A LOW-COST COMPREHENSIVE PROCESS FOR ASSESSING ELECTROMAGNETIC ENVIRONMENT (EME) EFFECTS ON FLIGHT-CRITICAL CONTROL COMPUTERS

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ABSTRACT

A process is presented for assessing the effects of electromagnetic environments on flight-critical aircraft control computers. The assessment process is a combination of analysis, simulation, and tests and is currently under development for demonstration at the NASA Langley Research Center in the High Intensity Radiated Fields (HIRF) Laboratory and Closed-Loop Test (CLT) Laboratory. The assessment process is comprehensive in that it addresses (i) closed-loop operation of the controller under test, (ii) real-time dynamic detection of controller malfunctions that occur due to the effects of electromagnetic disturbances caused by lightning, HIRF, and electromagnetic interference and incompatibilities, and (iii) the resulting effects on the aircraft relative to the stage of flight, flight conditions, and required operational performance. In addition, this method uses electromagnetic field modeling codes to determine internal electromagnetic environments to which onboard electronic equipment will be subjected. Lower cost demonstrations of certification compliance should be realizable using this method due to the reduction or elimination of costly full-aircraft tests.

1.0 INTRODUCTION

Trends indicate that advanced aircraft are becoming increasingly dependent on electronic systems for safe flight. Future advanced commercial aircraft such as the High Speed Civil Transport may require systems for stability augmentation and flutter suppression, as well as guidance and control [1]. Such systems will be flight-critical, since the flight of the aircraft will depend on reliable operation of these systems. The problem of verifying the integrity of the control computer in adverse, as well as nominal, operating environments is a key issue in the development, validation, certification, and operation of critical control systems. The integrity of critical fault-tolerant control computers can be viewed as the reliable system-level operation of controller functions such as redundancy management decisions, control law calculations, and input/output (I/O) rate and range checks [2]-[4]. Malfunctions in control law calculations result when the basic mathematical operations of the processor are performed incorrectly. An example of a malfunction in the redundancy management logic is the controller deciding that a correctly operating processor is faulty and ignoring its calculations. Rate and range checks are performed in the input parameter selection process and the output command selection process. Malfunctions in I/O rate and range checks can result in incorrect input parameters being used in calculations or incorrect commands being output from the controller. In the case of an unstable aircraft, maintaining stability with computer malfunctions is critical to continued safe flight of the aircraft. In the case of a stable aircraft, a malfunctioning controller can actually destabilize the closed-loop system [5]. Therefore, it must be shown in a systems context that malfunctions in the controller do not effect the stability and performance of the closed-loop system or compromise the continued safe flight of the aircraft.

An adverse operating environment of particular concern relative to validation and certification of critical systems is caused by electromagnetic disturbances such as lightning and High Intensity Radiated Fields (HIRF). These threats can cause common mode errors or upsets in critical systems whose fault tolerance is achieved through redundancy. The current state-of-the-art in electromagnetic environment (EME)
effects testing is to perform laboratory tests on aircraft computers as well as full-scale aircraft testing. Laboratory tests are primarily open-loop and static at a few operating points over the performance envelope of the equipment and do not consider system level effects. Full-aircraft tests are also static with the aircraft situated on the ground and equipment powered on during exposure to electromagnetic energy. These tests are extremely expensive to perform and do not provide a means of validating system performance over the operating envelope. This paper defines a lower cost comprehensive systems level assessment process for evaluating the effects of electromagnetic disturbances on critical control computers. Lower cost is achieved by reducing or eliminating the necessity for full-aircraft testing. The motivation for the assessment process defined in this paper is to provide a guideline for certification compliance demonstrations of complex integrated critical systems to requirements for operation in EME, such as lightning [6] and HIRF [7], and to requirements for fault containment [8] that would ensure continued safe flight and landing of the aircraft. The assessment process is a combination of analysis, simulation, and tests and is currently under development for demonstration at the NASA Langley Research Center. Issues to be addressed in the assessment process include (i) closed-loop operation of the controller under test, (ii) real-time dynamic detection of controller malfunctions that occur due to the effects of electromagnetic disturbances caused by lightning, HIRF, and electromagnetic interference and incompatibilities, and (iii) the resulting effects on the aircraft relative to the stage of flight, flight conditions, and required operational performance. Previous work in EME effects testing [9] - [27] did not consider these issues or did not consider testing of embedded computer systems such as aircraft control systems. In this sense, the process defined in this paper is comprehensive.

A sketch of the systems level EME Effects Assessment process is shown in Figure 1. The approach shown in Figure 1 consists of five primary elements: EM Field Modeling; EM Test Facility; Closed-Loop Test Capability; Real-Time Function Monitoring; and Failure Mode Effects Analysis. These process elements are discussed in Section 2.0. A summary and comments are presented in section 3.0.

