

Annex A

EMC and Functional Safety in the Aerospace Industry

Abstract

The aerospace industry has long been aware of EMC-related functional safety issues, due to their long-term use of electronics in mission-critical and safety-critical applications – such as autopilots and automatic landing systems. The modern aircraft is vitally dependant on electronics, even for manual controls (e.g. in ‘fly-by-wire’ systems the pilots movements of his controls are mediated by computers and servo-systems before being applied to the aircraft systems or control surfaces).

All aircraft are exposed to very powerful EM disturbances, e.g. from airfield radars, radio broadcasting transmitters, and direct lightning strike. Military aircraft have the additional burdens of electronic warfare and countermeasures.

EMC in the aircraft industry involves the application of continually-evolving comprehensive standards which attempt to cover all foreseeable exposure to EM disturbances, including low-probability events, plus strict project management procedures for controlling EMC specification, design, development, and verification (e.g. testing).

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A1. Introduction

This annex aims to highlight the special issues associated with the aerospace industry and the relationship between EMC and safety. It is intended that repetition of points made in the core text shall be avoided unless the requirements of the industry demand a different viewpoint.

Aircraft can and do fly in the main beam of the antennas of high-powered transmitters thus placing the structure and therefore the contained systems in extremely high field strengths. As a result the systems must be demonstrated to operate, without upset of normal operation, in very high fields, often in excess of the biological radiation hazard limits. This together with the capital and operational costs of the high power facilities to produce high intensity fields on the ground, creates special difficulties for qualification testing in the aerospace industry.

In addition to the radio frequency environment, aircraft are struck by lightning (on average, each civil aircraft is struck by lightning once a year) the airframe becoming part of the arc channel. This results in huge pulsed currents flowing through the airframe and therefore through the systems. Once again, this necessitates the demonstration of continued operation of systems during high-induced pulsed currents. Also the common occurrence of the lightning threat requires demonstration of maintenance of structural integrity and fuel safety during and following Lightning attachment. It should be mentioned that aircraft are, by their nature "flying fuel tanks" and therefore fuel explosion risks must be addressed, particularly in the case of lightning strike protection. However, this concern together with that of structural integrity, is beyond the scope of this report.

Aircraft are completely self-contained systems from an electromagnetic point of view, whose size ranges widely from small light aircraft to that of wide-bodied commercial aircraft carrying in excess of 400 passengers (e.g. Boeing 747). The systems are highly integrated and unlike a large ground-based system (e.g. power generation system or communication network), it is difficult to divide the problem up into distinct parts from an electromagnetic point of view and be confident that synergistic effects have not been missed. The illumination of such a physically large entity poses its own challenges.

Military aircraft are faced with a range of deliberate threats whose intensity and likelihood of occurrence is growing all the time. These must also be taken into account during design and qualification.

An added dimension to the particular problems of the aerospace industry is the sensitivity to mass and volume penalty arising from protection and the extreme costs arising from late modifications.

This annex attempts to highlight the particular issues associated with the design and clearance of aircraft against the threats outlined above.

A2. The aerospace electromagnetic environment

As mentioned in the introduction the electromagnetic environment in which aircraft and their systems must continue to operate safely is amongst the most severe for any system.

A2.1 Military aircraft

Military aircraft have been required to operate safely in harsh electromagnetic environments for some years as defined in Refs. 1, 2, 3, 4 & 5. The environment applied to military aircraft is dependent on the intended role of the aircraft and therefore can vary somewhat from one project to another. For example, aircraft that are intended to land on ships necessarily approach high powered transmitting antennas at extremely close range. This greatly influences the environment against which resilience must be demonstrated.

The external electromagnetic environment placed as a requirement on military aircraft is provided by the customer and is usually drawn from one of the specifications quoted above, sometimes modified by a particular operational consideration (e.g. radar threats from other aircraft). The requirements for any particular military aircraft are usually classified and therefore it is not possible to quote examples in this document.

In addition as mentioned in the introduction, the military environment is enhanced by a number of deliberate and malicious man-made threats. The best known of such threats is that of nuclear electromagnetic pulse (NEMP). This is the intense pulse arising from detonation of a nuclear warhead and it has been felt for many years that the NEMP may be the prime motivation for a detonation outside the atmosphere.

A2.2 Civil aircraft

Civil aircraft have, in the last ten years, been equipped with safety critical electronic systems. Considerable work has been done, internationally via The European Organisation for Aviation Equipment (EUROCAE) for Europe and the Society of Automotive Engineers (SAE) & The Electromagnetic Effects Harmonisation Working Group (EEHWG) for the entire world to arrive at an agreed set of environments for civil aircraft.

