HIRF Certification of Civilian Aircraft

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Introduction

Within the civil aerospace industry, there are stringent performance and safety requirements specified for modern aircraft and their avionics systems. These requirements include assessments for the effects of electromagnetic interference (EMI) from a variety of sources, such as the aircraft's own onboard transmitters and external transmitters both airborne and on the ground (Figure 1).

This article provides an overview of the high intensity radiated field (HIRF) requirements for civilian aircraft, together with a review of the appropriate test methods which are available to demonstrate compliance. The criticality classifications of equipment and the potential effects of interference are discussed together with coupling mechanisms and measurement methods.

Low-level swept current (LLSC), low-level direct drive (LLDD) and low-level swept field (LLSF) are some of the aircraft coupling test methods used to determine the transfer function/coupling from external fields to wiring bundles and equipment bays. Aircraft susceptibility tests using bulk current injection (BCI), radiated field susceptibility and direct-current injection (DCI) are described.

The Development of HIRF Requirements for Aircraft

HIRF was not a problem for the older generation of aircraft, whose various systems and functions were controlled using mechanical linkages, bowden cables, pulleys, and chains. Twenty years ago, civilian aircraft EMC test specifications called for equipment radiated field susceptibility test levels with values of only 0.1 V/m extending to a maximum frequency range of only 1 GHz, as specified in British Standard BS 3G 100.[1] For military aircraft, the limits were increased to 5 V/m and extended to a maximum frequency range of 10 GHz. BS 3G 100 also specified limits for conducted susceptibility and both conducted and radiated emissions.

With the increasing complexity of avionics systems which are relied upon to provide a variety of flight safety critical functions, such as engine control, flight control, navigation, and electrical power, there are serious concerns about the effects of HIRF from external sources such as high-power radars and broadcast transmitters.

The launch of the Airbus A320 with its computer controlled systems, such as digital fly-by-wire (FBW), full authority digital engine control (FADEC) and electronic flight instrumentation systems (EFIS), forced airworthiness authorities to address the lack of specific requirements for aircraft HIRF certification.

In 1986, the Joint Aviation Authorities (JAA) and the Fed-

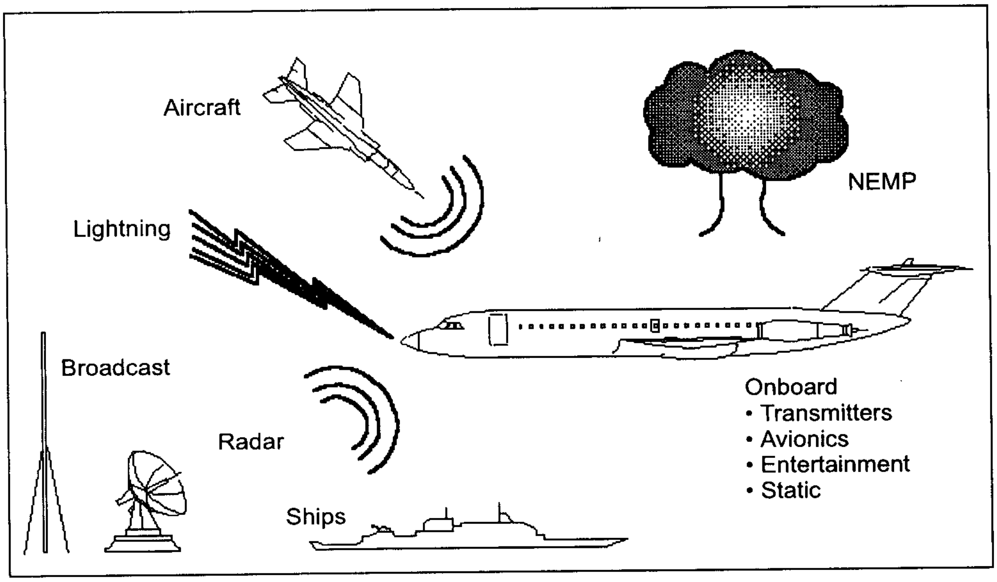

Figure 1. *Potential Electromagnetic Threats to Aircraft.*

eral Aviation Administration (FAA) tasked the European Organisation for Civil Aviation Equipment (EUROCAE) and the Society of Automotive Engineers (SAE), to investigate the problem of HIRF-induced system malfunctions and develop the necessary compliance criteria for a common HIRF requirement. During 1992, the airworthiness authorities issued mandatory interim "special conditions" which specified the generic requirements for aircraft equipment performance during exposure to various HIRF environments over the entire frequency band between 10 kHz and 40 GHz. Compliance with the "special conditions" can be demonstrated by a combination of aircraft and equipment testing.

