General issues of ensuring electromagnetic compatibility of aircraft on-board equipment

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Abstract. The article examines the effect of electromagnetic interference on the electrical components of the aircraft from the point of view of external and internal electromagnetic environments. The external electromagnetic environment consists of high-intensity radiated fields and lightning strikes. Internal threats can be divided into four types: intersystem, intra-system, induced radiated fields of high intensity and internal transients during a lightning strike. On the basis of the considered impact, the article defines the directions of development in the field of providing electromagnetic compatibility for an all-electric aircraft.

1 Introduction

Aircrafts are constantly exposed to intense electromagnetic effects from aerodrome radars, broadcast transmitters, radio electronic devices and lightning strikes [1]. Any electromagnetic influence has a negative impact on the operation of on-board equipment, therefore it is necessary to qualitatively and quantitatively assess this influence and implement all necessary measures to neutralize this influence (ideally) or minimize this impact. Electromagnetic influence is included in the concept of electromagnetic compatibility, which combines the entire spectrum of electromagnetic interference, from a slight voltage deviation to a destructive pulse current.

2 Electromagnetic compatibility parameters on the aircraft board

Electromagnetic Compatibility (EMC) describes the ability of a system, a piece of equipment, or some other electrical device that utilizes electromagnetic energy, to operate in its intended environment without suffering an unacceptable degradation in its performance, or negatively impacting the ability of another device to perform its intended function (Fig. 1).

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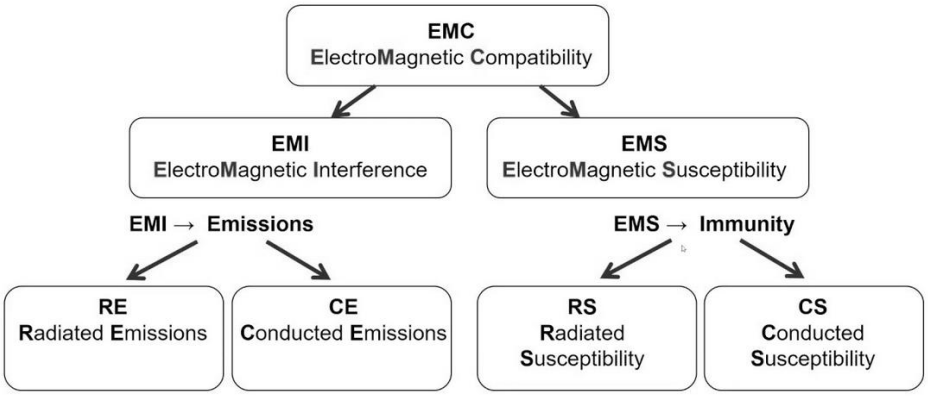

Fig. 1. The relationship of the basic concepts of electromagnetic compatibility.

Electromagnetic Interference (EMI) is either a continuous or intermittent electromagnetic disturbance or electrical signal that, if not properly addressed, can be transmitted into, or out of, electronic equipment and can disturb the normal and intended operation of electronic systems (Fig. 2).

EMI can be divided into two categories: Continuous interference and Impulse interference.

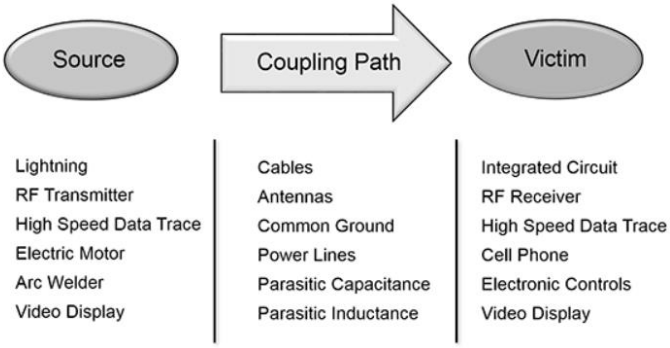

Fig. 2. The way of coupling path of the electromagnetic interference.

Electromagnetic compatibility of electrical units is defined as the ability of these units to work simultaneously with other technical means in a real electromagnetic environment (EME) under external influence, performing regular functions without interfering with other technical means and electrical units [2].

External influences include disturbances of natural and techno genic origin, including electrostatic discharge (ESD). The frequency spectrum of interference extends into the range of many gigahertzes. The presence of interference can lead to malfunctions in the operation of electronic devices, in some cases to their failure [3].

The aircraft equipment must meet the requirements of EMC, and the importance of this factor is confirmed by the following main trends in technology:

- the complication of the electromagnetic environment at all stages of the aircraft life cycle;

- an increase in the number of key elements generating pulse interference during switching, as an inevitable by-product of digital technology, which leads to an expansion of the spectrum of interference signals inside the object;
- semiconductor IC crystals have smaller physical dimensions and levels of information and supply voltages and, as a direct consequence, are more likely to experience failures or damage due to EM interference;
- expanded use of electronics to control actuators that replace mechanical, hydraulic, etc. devices.