The high intensity radiated field (HIRF) environment has been divided into four environments:

- The *Normal* environment
- The *Severe* environment
- The *Certification* environment
- The *Rotorcraft Severe* environment

The **Normal environment** is the HIRF environment that can be experienced at airfields, usually as a result of the transmitters on the airfield which are part of the operational support infrastructure. It is considered that many aircraft experience parts this environment, perhaps fleetingly, on a daily basis.

The **Severe environment** is the environment which could possibly be experienced by flying anywhere in the World, the only constraint being that the flight path must be within the rules set out by the International Civil Aviation Organisation (ICAO).

The **Certification environment** is based on the severe environment, however, some of the aircraft to transmitter distances have been re-assessed on the basis of likelihood of occurrence in normal flying conditions.

The **Rotorcraft Severe environment** is once again based on the severe fixed wing environment however, the much smaller separation distances that can be achieved with rotorcraft has been considered.

These environments are shown in Table A1, drawn from Refs. 6 & 7. The philosophy and history behind the development of the agreed environment for civil aircraft is chronicled clearly in Ref. 8.

It can be seen that even large civil aircraft that do not fly at low altitude or approach high power transmitters at short range are required to demonstrate resilience to extremely large fields. In addition to the radio frequency HIRF environment requirements placed on civil aircraft by the regulatory authorities of the European Joint Airworthiness Authorities (JAA) and the U.S. Federal Aviation Administration (FAA), as mentioned earlier, civil aircraft must continue flying safely during and after a Lightning attachment to the airframe. The lightning threat is defined in Ref. 9.

The RF electromagnetic environment created by distant sources (HIRF) is only part of the environment in which systems must continue to operate. All aircraft utilise on-board radio systems using externally mounted antennae. Such systems produce a RF electromagnetic environment external to the skin of the aircraft and this must be part of the requirements to be met by the design. In addition, internal to the aircraft skin the large numbers of electrically diverse systems (high power switched loads, low level analogue and digital systems) are required to be installed in close proximity. Of particular concern is the cable loom design where potentially highly sensitive systems are tightly coupled (electromagnetically) to emissive systems. This is the internal, inter-system environment and yet another design requirement.

Equipment used in aircraft is required to be qualified in susceptibility terms to a range of time domain and frequency domain signals. These levels are chosen on the basis of the combined external environment and its transfer function through the aircraft skin to the systems and the coupling between co-sited systems. In addition, the equipment must be qualified to acceptable levels of emitted signal in both time and frequency domain. This controls the inter-system threat levels and is constrained, in the main by the need to minimise noise levels in the receiver channels of on-board radio systems.

The aircraft prime contractor must firstly choose the appropriate qualification requirements for the aircraft equipment in line with the requirements for the entire aircraft. It is then important to ensure that the system integration design, systems installation design and airframe design (from an electromagnetic point of view) are all complementary and aiming towards achieving threats below the qualification levels of the equipment in order to ensure a successful aircraft demonstration of resilience.

The rest of this annex will outline this process for achieving successful qualification of the complete aircraft.

A3. Overview of aircraft safety-critical systems

There is a growing use of electronics in the safety critical functions of aircraft systems. Those of clear concern include:

- The flying controls
- The engine controls
- The electrical generation control system.

If any of these systems are upset from their normal operation, then there is a high risk of loss of the aircraft.

There are other systems that can be safety critical or safety involved, for example:

- Cockpit display systems
- Fuel management systems
- Air data systems

As a result of much greater integration in aircraft systems many more functions become involved in the safe flight of the aircraft, either during normal operation or during a reversionary situation.

In order to achieve the reliability required for safety critical systems (loss of the function through any one cause must be occur less than once in 10^7 flying hours for military aircraft and one in 10^9 for civil aircraft) such systems are arranged as parallel, multiply redundant systems. For example, flying control systems entirely using electronic systems (Fly-by-wire) are operated as quadruplex systems for military aircraft and often quintuplex for civil aircraft. Unfortunately, such redundancy does not necessarily protect the system against the effects of EM illumination because all the redundant system channels may be exposed to the EM threat simultaneously and could suffer common-cause errors or malfunctions.

A4. The complete qualification process

The potential and recognised routes to qualification are given in Ref.7. This reference takes account of criticality of the system and the level of demonstration required. It is worth examining the design and development process more thoroughly. The next section attempts to explain the process adopted to cope with the particular constraints of the aerospace industry.