New aircraft are certified by the various aviation authorities and generally require the aircraft manufacturer to undertake a variety of avionics equipment tests to internationally recognized and adopted standards such as RTCA/DO-160C [2] and its European equivalent, EUROCAE ED-14C. These standards specify the minimum environmental test conditions and the applicable test procedures for airborne equipment. The aircraft HIRF test methods and limits are specified in documents such as the advisory circular/advisory material joint AC/AMJ 20.1317[3] and the EUROCAE users guide for AMJ.[4]

There are currently variances between requirements of the JAA and FAA "special conditions," including different test requirements for critical and essential systems, with the FAA requiring tests only on critical systems. Within the next year, it is intended that the "special conditions" will be replaced by a harmonized standard produced by the Electromagnetic Effects Harmonisation Working Group (EEHWG), which for the JAA will be a Notice of Proposed Amendment (NPA), and for the FAA will be a Notice of Proposed Rulemaking (NPRM).[5]

The test limits selected from these documents are determined from an analysis of the function of the equipment under test and its intended application. This analysis is applied to each of the avionics systems to examine the criticality of the function and to determine the appropriate test limits and method of test.

The FAA special conditions are applicable to all equipment which provides critical functions. Compliance can generally be demonstrated by equipment testing to a default level of 100 V/m (200 V/m for some engine systems), or the external field threat defined by the FAA, less the attenuation performance of the airframe.

The JAA special conditions require equipment providing critical functions to be tested at levels equivalent to the external field threat defined by the JAA, less the attenuation performance of the airframe. The test levels required for the JAA are generally significantly higher than 100 V/m, particularly at frequencies above 400 MHz.

The HIRF Electromagnetic Environment

During its operational profile, an aircraft is exposed to a variety of electromagnetic environments, generated by sources such as radar, radio, and television, which may be either fixed or mobile, ground based, airborne or carried onboard ships.

To define these HIRF environments, a database was set up to import information from all authorized transmitters operating within Western Europe and the USA. The field strength values produced by each of these transmitters was calculated at a variety of distances determined from the flight profiles of aircraft. The frequency range between 10 kHz and 40 GHz was divided into 17 different frequency bands to provide a HIRF envelope of the field strength values.

The three resulting HIRF environments for fixed wing aircraft have been defined as severe, certification and normal,[5] as summarized in the following paragraphs.

- *Severe environment* is a worst-case estimate of the field strength where flight operations are permitted and includes the airport environment, non-airport ground transmitters, shipboard transmitters and air-to-air transmitters. This severe environment is used as a basis for the derivation of the certification and normal environments.
- *Certification environment* is a subset of the severe environment and is an estimate of the field strength levels which could be encountered during routine flight operations. The field strength values are generally lower than the severe environment.
- *Normal environment* is based on a representative electromagnetic environmental profile of the field strength values which would be encountered in the vicinity of airports in Western Europe and the USA. The field strength values are generally lower than the certification environment.

In addition to the environments established for fixed wing aircraft, there is a suite of complementary environments which have been proposed for rotary wing aircraft.[6] These environments include the rotorcraft severe HIRF environment, which is a worst-case estimate of the field strength in which rotorcraft flight operations are permitted. This environment is generally significantly higher than the corresponding environment for fixed wing aircraft since rotorcraft can fly close to transmitters.

The RF environment external to the aircraft will penetrate the fuselage and establish an internal RF environment to which installed electrical/electronic systems will be exposed. The resulting internal RF environment will be developed from many factors, such as the seams and apertures in the aircraft construction, the effects of re-radiation from structures and wiring internal to the aircraft and characteristic aircraft electrical resonance. The resultant internal environment will be essentially

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aircraft and zone specific and should be established by test and/or analysis for the system under evaluation.

Equipment Criticality Classification

Aircraft contain many different types of avionics systems which provide numerous functions which may be degraded or fail due to exposure to HIRF. The consequences of these effects may lead to events onboard the aircraft which can be categorized by the failure conditions and their impact on the continued safe operation of the aircraft.

The current classifications under the "special conditions" specify the functions provided by systems as either critical or essential. However, the new requirements will specify the failure condition classifications as follows:

- Catastrophic: failure conditions which would prevent continued safe flight and landing.
- Hazardous/Severe-Major: failure conditions which would significantly reduce the capability of the aircraft or the ability of the flight crew to cope with adverse operating conditions.
- Major: failure conditions which would reduce the capability of the aircraft or the ability of the flight crew to cope with adverse operating conditions.
- Minor: failure conditions which would not significantly reduce the aircraft safety and which involve crew actions that are well within their capabilities.
- No Effect: failure conditions which do not affect operational capability of the aircraft or increase crew workload.