Figure 1: Sketch of the EME Effects Assessment Process

2.0 EME EFFECTS ASSESSMENT PROCESS ELEMENTS

Elements of the EME Effects Assessment process are (1) EM Field Modeling, (2) EM Test Facility, (3) Closed-Loop Test Capability, (4) Real-Time Function Monitoring, and (5) Failure Mode Effects Analysis. Each of these elements is discussed in the subsequent sections.

2.1 EM Field Modeling

The objective of this process element is to develop a methodology for determining the internal EME for avionics testing, given the external HIRF spectrum specified by the FAA. The approach is to develop the EM software code capability to perform the necessary field modeling and is illustrated in Figure 2.

Figure 2: EM Field Modeling Approach

Given the FAA HIRF spectrum and the aircraft geometry, finite-difference time-domain (FDTD) code is used to calculate the electromagnetic fields surrounding the aircraft, the interior fields that occur in the aircraft due to field penetration at seams and apertures, as well as the voltages and currents that would be induced on avionics
equipment cables [28] - [29]. These interior fields and induced signals are used in the laboratory to emulate the environment on the aircraft without performing full-aircraft tests. A geometric computer model for the B757 is complete for use in the FDTD code. The EM modeling code is being validated using empirical data obtained from B757 ground tests and flight tests [30] - [32]. Measurements made on the B757 during the ground tests and flight tests are compared to field levels determined analytically using the EM computer code to establish the validity of the modeling approach. B757 ground tests were conducted at the Phillips Lab Large Electromagnetic System Level Illuminator (LESLI) facility. Flight tests were conducted at the Voice of America broadcast site in Greenville, NC, and at the NASA Wallops Flight Center.

2.2 EM Test Facility

Once the internal electromagnetic environment has been determined using FDTD code, laboratory tests can be performed in which this environment is emulated and faults introduced into the digital system. Faults are introduced into the digital system via (i) the HIRF Laboratory to assess HIRF effects and (ii) Bulk-Cable Injection (BCI) tests to assess lightning induced effects. The HIRF Laboratory consists of three mode-stirred reverberation chambers and one GHz Transverse Electromagnetic (GTEM) test cell. The mode-stirred reverberation chambers have a frequency range of 75 MHz to 18 GHz. A sketch of the chambers is shown in Figure 3.

![Reverberation Chambers in the HIRF Laboratory](image)

The GTEM supports a plane wave which enters at the apex and is absorbed at the base of the chamber. High power amplifiers must be used to generate high power fields. The chamber is cooled with forced air and vortex cooling units. The Equipment Under Test (EUT) must be rotated for subjection to fields at various angles of incidence.

The BCI Test Station consists of two waveform generators, a wideband power amplifier, and a PC-based computer. A sketch of the BCI Test Station is shown in Figure 5.

![Bulk Cable Injection Test Station](image)
computer via a fiber optic interface for electrical isolation. Analog signals are generated using polynomial waveform synthesizers and amplified to desired magnitudes and induced onto signal lines of the EUT. The instrumentation and experimental equipment are computer controlled.

2.3 Closed-Loop Test Laboratory

The laboratory testing requirement that is fundamental to the EME Effects Assessment process is the ability to operate the EUT in closed loop with a computer simulation of the aircraft, sensors, actuators, and engines in flight with atmospheric conditions. The capability to perform closed-loop tests on the digital system is required to develop a test methodology that enables closed-loop dynamics over an entire flight profile to be represented during testing [33] - [34]. Thus, the actual application software can be used and exercised during testing [35]. The EUT is interfaced with a computer simulation of the aircraft and atmosphere during a specific phase of flight. Closed-loop simulation enables the integrity of the control function of the EUT to be assessed at each point over the entire operating envelope during tests. In addition, simulating the atmosphere enables the integrity of the EUT to be assessed when the aircraft is subjected to potentially destabilizing conditions such as wind gusts, turbulence, and wind shears [29]. Electrical isolation between the EUT and the simulation computer is achieved using fiber optic signaling.

A Closed-Loop Test Laboratory has been established to demonstrate this approach and to provide the analytical and experimental environment to conduct research in digital upset, fault tolerance, and fault containment. A block diagram of the current capability of this Laboratory is shown in Figure 6. The current testbed is a quad-redundant military flight control computer (FCC) obtained from AlliedSignal under a Memorandum of Agreement. The FCC is programmed to execute the B737 Autoland control laws and its outputs are the commands for the throttle, elevator, ailerons, and rudder. Current aircraft simulation software is the B737 Autoland. The simulation includes the B737 equations of motion, aerodynamic models, engines, sensors, and actuators. The servo loop is closed in the simulation. Atmospheric disturbances currently being simulated include wind gusts, clear air turbulence, and thunderstorm level winds. Closed-loop operation has been demonstrated with the AlliedSignal FCC. The control loop can be closed with the analog signals, or using the 1553 bus data. Electrical isolation between the FCC and simulation computer is achieved via fiber optic interfaces on the analog/discrete signals as well as the 1553 data bus.