The external electrical system of a typical aircraft (Fig. 3) includes well-known threats, where high-intensity radiated fields and lightning strikes are considered the main hazards at the aircraft level [4-5]. This category evaluates the interaction between the aircraft and ground communication stations and lightning strikes. In addition, vital systems must be able to operate correctly during and after the occurrence of an impact, and precautions should be taken to ensure that the resulting currents do not act as fuel igniters [6]. Typically, navigation and communication equipment such as radio altimeters, an automatic direction finder, an omnidirectional UHF band, and air traffic control systems may depend on external sources such as radio communication stations and other radar infrastructures [5].

Internal electrical system can be divided into four types of threats: intersystem, intra-system, induced high-intensity radiated fields and internal transients during a lightning strike [5-6]. Within this category, avionics, wiring and other electrical systems are evaluated in order to assess their impact on the safe operation of the surrounding equipment. In a typical aircraft, such elements are represented by electronic flight control system, auxiliary power plant, radio and other electronic equipment (Fig. 3) [7].

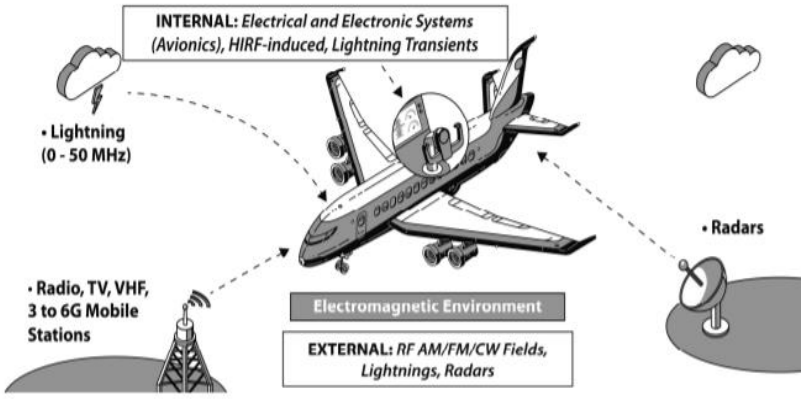

Fig. 3. Electromagnetic environment of the aircraft.

The external electrical system is highly dependent on mobile communication improvements, i.e. the current 5th generation (5G). The interaction of the aircraft in flight with 5G mobile communications operating in frequency bands up to 28 GHz, in an unfavorable scenario, may interfere with the operation of radar altimeters (4.2–4.4 GHz). Such equipment is present on most aircraft and is responsible for safety-critical flights. Consequently, an external electrical system experiencing such EMI is exposed to potential adverse effects, since in an aircraft with autonomous control, control over its maneuverability during and after exposure can be completely neglected. This scenario is compounded by the implementation of autonomous or remote control, as in the case of an Airbus aircraft with electric vertical takeoff and landing (eVTOL), CityAirbus, in which the

absence of a direct human reaction to changes in control and navigation will increase the requirements for electric power supply system [8]. The Pixhawk PX4 autopilot system was disrupted due to the modulation of the 2.001 GHz signal using a 300 Hz PWM waveform.

Lightning strikes, although dangerous, are a phenomenon that occurs on average once a year or every 3,000 flight hours [9]. Nevertheless, the transient effects of lightning in relation to avionics and other components are being evaluated, since large currents can flow through these systems, causing serious malfunctions or short-term malfunction. In addition, failures in the interface circuits of the equipment caused by high-intensity radiated fields are of serious concern, since the wiring acts as an antenna at $f \leq 400$ MHz, and at $f > 400$ MHz, energy is usually transmitted through the apertures of the equipment [10].

3 Requirements for the electricity quality on the aircraft board

The requirements for reliable operation of technical units (TU) in the presence of interference and changes in the parameters of the supply network relate to the concept of electricity quality (EQ) and are normalized by the current standards for types of equipment. The requirements for power supply systems (PSS) of airplanes and helicopters are regulated by GOST R 54073-2010 (RF) and CT-160D (I), RTCA/DO-160E for avionics (Table 1).

Table 1. Aerospace standards.

Field	Standard	Details
Aerospace	DO-160	Aircraft EMC requirements
Aerospace	SAE ARP5412B	Aircraft lightning environment and related test waveforms
Aerospace	SAE ARP5416A	Aircraft lightning test methods

To ensure reliable operation of the equipment during operation, it is subjected to acceptance and periodic tests under production conditions according to standards in accordance with the requirements specified in the standards. For these purposes, special testing equipment is used that strictly reproduces the norms of standards and other regulatory documents – simulators of power supply systems. In addition to the standard norms, it is of interest to simulate more stringent values of the EQ indicators compared to those established in regulatory documents. The occurrence of such values during long-term operation can create a critical situation on the aircraft board. To avoid this (or significantly reduce it), the on-board equipment must have a certain margin of stability. For these purposes, the test equipment must provide values of the EQ indicators exceeding the requirements of the current regulatory documents [11].

The indicators of the electric power energy quality of direct current include:

- Voltage deviation. Prolonged, more than a second, voltage changes;
- Voltage dips or outliers for tens of milliseconds;
- Superimposition of high-frequency pulsations on a constant voltage.