It should be noted that detailed definitions of these failure conditions are given in relevant guidance material.[3-4] The test levels which are applied to different systems with the same criticality may vary depending on the phases of flight operation during which the functions are critical. The primary aircraft systems which must always be considered are those which provide a direct control function, such as engine and fuel control, flight control and electrical power generation.

Aircraft HIRF Test Methods

There are a variety of different HIRF test methods which are defined for the verification of aircraft HIRF compliance.[3-5] The methods which are applicable will primarily be determined by the criticality of the equipment, but the options are basically selected from the following list:

- Whole aircraft exposure to high-level fields
- Whole aircraft low-level coupling tests and high-level equipment tests
- Similarity with existing certified aircraft

To determine the degree of coupling between the aircraft and the HIRF environment, methods which are available for the whole aircraft low-level coupling tests and onboard aircraft high level equipment tests are:

- Below 10 MHz: low-level direct drive (LLDD) current methods are used to determine the induced bulk current on the aircraft wiring bundles referenced to the external field strength.
- Up to 400 MHz: low-level swept current (LLSC) coupling methods are used to determine the induced bulk current on the aircraft wiring bundles referenced to the external field strength.
- Above 100 MHz: low-level swept field (LLSF) attenuation methods are used to assess the internal fields set up within the aircraft referenced to the external field strength.

Following these coupling assessments, a comparison can be made between the measured internal environment and the susceptibility levels to which the equipment or system has been tested during the equipment qualification tests carried out in the laboratory. Where necessary, additional on-aircraft susceptibility tests can be carried out at enhanced levels using the following methods:

- Below 400 MHz: BCI susceptibility methods are used to inject high-level bulk currents into the aircraft wiring bundles up to the required test level.
- Up to 18 GHz: radiated field susceptibility methods are used to produce high-level field strengths at the aircraft equipment up to the required test level.
- Below 100 MHz: direct-current injection (DCI) susceptibility methods are under consideration as an alternative test method which injects high-level currents directly into the aircraft fuselage.

At frequencies below a few hundred megahertz, the predominant HIRF coupling mechanism is via currents which are induced in the aircraft wiring bundles. These induced currents are conducted into the avionics boxes where they can cause malfunctions and spurious performance. At higher frequencies the predominant HIRF coupling mechanism is via fields illuminating the fuselage and penetrating the avionics boxes to couple with the internal circuitry, causing malfunctions and spurious performance.

During the aircraft HIRF testing, the aircraft should be built to full production standard. However, it is usually acceptable to include the addition of some flight test instrumentation and wiring. All the applicable build standard requirements should be enforced, since their conformity will be verified by the relevant airworthiness representatives prior to each test phase.

The tests are all undertaken with the aircraft firmly on the ground, and where necessary, the aircraft is configured to simulate flight conditions for the purpose of conducting the test. In order to undertake the tests, it is necessary to gain access to the aircraft equipment with probes and sensors as indicated in Figure 2.

Aircraft Low-level Coupling Test Methods

The aircraft low-level coupling tests yield the relationship between the external environment incident on the aircraft and the resulting internal envi-

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ronment. At frequencies below 400 MHz the internal environment is expressed in terms of the wiring bundle-induced current to the avionics systems. At frequencies above 100 MHz, the internal environment is expressed in terms of the field strength to which the avionics systems will be exposed.

LOW-LEVEL DIRECT DRIVE (LLDD) COUPLING

Low-level direct-drive (LLDD) coupling tests are applied to the aircraft to determine the transfer function between external electromagnetic fields and the induced wiring bundle currents over the swept frequency range between 10 kHz and the primary aircraft resonant frequency (generally extended to 10 MHz).

The initial process towards obtaining the LLDD transfer function is to obtain the relationship between free field external radiation of the aircraft and the aircraft fuselage surface current density. These predictions can be obtained using computer modelling methods such as three-dimensional transmission line matrix modelling (TLM).

The aircraft is installed within a wire return conductor network or ground plane to provide a return path for the current driven into the aircraft fuselage.

The initial measurement which must first be carried out is the calibration of the fuselage drive current. In addition to measuring the fuselage drive current, the surface current density is measured on the external surface of the fuselage for comparison with the results of the modelling to generate a correction data file for the induced current measurements on the aircraft wiring bundles.