A4.1 The design and development process

The design and development process outlined in Fig. A1 has become accepted for the design, development and qualification of complex, highly integrated, safety critical systems in aircraft. The philosophy of the process is based around establishing the validity of the design as early as possible (i.e. pushing exposure of design risk as early as possible in the programme). There is a growing reliance on computational analysis in which the detail of the model grows throughout the programme thereby reducing model-rebuilding time.

It is clear that the qualification of the complete aircraft is based on five sources of data, namely:

- a) Design traceability & a deviations register
- b) Airframe and system installation component test results
- c) Equipment test results (including concessions)
- d) Computational analysis results
- e) Whole aircraft test results

Such a wide source of data arises from recognition that it is impossible to test all systems, in all modes across all frequencies with all modulations and from all angles of illumination. The qualification is therefore targeted depending on criticality.

The use of computational analysis in the process is now more common. It contributes to the exploration and selection of design concepts. It enables a quantitative basis for specification and design guide setting and an examination of critical areas requiring deviations from the design guidance.

The analysis is also vital as a test support tool, contributing to the design of the test arrangement, determining test levels, extrapolating from the test conditions to the real situation and finally providing data on areas in which test evidence cannot be acquired.

The design and development process illustrated is more or less accepted for complex airborne system design however, it is recognised that the entire process may not always be used. For example, because of the extremely long airframe life available compared to the rate at which systems become obsolete, it is common to upgrade systems within an existing airframe. A sub-set of the process described in Figure A1 would be used.

A4.2 Codes of Practice and Specifications.

It is shown in the design process that design guides must be applied to the systems integration, systems installation and airframe designs. At a certain level such design guidance already exists (see Ref.10 & 11), however it is usually appropriate to produce design guides at a more detailed level (sometimes called "process specifications") which are particular to the product under consideration and the internal technical activities. It should be remembered that many engineers not knowledgeable in EMC design must be involved in incorporating the appropriate design features in the product.

The value that the aircraft prime contractor brings to the EMC design of the aircraft is the appropriate balance of equipment specification, system installation and airframe design to match the requirements for EMC performance of the complete aircraft.

Although the systems in an aircraft remain fixed relative to one another once the aircraft design and qualification is complete, the variety of external threat interaction geometry is huge. Furthermore, the aircraft and its systems installation is not and never can be a RF circuit. Large build variations must be expected. Finally, the very long service life of aircraft (>30yrs) poses an in-service surveillance problem.

A4.3 Test Procedures

The process of Fig.A1 shows test evidence requirements at a number of levels, namely:

- Components (e.g. connectors, cable screening material etc)
- Equipment (e.g. a flying control computer)
- Airframe component (e.g. wing tank)
- Whole aircraft

There are many well-known test techniques for component testing and these do not differ from those applied in the commercial or industrial sectors. The equipment test techniques have been continuously improved since the late 1960s and do represent the very latest equipment testing methodology. Examples of such approaches are given in Ref. 12, 13 &14. The documents referenced are the latest versions of the specifications. In practice, the previous versions (prior suffix letter) are often used even at present.

The latest equipment test standards referenced have been developed in order to address a number of recent concerns which have arisen as a result of business changes in the technological and economic areas. Typical developments include:

- Improvements in accuracy and repeatability of results.
- Reductions in testing costs
- Improved representation of the environment found in use.

Testing of airframe components is often limited to Lightning survivability testing and the details of such test procedures are derived on a case-by-case basis. However, there is much good advice in Ref. 15. In the case of electromagnetic testing of airframe components the details of the test procedure must be derived for any particular situation.

In the case of whole aircraft testing there are many challenges, including:

- High level illumination of a large object.
- High level illumination at ground level.
- Ensuring appropriate flight systems modes during testing.
- Targeting testing to ensure effective qualification within a realistic budget.

There is some advice published and this can be found in Refs. 16, 17 & 18. Once again the derivation of the detailed test procedure must be tailored to the details of the product being tested and the objectives of the test. As stated earlier, the design and development process of Fig.A1 produces evidence of qualification much earlier than the final aircraft test. There is also the possibility of acquiring much greater detail at an earlier stage. This elevates the final aircraft test to the status of confirmatory testing. This aim is totally consistent with pushing risk of design failure earlier in the programme thus minimising costs of re-working.

A5. Current developments

As is the case for any situation, regulatory and customer demands and the advances in technology to achieve those demands, is continually requiring new considerations in the EMC design, development and clearance of aircraft. The following advances require due consideration in the field of EMC.

