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R. A. Zacharias
C. A. Avale
K. S. Kunz
N. E. Molau
S. T. Pennock
A. J. Poggio
R. M. Sharpe

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A METHODOLOGY FOR ASSESSING HIGH INTENSITY RF EFFECTS IN AIRCRAFT

R.A. Zacharias, C. A. Avalle, K.S. Kunz, N.E. Molau, S.T. Pennock, A.J. Poggio, and R.M. Sharpe

Lawrence Livermore National Laboratory, L-153
Post Office Box 808
Livermore, CA 94550

ABSTRACT

Optical components have an inherent immunity to the electromagnetic interference (EMI) associated with High Intensity Radiated Fields (HIRF). The optical technology embodied in Fly-by-Light (FBL) might therefore minimize the effects of HIRF on digitally controlled systems while providing lifetime immunity to signal EMI. This is one of the primary motivations for developing FBL systems for aircraft. FBL has the potential to greatly simplify EMI certification by enabling technically acceptable laboratory tests of subsystems, as opposed to expensive full airplane tests. In this paper we describe a methodology for assessing EMI effects on FBL aircraft that reduces or potentially eliminates the need for full airplane tests.

This methodology is based on comparing the applied EMI stress -- the level of interference signal that arrives at a unit under test -- versus the EMI strength of the unit -- the interference level it can withstand without upset [1, 2, 3]. This approach allows us to use computer models and/or low power coupling measurements and similarity (to other previously tested aircraft) to determine the stress applied to installed subsystems, and to use benchtop cable injection tests and/or mode stirred chamber radiated tests to determine the strength of the subsystem.

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BACKGROUND

Modern transportation systems are increasingly dependent on sophisticated electronic controls. At the same time, the potential for EMI susceptibility of electronic systems is increasing for several reasons. Modern integrated circuits with higher densities and speed are often more sensitive to EMI transients. Composite material structures may provide poorer EMI shielding. The EMI power in the environment is increasing as more users share the airwaves. Because of these factors, the need to assure the survivability of electronic systems that may be exposed to HIRF has become of great interest. Advisory regulation has recently been drafted for aircraft which would require testing and/or analysis to assure the EMI hardness of critical and essential equipment

ASSESSMENT METHODOLOGY

The HIRF threats exist from the broadcast bands to well up into the microwave region. The frequency spectrum can be

broken into three regions as far as EMI susceptibility analysis is concerned: 1) the low frequency region where the threat wavelength is long with respect to the aircraft and its subsystems; 2) the transition region where the wavelength is about the same as the dimensions of the aircraft and significant points of entry into the airframe; and 3) the high frequency region where the wavelength is small compared to the aircraft and compared to the dimensions of major aperture and wire points of entry. Techniques that work well in the resonant and low frequency regions may not necessarily be useful in the high frequency region. Thus, the appropriate point in the system at which to compare strength against stress (at wires, at boxes, etc.) is a function of frequency.

The Upset Path. A complete methodology for assessing RF effects on aircraft systems must consider the path from the RF source to system upset. Consider the top portion of Figure 1 that examines a simplified path to aircraft system upset. HIRF originates at the source - in this cartoon a ground based transmitter but in general it could be ground or aircraft based. The HIRF illuminates the aircraft with a field or power density whose amplitude depends on source power, antenna gain, and slant range. This incident field then couples into the interior of the airframe. Internal fields then induce currents on interior wire bundles. Voltages are generated at the pins of devices in installed avionics boxes either by the currents on attached cables, or directly from the interior fields by way of aperture coupling into the boxes. If these induced voltages are sufficient, the device is upset, experiencing a change of operating state. The voltage required to cause a change of state is circuit dependent. Device upset may or may not trigger subsystem upset, which in turn may or may not cause system upset, depending upon function and redundancy.

In concept, the most straightforward way to test for upset would be to have the airplane fly the closest approach to a high power source while monitoring aircraft systems for upset. This assessment path is shown at the top of the lower part of Figure 1. However, this is neither safe nor cost effective. There are many tools and techniques available to determine the relationship between threat levels and system upset. Two other paths that employ analysis, modeling, and low power tests, are shown for assessing upset. One path, appropriate for frequencies below about 400 MHz compares cable current stress versus strength at the avionics boxes. The other, appropriate for frequencies above about 400 MHz, compares the field stress applied to avionics boxes determined by measurement and statistical methods against the radiated upset strength of the boxes as measured in a reverberation chamber.