The aircraft wiring bundles are instrumented using current probes to measure the currents induced in the wiring bundles. Where necessary, additional injection/termination configurations are used to obtain worst-case data for the coupling. The test data is then extrapolated to the appropriate full intensity field strength environment to provide test limit targets for the BCI susceptibility test.

LOW-LEVEL SWEPT CURRENT (LLSC) COUPLING

Low-level swept current (LLSC) coupling tests are applied to the aircraft to determine the transfer function between external electromagnetic fields and the induced wiring bundle currents over the swept frequency range between 1 MHz and 400 MHz. The lower frequency limit is determined by the uniformity of the field generated during the test and the sensitivity of the measuring equipment, while the upper frequency limit is bounded by the resonances and standing wave effects on the cable bundles under test.

The LLSC test technique requires illuminating the aircraft over its entire volume and from four sides, with a known low-level, swept frequency electromagnetic field and measuring the resulting induced wiring bundle currents.

The first phase of the LLSC measurement program is to carry out the field strength calibration measurements from each of the transmitting antennas, in turn, prior to the installation of the aircraft.

For the second phase of the LLSC tests, the aircraft is positioned at the center of the test site and the wiring bundles are instrumented with current probes installed on the appropriate test points.

The test data is then extrapolated to the appropriate full intensity field strength environment to provide test limit targets for the BCI susceptibility test.

Figure 2. Accessing Aircraft Equipment Bays for Instrumentation.

LOW-LEVEL SWEPT-FIELD (LLSF) ATTENUATION

Low-level swept-field (LLSF) attenuation tests are applied to the aircraft to determine the degree of protection afforded by the structure of the airframe against external electromagnetic fields over the swept frequency range between 100 MHz and 18 GHz.

The LLSF test technique requires illuminating the aircraft from various angles, with a known, low-level, swept-frequency electromagnetic field and measuring the resulting fields within the various bays housing the aircraft avionics to determine the attenuation provided. Figure 3 shows the nose of an aircraft being illuminated by RF from an antenna. The results of these attenuation measurements are then used to determine the test limits for the radiated field susceptibility tests.

There are, however, significant problems in making field strength measurements within metal enclosures due to the standing wave patterns that are set up within the bay. Therefore, the only realistic and repeatable measurement that can be made is to determine the maximum field, regardless of location within the bay, for a given frequency for all polarizations of external field.

This can be achieved by measuring at one location and using mechanical mode stirrers to modify the standing wave pattern to ensure that the peak field existing within the bay occurred at the location of the sensor, at one instant of time, during one revolution of the mode stirrer. Alternatively, the bay can be instrumented with multiple sensors to determine the worst-case attenuation values.

The first stage of the LLSF attenuation process is to carry out the field strength calibration measurements from each of the transmitting antennas in the absence of the aircraft. The resulting field strength is measured using an ERA miniature omni-directional biconical antenna and pre-amplifier.

The field strength at the aircraft test points is measured from each transmitting antenna in turn, and a spectrum analyzer and computer system are used to normalize the aircraft internal field to the field calibration values to obtain the fuselage attenuation.

The attenuation results are extrapolated to the required field strength environments for comparison with the relevant test levels and to provide test levels to be used during radiated field susceptibility tests.

Aircraft Susceptibility Test Methods

During the aircraft susceptibility tests, specific pass/fail criteria will be required for each system together with the means for monitoring these criteria. All effects which go towards the definition of pass/fail criteria must be the product of an identifiable and traceable analysis, which includes both separate and interactionary operational characteristics of the systems. The analysis shall consider the failures, either single or in combination, which could adversely affect the system performance. This should include those failures which could negate any built-in redundancy within the system or those which could influence more than one system performing the same function as a result of the exposure to HIRF.

This will usually involve performing a system safety assessment which demonstrates that single failures, including failures in the presence of latent faults, do not jeopardize continued safe operation of the aircraft. A top-down analysis, at least to assembly level, and a "common cause analysis" should be performed to assure that significant single faults or combinations of faults are not adverse or meet the probability criteria related to the failure condition classification. This common cause assessment will normally include verification of any fault independency assumptions.

BULK CURRENT INJECTION SUSCEPTIBILITY

The BCI susceptibility tests are applied to the aircraft wiring bundles to simulate the effects of induced cable currents due to electromagnetic fields in the frequency range 10 kHz to 400 MHz.

The test requires clamping an injection probe around the wiring bundle under test to simulate the cable currents which would be induced due to high-level external electromagnetic fields. The performance of the aircraft equipment during the BCI testing is compared with the full intensity test levels to determine compliance with the limits. Any particularly sensitive or weak wiring looms or systems are rapidly identified together with their failure modes.