- Ever-increasing threat levels
- Integrated modular avionics (IMA)
- More electric aircraft (MEA) proposals
- Demands for in-service hardness assurance (HARMS)
- Use of commercial-of-the-shelf (COTS) components

A5.1 The ever-increasing threat levels

The ever increasing threat levels and diversity of signals against which aircraft are to be qualified requires constant review of the development process to ensure that effective clearance, within affordable budget constraints is achievable.

Whole aircraft test techniques such as direct current injection in which the current induced on the airframe during illumination is injected directly on to the airframe are being developed and validated. Such a technique greatly reduces the power required to simulate a given field strength in the HF and VHF bands. At higher frequencies, techniques that do not require huge UHF and microwave power and make use of laboratory based testing of the systems or equipment in mode-stirred chambers are being considered.

A5.2 Integrated Modular Avionics (IMA).

IMA systems have been considered for some time (~10years) but only recently have such systems appeared in operational aircraft (Boeing 777 & F22). The concept of the architecture is associated with the hardware and software packaging of future avionic systems into re-usable, re-configurable similar modules. At present each piece of equipment in an aircraft is unique to a particular function in that aircraft. The packaging comes in all shapes and sizes and the equipment performs a given function once supplied with aircraft power. In the case of IMA there will only be a small number of functionally different (from a hardware point of view) modules, packaged identically and mounted in a rack (viz. VMS). The functionality of the modules will be more-or-less derived from the software used within the module. The systems will be quickly re-configurable on the ground and ultimately re-configurable in the air as faults arise and missions change.

The cost of modules will be much reduced compared to existing aircraft equipment. The challenge for the EMC community is the development of test and clearance techniques at module, system and whole aircraft level that can meet the cost constraints and flexibility of the new architecture.

A5.3 More electric aircraft (MEA) proposals.

There is a desire to reduce the use of hydraulics in aircraft systems such as flying controls and undercarriage deployment. High power electric actuators would replace the hydraulics. It is inevitable that this will lead to much higher currents flowing in the systems cables and the airframe than at present.

These challenging mixes of low level sensitive signalling and extremely high power systems in very close proximity will require a review of the design guidance and codes and practice for systems

installation design. It is possible that the low frequency conducted susceptibility limits may have to be increased in the equipment qualification specifications.

A5.4 Demands for in-service hardness assurance (HARMS).

Much of the electromagnetic hazard protection in aircraft systems is ensuring that safety critical functions are not upset during illumination in high intensity fields. The aircraft type is demonstrated to be free of such effects prior to entry into service.

During service life, normal maintenance, wear & tear and damage will result in changes to the performance of such protection. Such changes are not tested for during service life and present technology makes such testing difficult or even impossible. This issue is starting to be addressed by the industry.

A5.5 Use of commercial-of-the-shelf (COTS) components

There is increasing pressure to reduce system costs by incorporating COTS equipment in aircraft. Considering the remarks made earlier about the intensity of the environment for aircraft, the use of COTS is viewed with some concern by industry specialists. The difference between the COTS equipment qualification levels and those ideally required by aircraft application must be made up by installation techniques and design. Such an approach is not optimal from a weight and volume point of view. This subject is being addressed in a number of forums.

A6. References

1. Def Std ??? TBA
2. NES ?? TBA
3. OB PROC
4. Mil Std 464
5. AEP4
6. EUROCAE USERS GUIDE
7. AC/AMJ 20-1317 — The Certification of Aircraft Electrical and Electronic Systems for Operation in HIRF Environments.
8. Development of the HIRF Environment, D.A. Bull, Final Report, ERA Report 98-0816, ERA Project 35-03-0667, October 1998.
9. Civil aircraft lightning threat
10. BSG 257, Parts 1 & 2.
11. Integrated Hardening Design Guide
12. Def Std 59-41
13. Mil Std 461E
14. DO 160E
15. Lightning test procedures TBA
16. BSG 257, Parts 3
17. See ref. 7
18. See ref 11