Both of these paths require the relationship between sources and threat level fields and the relationship between

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Figure 1. Upset path for aircraft and three potential assessment paths

subsystem upset and system upset to be defined. The conversion from source power levels to threat fields or power densities has been defined for the commercial aircraft community by the SAE/FAA AE4R committee. This committee surveyed known sources (including classified sources) and used minimum allowable slant ranges to derive a worst case threat spectrum for commercial aircraft. The relationship between subsystem upset and system upset can be defined by making the worst case assumption that any subsystem upset causes a system upset, and is unacceptable.

Given these definitions, system upset can be assessed by the relationship between threat levels and subsystem upset in each frequency region. In the low frequency region where the predominant coupling into subsystems will be through power cables, modeling codes such as TSAR may be used to estimate coupling (stress). We will describe the code and its capability to predict cable currents. The strength measure that corresponds to cable current stress estimates is direct injection tests where the extrapolated threat currents are injected into cables into the subsystems.

In the high frequency region where the wavelength becomes on the order of the size of the equipment or smaller, computer modeling begins to become expensive due to the model complexity and the amount of computer memory and processing time required. Here, the appropriate stress estimates will be based upon low power measurements of similar aircraft, and statistical electromagnetics. Furthermore, apertures into the subsystem boxes become important and cable current injection no longer can accurately account for all potential failure paths. To account for this, mode stirred chamber tests may augment injection tests for determining subsystem strength.

COMPUTER MODELING

Computer coupling modeling can provide a more complete and accurate understanding of how energy couples into an airframe and electronics packages and, in the low frequency regime, it can reduce or eliminate full aircraft testing by providing wire-current stress estimates, trends, or bounds without full aircraft tests. To accomplish this, we use a three-dimensional, finite-difference, time-domain (FDTD) code named TSAR (Temporal Scattering and Response). Associated with this code is a suite of pre- and post-processing tools to enable efficient modeling of complex objects and to aid interpretation of results. These tools include a solid-model based mesh generator, a mesh verification aid, a color and surface contour plotter, and standard signal processing capabilities. Most of these utilities run interactively on graphics workstations which can be connected to image-saving film or video systems. With these tools, users can create and view complex three dimensional models, generate and visually check meshes of the models, compute a wide variety of electromagnetic parameters, and observe the results in several formats.

The TSAR Numerical EM Modeling Code. TSAR was written to combine key features of several previous FDTD codes into one "production quality" program. The code is based on Yee's [4] finite difference solutions of Maxwell's curl equations and the Mur [5] radiation boundary conditions. It was designed to be modular for easier maintenance and future development, and is written in standard FORTRAN-77 to enhance portability. TSAR was designed to take advantage of large memory or virtual memory CPUs.

TSAR models reside in a 3-D, regular cubic lattice geometry. Electromagnetic sources can be plane waves, or electric or magnetic dipoles. Both linear and dispersive media may be modeled. Diagnostic sensors can measure electric and magnetic field components, current density components, power (Poynting Vector), and total energy. These parameters can be observed at a point, over a planar region, or in a volume.

TSAR Pre-processing Tools. In order to simplify the gridding process and improve accuracy, LLNL has developed an automatic mesh generator based on a solid modeling approach [6]. Using MGED [7], a solid modeling program, a user creates a mathematically precise representation of the object from unions and intersections of canonical 3-D shapes such as rectangular boxes and cylinders. A mesh generating program called ANASTASIA dissects the solid model of the object to automatically produce the FDTD mesh. This approach is faster and more reliable than earlier methods, and it allows models to be built independent of cell resolution size. If a finer mesh is required, only the mesh generation program needs to be re-run.

The second pre-processing tool associated with TSAR is used for mesh verification. LLNL has developed a highly interactive visualization code called IMAGE. This code runs on color workstations, enabling users to rapidly rotate, slice through, and zoom in on various portions of the mesh. Additionally, this program can provide mesh coordinate values, and display materials or field components in different colors to aid in the inspection of complex meshes.

