstrates how complex CEM simulation models can be developed and simulated to determine high fidelity transient responses in a transport category aircraft. The simulation results were compared to full vehicle LTA test results to validate the model. Some discussions were provided about margin development. The ATLs determined using EMA3D can be used to support an IEL certification program and to evaluate the lightning response of a complex aircraft electrical system. The simulation approach described in paper is recognized in the guidance material as acceptable analysis method can be applied to many different aircraft and lightning attachment scenarios. Whenever using simulations to support a certification program it is critical that an analysis approach be discussed with the appropriate certifying authorities.

An analysis approach for IEL verification is an attractive possibility to reduce full aircraft lightning testing. Full aircraft LTA tests are expensive to perform and tie up valuable aircraft availability during certification phases when the aircraft could be addressing valuable flight time or other certification activities. Another significant advantage of using simulations for the transient determination is the aircraft can be considered in its natural in-flight configuration that would occur during a lightning event. Whenever LTA tests are performed on aircraft, they are completed with return networks, equipment and test configurations that can alter the natural lightning coupling response of the cables. Simulations can produce transient results that are, in many ways, less perturbed than the test results.

As noted in ARP5415 “The level of confidence required in the modern aerospace industry for system installation design, airframe design, and airworthiness certification cannot be easily accomplished without using analytical methods.” [2]

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