Initialization of experiments and data acquisition are computer controlled. Under computer control, the EUT and B737 simulation are initialized and data is collected via a dual-port memory. The dual-port memory allows command and sensor signals between the EUT and the B737 simulation computer to be ported to the data acquisition computer for storage. Control function is monitored in real-time during tests, and the upset detector can trigger data storage. This enables data to be stored that reflects EME effects of interest. The user interface enables the experimenter to perform experiment set-ups and data retrieval, analysis, and display. Current analysis tools include Matlab/Simulink and PVWave.

2.4 Real-Time Function Monitor for the Equipment Under Test (EUT)

Sub-system functions of the EUT such as control law calculations, redundancy

![Figure 6: Current Closed-Loop Test Laboratory](image-url)
management, and input/output rate and range checks are monitored in real-time during testing. This enables degradation in performance and/or reliability to be detected in real time during the tests. Figure 7 depicts the Control Function Monitor in the context of the Closed-Loop Test Laboratory.

The control function monitor detects errors in control law calculations, redundancy management decisions, and input/output rate and range checks. The error decision output from each of these detectors is combined into a scalar decision using an optimal decision fusion rule. Error decisions at all levels within these detectors are stored as a diagnostic aid for post test data analysis. Since the EUT is operating in closed-loop with a simulation of the aircraft, the detection process is dynamic over the operating envelope of the flight. In addition, the detectors must account for process noise caused by unmodeled dynamics and disturbances to the aircraft such as wind gusts and turbulence, and measurement noise that arises from multiple signal conversions.

The design of a monitor for detecting malfunctions in the control law calculations of a quad-redundant controller has been completed [2] - [4]. This monitor uses a model-based detector design and has been simulated for the case of a four processor controller executing B737 Autoland longitudinal control laws. The monitor is designed and simulated for the landing profile from glideslope engaged until flare with heavy clear air turbulence. Implementation of these algorithms in the laboratory for demonstration with the Bendix quad FCC is underway.

2.5 Failure Mode Effects Analysis

Modeling and analysis of EUT failure modes that occur during testing must be performed and used to assess the effects on closed-loop system safety and performance. A conceptual diagram of the potential elements of this analysis are shown in Figure 8:

The two primary analysis elements are to determine closed-loop performance and stability. Performance considerations include required navigation performance (RNP) for satellite guided flight and required system performance for each flight mode. RNP for satellite guided flight is characterized by a containment surface that cannot be penetrated by any part of the aircraft during each phase of flight [36] - [37]. Determining the effects of degraded subsystems on complex or integrated systems can be determined using existing fault tree tools [38]. Determining the effects of degraded performance on system reliability can be determined using existing reliability tools [39]. Stability considerations are with respect to the closed-loop system which is comprised of the aircraft and a controller with error modes characterized by stochastically varying parameters in functional models. Monte Carlo simulation techniques have been applied in previous work to determine stochastic stability [40]. Analytical criteria for asymptotic stability have also been developed [41] and applied to the case of systems with a faulty controller [42].
A process has been presented for assessing the effects of electromagnetic environments on flight-critical aircraft control computers. The assessment process is a combination of analysis, simulation, and tests and is currently under development for demonstration at the NASA Langley Research Center in the High Intensity Radiated Fields (HIRF) Laboratory and Closed-Loop Test (CLT) Laboratory. The process consists of five primary elements: EM Field Modeling; EM Test Facility; Closed-Loop Test Capability; Real-Time Function Monitoring; and Failure Mode Effects Analysis. Electromagnetic field modeling codes are used to determine internal electromagnetic environments to which onboard electronic equipment will be subjected. Internal disturbance levels computed analytically using the field modeling codes are generated in the laboratory during testing. The equipment under test is interfaced during tests to a computer simulation of the aircraft, engines, sensors, actuators, and atmosphere so that closed-loop dynamics are represented during tests and controller performance integrity during destabilizing flight conditions can be validated. Effects of failure modes on the aircraft safety and performance are determined using analytical techniques, reliability tools, and fault tree analysis tools.

The assessment process is comprehensive in that it addresses (i) closed-loop operation of the controller under test, (ii) real-time dynamic detection of controller malfunctions that occur due to the effects of electromagnetic disturbances caused by lightning, HIRF, and electromagnetic interference and incompatibilities, and (iii) the resulting effects on the aircraft relative to the stage of flight, flight conditions, and required operational performance. Upset detection is performed in real-time during tests and is achieved using a dynamic model-based detection scheme that accounts for unmodeled dynamics, disturbances to the aircraft such as wind gusts and turbulence, and measurement noise caused by signal conversions. In addition, lower cost demonstrations of certification compliance should be realizable using this method due to the reduction or elimination of costly full-aircraft tests.

REFERENCES