TSAR Post-processing Tools. A variety of post-processing tools have been developed to efficiently handle the vast quantity of data which can be produced by a single TSAR simulation. One code in particular, SURFACE, runs in a highly interactive manner on a graphics workstation. This program allows the user to display a two dimensional slice of data as either a surface plot or a color fringe plot. Two dependent variables (i.e., two different field components) can be displayed simultaneously using both color and height. As with IMAGE, SURFACE allows the user to easily change the orientation, slice through the object, and zoom in on any portion of the plot.

TSAR Coupling Analysis of a Boeing 737. TSAR was used to perform a detailed EM coupling analysis on the cockpit of a B737 aircraft. A series of computer simulations were performed on a simplified model of the B737 cockpit in order to gain insight into the effect of altering cockpit details such as its length, the instrument console, and the size of the cockpit windows. The simplified cockpit consisted of the cockpit portion of the B737 fuselage with a solid cockpit floor (no apertures leading to the cargo bay), a solid cockpit wall (no doorway to the passenger cabin), and the instrument console. This simplified cockpit model effectively isolated the cockpit from the rest of the aircraft. The analysis proceeded by changing only one detail at a time and observing the affect on the coupling spectrum. The location of the fundamental resonance was determined to be around 80 MHz by varying the cockpit length and observing which resonances in the coupling spectrum shifted. The affect of the instrument console was determined by performing a coupling analysis both with the console in place and with it removed. The fundamental resonance due to the instrument console was determined to be around 50 MHz which corresponds to its half-wave resonance. The affect of the cockpit window was

investigated by altering its size and observing the resulting change in the coupling spectrum. As its size was increased, the resonances in the spectrum broadened out due to the lower Q of the cockpit cavity, and the aperture cutoff shifted to lower frequencies.

During the course of this analysis on the simplified B737 cockpit model, it quickly became apparent that the coupling spectrum of a more detailed model of the B737 aircraft would be very complicated due to the combined effects of the various details of the geometry such as cavity lengths, coupling apertures, and location of the console. A coupling analysis was performed on the cockpit (refer to Fig. 2) of a model of the complete B737 aircraft consisting of a cockpit with an instrument console and containing coupling apertures into the cargo bay and passenger cabin. To demonstrate the added complexity of the more detailed model, the coupling spectrum is shown in Figure 3 along with the spectrum of the simplified cockpit model. While the spectra compare quite well at the lower frequencies, with the resonances due to the fundamental cockpit resonance (80 MHz) and the instrument console (50 MHz) in good agreement, the spectra show significant differences at the higher frequencies. The added structure that is apparent in the spectrum of the more detailed B737 model is due to the combined affects of the added geometrical structure such as the coupling apertures to other parts of the aircraft. As structure is added to the aircraft model, it becomes increasingly difficult to be able to pinpoint individual resonances and to precisely determine their origins, especially at the higher frequencies where multiples of the fundamental resonances show up. One should, however, be able to pinpoint the fundamental resonances of gross features such as cavity dimensions which occur at the lower frequencies. For the higher frequencies, a more suitable approach may be to look at the overall trend rather than individual resonant peaks.

Figure 2. A view of the cockpit of a B737 model, that includes coupling apertures into the cargo bay (a slot near the front bulkhead) and into the passenger cabin. The outer fuselage has been rendered semi-transparent for ease of viewing into the cockpit cavity.

New TSAR Features. A major limitation of the basic FDTD algorithm is that it has difficulty modeling thin slots and wires whose thickness is small with respect to a resolution element. To alleviate this limitation, a thin wire algorithm,

Figure 3. EM coupling into the cockpit cavity for the simplified B737 cockpit model (solid line) and for the more detailed B737 model (dashed line).

based on work by Merewether and Fisher [8] and written by Riley and Turner [9], has been incorporated into the TSAR package. This algorithm allows both distributed and lumped elements to be included. This is a necessary feature as wires and the boxes to which they connect are among the most important features in modelling an aircraft's response, and attempting to reduce cell size to include such features is not feasible. The addition of this algorithm allows the overall problem size to remain reasonable while incorporating physics critical to correctly predict response.

A second feature that has recently been incorporated into the code is parallelization. This is a partitioning of the code to allow it to run on parallel processing machines. These machines which employ many processors simultaneously can greatly reduce the processing time for certain classes of problems if the software is properly written to take advantage of the parallelization. TSAR has been demonstrated on an eight node machine with reasonable efficiency, meaning that it ran nearly eight times faster than when processed serially.