Figure A1

The Electromagnetic Hazard Protection Design and Clearance Process Framework

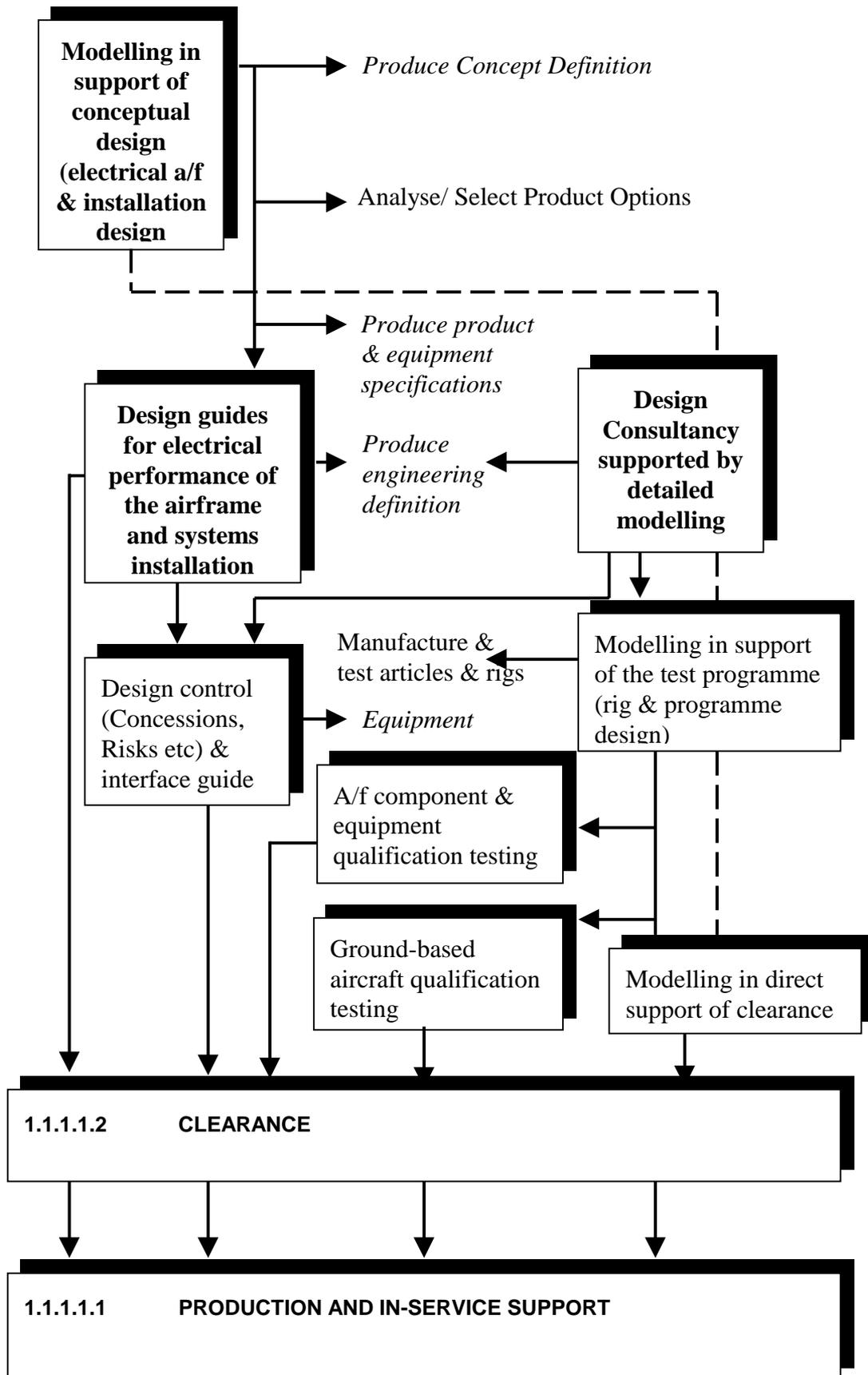


Table A1

The Internationally agreed High Intensity Radiated Field (HIRF) strengths applied in the certification process of civil aircraft

Frequency (Hz)	Field strengths (Volts/metre)							
	Rotorcraft Severe		Fixed Wing Severe		Certification		Normal	
	Pk	Av	Pk	Av	Pk	Av	Pk	Av
10k - 100k	150	150	50	50	50	50	20	20
100k – 500k	200	200	60	60	50	50	20	20
500k - 2M	200	200	70	70	50	50	30	30
2M — 30M	200	200	200	200	100	100	100	100
30M — 70M	200	200	30	30	50	50	10	10
70M — 100M	200	200	30	30	50	50	10	10
100M — 200M	200	200	90	30	100	100	30	10
200M — 400M	200	200	70	70	100	100	10	10
400M — 700M	730	240	730	80	700	50	700	40
700M — 1G	1400	240	1400	240	700	100	700	40
1G — 2G	5000	250	3300	160	2000	200	1300	160
2G — 4G	6000	490	4500	490	3000	200	3000	120
4G — 6G	7200	400	7200	300	3000	200	3000	160
6G — 8G	1100	170	1100	170	1000	200	400	170
8G — 12G	5000	330	2600	330	3000	300	1230	230
12G — 18G	2000	330	2000	330	2000	200	730	190
18G — 40G	1000	420	1000	420	600	200	600	150