The modulated RF current is injected into the cable bundle and slowly swept over the required frequency range. The drive level to the injection probe is gradually increased until either the threshold of malfunction of the avionic

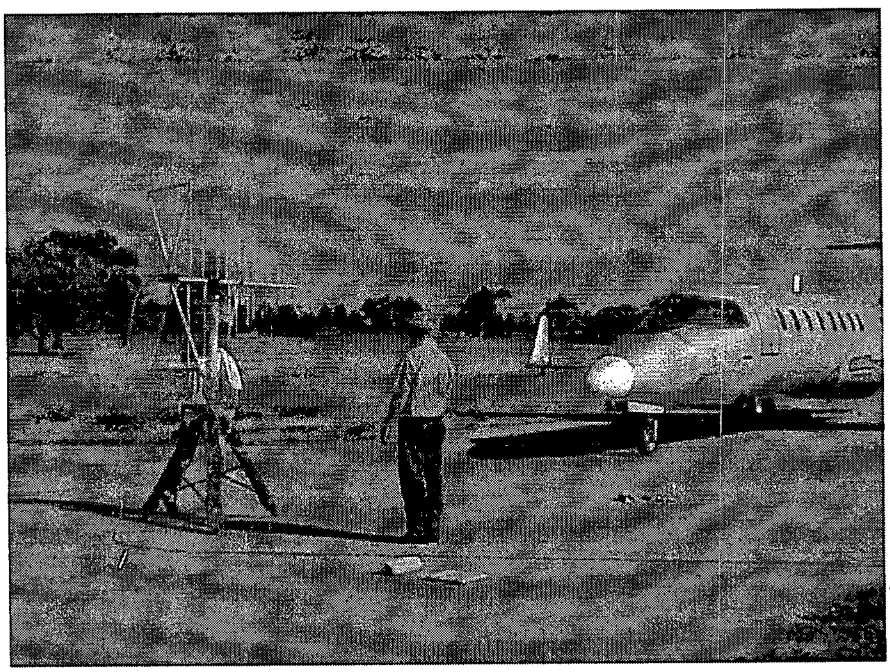

Figure 3. *Low-level Radiated Field Coupling Test Antenna.*

equipment is reached or a maximum induced current or forward power limit is achieved.

In addition to an intercom system between the aircraft and the instrumentation trailer, a hardened closed circuit television (CCTV) system should be used to monitor the various systems on the aircraft during the BCI tests.

For systems which have multiple redundancy (e.g., fly-by-wire), the single-loom injection BCI test may not be adequate since some of the malfunction modes may be concealed. It is necessary to simultaneously inject signals into each of the redundant systems using additional probes and amplifiers.

RADIATED FIELD SUSCEPTIBILITY

High level radiated field strength susceptibility (RS) tests are applied to the various selected items of avionic equipment to determine the equipment performance in HIRF in the frequency range 100 MHz to 18 GHz. The test requires illuminating the equipment under test to simulate the field strength levels which would be incident on the equipment due to high-level external electromagnetic fields.

To generate the required high field strength levels, localized radiation methods are employed onboard the aircraft using high-power antennas and amplifiers.

At each test frequency, the drive level to the transmitting antenna is gradually increased until either the threshold of malfunction of the avionic equipment is reached or the maximum field strength test limit is reached. The tests are undertaken for both horizontal and vertical polarization of the transmitting antennas.

DIRECT-CURRENT INJECTION (DCI) SUSCEPTIBILITY

The use of direct-current injection (DCI) susceptibility test methods is currently being investigated as an alternative method for conducting HIRF susceptibility measurements on the whole aircraft over the frequency range 10 kHz to 400 MHz.

The DCI test involves directly energizing the whole fuselage of the aircraft from the output of a high-power amplifier to induce surface current densities and wiring bundle currents which simulate the effects of the aircraft being exposed to HIRF fields. The aircraft is installed either above a ground plane or within a return conductor system to enable various injection points and exit points to be configured.

Modulated RF current is injected into the aircraft fuselage and is slowly swept over the required frequency range. The drive current into the fuselage is gradually increased until either the threshold of malfunction is reached or until a maximum induced current on the wiring bundle under test or the forward power limit is reached.

Summary and Conclusions

This paper has provided an overview of the HIRF requirements for civilian aircraft, including the latest state-of-the-art test methods which are available for application to aircraft. HIRF test requirements have been discussed and clearance methods have been identified to provide the necessary information for aircraft HIRF certification.

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