Because processing time scales as f^4 , at frequencies above about 400 MHz, interior aircraft wire coupling modeling becomes prohibitively expensive to computationally model using brute force approaches such as FDTD, even with thin wire algorithms and parallel processors. Simply generating the complex interior geometry of the model is a daunting task when centimeter cell sizes or smaller are called for. One alternative that looks promising is an asymptotic high frequency technique combining the Smyth-Kirchoff Time Domain (SKTD) method for approximating interior cavity fields arising from aperture penetration with a local FDTD treatment of a wire or wire bundle.

The fields along a wire bundle of upwards of 100 wires can be approximated via SKTD at a computational cost of less than the local FDTD computation. The local FDTD computation is over a volume typically so small (say 6cm x 6cm x several meters) that the savings are on the order of 200,000 fold over an FDTD treatment of the entire aircraft. A single bundle can be treated in days on a good workstation while the entire aircraft model would require a teraflop super computer and days of computer time.

The tradeoff is accuracy. The interior fields are found using an asymptotic expression for the aperture fields

involving a $J(x)/x$ expression only good above aperture cutoff. These fields are then imaged analytically for a simplified rectangular geometry. Losses in the form of aperture reradiation are treated from a ray optics viewpoint. While geometry refinements such as beveled side walls and wire loads can be incorporated, the method is designed to give only reasonable field levels and resonant structure, not an exact replica of the fields. The local FDTD model may also be forced to leave out secondary features such as branching cables that leave the problem space. Again some corrections can be made, however the goal is to establish trends and general behavior characteristics and bounds of the response, not exactly match it.

It is estimated that field levels can be matched to within a factor of two and that the cavity resonant modes are near the exact frequencies and have the correct modal density. The local FDTD calculations allow the wires, cladding, individual load terminations and wire interleaving to be modeled. In summary, a good approximation of the responses and the response trends is possible at high frequencies.

MODE STIRRED CHAMBERS

At frequencies above about 400 MHz, computer models to deterministically calculate wire currents become very large and complex, even with parallelization and thin slot and wire approximations. At some point, the complexity becomes insurmountable and other methods must be used. Our experience in coupling has shown that when a cavity is large relative to a wavelength and has high interior physical complexity, the coupling over frequency or over space begins to exhibit a complexity that appears random. One way to take advantage of this is to reformulate the coupling problem in statistical terms and to use a mode stirred chamber (MSC).

The analysis tools to deal with this randomized coupling are based on statistical electromagnetics [12, 13]. This theory predicts that the microwave power measured at an arbitrary point (not near the walls) within an overmoded, randomly complex cavity has a Chi Squared statistical distribution with two degrees of freedom. This is a single-parameter distribution. Therefore, the mean power density measured at an arbitrary point in the cavity would be sufficient to develop a complete statistical model of the power at any arbitrary interior point. By showing that a randomized aircraft equipment bay has sufficient Q and ensemble variations to behave as such a random complex cavity, then the mean coupling measured at a point in the cavity would be sufficient to predict the microwave stress (statistical distribution of fields) to which an avionics box would be exposed over an ensemble of like aircraft (the fleet). A MSC could be used to generate the same statistical power distribution for testing avionics boxes uninstalled.

A mode stirred chamber (MSC) is a metal-walled chamber, large relative to a wavelength, into which electromagnetic energy is injected [10]. It usually contains a stirrer paddle to randomly change resonant mode patterns as a function of time. (Another method which has been shown to be effective is to randomly dither the drive frequency over a small bandwidth [11].) The advantages of a MSC over the more conventional anechoic test chamber is that it better represents the near field environment inside of an aircraft at high frequencies and the high cavity Q allows threat level testing with lower power RF sources.

A simplified block diagram of a typical MSC and instrumentation is shown in Figure 4. A motor-spun stirrer paddle, large compared to the wavelength, randomizes the field pattern as a function of time. At frequencies greater than several times the cavity cutoff, the mode density is large and the stirring produces random field patterns. A microwave source delivers the EM energy into the chamber through a horn antenna placed inside the chamber. A power leveling unit may be used to dynamically adjust the power to compensate for power reflected at the transmit antenna due to changes in the voltage standing wave ratio (VSWR) as the stirrer turns. A spectrum analyzer or scalar network analyzer may be used to measure power at receive points in the chamber. Fully automatic control and data acquisition is usually implemented with a computer.

Figure 4. Simplified diagram of a Mode Stirred Chamber.

Four issues must be resolved before certified, quantitative subsystem assessments can be made in MSCs:

1. MSC tests must be shown to be repeatable, predictable, and rigorous. This is necessary for the technique to be accepted by government regulators and industry.
2. The power distribution in the MSC must match that found in the system cavity. This assures that the subsystem sees the same EM environment as if it were installed.
3. Coherence length must be understood and the effects of structures near the subsystem taken into account. A structure installed in the cavity will interact with a subsystem if their separation is within a coherence length. Therefore, structures within this length will need to be simulated in the MSC for accurate results.
4. The transfer function describing coupling to devices in the subsystem must be shown to be separable into a product of coupling from outside the system cavity to its interior, and coupling from the cavity interior to the devices within the subsystem. An example of a non-separable case would be when the major coupling into the subsystem is through a waveguide that exits the cavity. In this case, the random field environment in the cavity is immaterial, and MSC tests would not provide accurate results.

Statistical Electromagnetics. The first of these issues, a theory, has been addressed by Lehman and Price. [12,13]. This theory includes probability density functions describing the field or power variations at an arbitrary point in space in a cavity. It is complementary to SKTD methods which provide trends such as the effects of cavity aperture coupling over frequency, but do not describe local variations.

Statistical Power Distributions. The second issue, validating statistical distributions, was addressed by comparing MSC measurements against those made in two equipment bays of a Boeing 707 aircraft. These tests were funded by the NASA Langley Research Center and were conducted in collaboration with the US Naval Surface Warfare Center, Dahlgren.

Tests were conducted at Davis Monthan Air Force Base in Tucson, AZ. The experimental setup is shown in Figure 5. Each equipment bay under study was instrumented with two transmit and two receive antennas. Each pair consisted of a long wire and a horn antenna. The transmit antennas were driven by low power microwave sources installed in an adjacent instrumentation van and were oriented to avoid direct illumination of the receiving antennas. Spectrum analyzers were used to measure power at various points within the bays, while a motorized stirrer paddle varied the mode pattern as a function of time. The stirrer motion simulated random variations in the position of equipment in the bay over the aircraft fleet. Portable computers were used for data acquisition and analysis. Power was measured at discrete frequencies for each of the four possible transmit and receive antenna combinations. Measurements were repeated at several antenna locations within each bay.

Figure 5. Block diagram of instrumentation for microwave power statistical distribution measurements made on a B707.

The time (or stirrer position) waveforms for both the MSC and aircraft data looked similar in that the received amplitude varied rapidly with excursions of 20 dB or more.

The time data was statistically analyzed to generate probability density histograms of the power (in dBm). These are shown in Figures 6a and 6b, for the aircraft and MSC respectively, along with the theoretical probability density (dashed curves). The predicted density was derived from a two degree-of-freedom Chi-squared density using a variable transformation to convert to dB. The aircraft and MSC data compare well to each other and to theory.

Figure 6. Probability density of measured power in (a) the mode stirred chamber and (b) the equipment bay of a B707.

Coherence Length and Separability. Coherence length and separability have also been investigated. Laboratory experiments in our MSC have shown that in some cases where a wire forms a transmission line with a nearby ground plane, differential mode currents on the wire do not interact strongly with fields in the cavity. The MSC would not do a good job of simulating an RF threat path through a wire that is driven from outside the cavity if the wire path is not sufficiently complex to reradiate its energy. An example of this might be a wire that is exposed to strong external fields near say the cockpit window and then is dressed along the fuselage forming a transmission line leading to an avionics box in an electronics bay. MSC tests would have to be supplemented with direct injection tests to completely determine the RF strength of the avionics box. Fortunately, in the FBL/PBW aircraft, there is only one wire set leading to each box - the power lines. This does not become an insurmountable problem.

CONCLUSION

By using stress vs. strength approaches it may be possible to reduce or eliminate full aircraft tests to assess EMI effects. In the low frequency regime, computer models may be used to estimate stress and subsystem direct injection tests may be used to measure strength. In the high frequency regime, the stress becomes random, and statistical electromagnetic analysis and aircraft similarity may be used to estimate the probability density of the EMI stress applied to subsystems. Mode stirred chamber tests and direct injection tests may be used to measure subsystem strength.

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