The indicators of the electric power energy quality of alternating current include:

- Voltage deviation. Prolonged, more than a second, voltage changes;
- Frequency deviation;
- Voltage dips or outliers for tens of milliseconds;
- Superposition of higher harmonic voltages;
- Frequency change (deviation);
- Phase shift. Phase entanglement.

The main source of electromagnetic interference is the device blocks, which have their own radio emission due to surface currents that appear due to leakage at the junctions, connectors, insufficient tightness and external guidance additional sources of radiation are the supply cables. These disturbances are caused entirely by the features of the equipment. Other types of interference occur during the flight of the aircraft caused by factors external to the instrument compartment of the aircraft complicate the electromagnetic situation.

4 The effect of external electromagnetic interference on the operation of aircraft systems

Electric fields are caused mainly by the electrification of the aircraft, the main causes of which are the interaction of aircraft with magnetospheric plasma. Intense electron fluxes of high-energy electrons form a negative current on the aircraft, leading to charging of the device to high negative potentials, which, with poor surface and volumetric electrical conductivity, leads to a sharply inhomogeneous charge distribution over the surface and the possibility of a breakdown of the compartment shell. Streams of electrons and hard cosmic radiation can penetrate into the apparatus and lead to the appearance of charges on electrically isolated structural parts and on dielectrics, the values of which are sufficient to break through dielectrics and insulating coatings. Discharge phenomena between inhomogeneously charged parts of the aircraft, in addition to direct destruction of electronics (in the case of sufficiently high power), create intense electromagnetic interference (even at low power) and disrupt the operation of electronic devices. When an aircraft passes through the Earth's atmosphere, a malfunction of the equipment can also be caused by lightning discharges.

During the operation of radio-electronic equipment (REE), pulsed conductive electromagnetic fields (CEMF) also arise, which directly and through parasitic wire-body communication capacitances, passing through the REE, get to the input of functional equipment and disrupt its operation (Fig. 4).

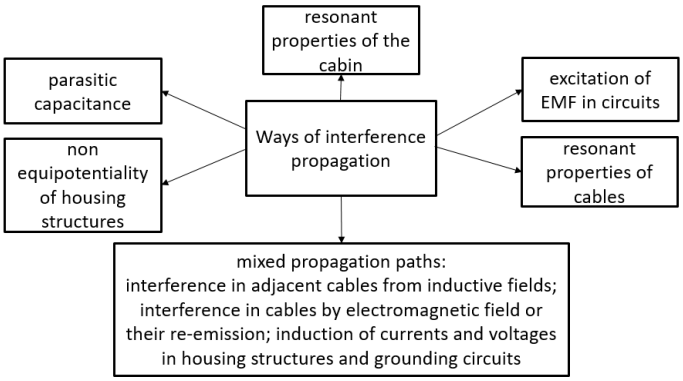

Fig. 4. EMF propagation paths.

The aircraft can be in the main beam of the antennas of powerful transmitters, thus being exposed to extremely high intensity electromagnetic fields [1]. In this case, the electronic systems of the aircraft must function without violating the normal regime. Often, the intensity of such fields can exceed sanitary standards, which, together with the technical difficulties of implementing such fields, makes it difficult to test equipment.

The frequency of powerful impacts may vary, but on average, every civilian aircraft is exposed to lightning once a year. At the same time, its body becomes part of the arc

channel, which leads to huge pulse currents flowing through the body and therefore through the systems. This requires ensuring long-term operation of the systems during induced pulse currents. Also, the threat of lightning requires a demonstration of structural integrity and fuel safety during and after its impact. It should be mentioned that airplanes, by their nature, are a "flying fuel tank", and therefore the risks of fuel explosion, especially in the event of a lightning strike, should be taken into account.

Electrostatic discharges (ESD) for aircraft equipment pose a serious threat by affecting the cable systems of the aircraft. Induced currents and voltages entering the inputs of the system units can cause failures and other system malfunctions with unpredictable consequences. ESD is a serious danger when refueling aircraft, increasing the risk of explosion under certain conditions. The study of cable systems [12, 13] shows that they remain one of the most sensitive elements of electronic aircraft systems. They can be considered as "random" antennas that effectively perceive the influencing fields, including from the ESD. Having a certain current transformation coefficient [12], the ESD excites currents in shielded cable lines, which create interference voltages at the inputs of the electronic components of the aircraft system.

An airplane during a thunderstorm may fall into the field of lightning. This usually happens when flying through thunderclouds, as well as during takeoff and landing. Most incidents of lightning strikes go unnoticed and are manifested only by minor failures of the electronics in the aircraft system [14]. There are a number of government requirements for aircraft that determine their suitability for flying in any weather, they are called Airworthiness Standards. To date, there are a lot of methods and technologies used to create reliable protection against lightning.

Aircraft protection from lightning can be carried out in various ways [15]. The main task of such systems is as follows:

- preventing the slightest spark from occurring in the aircraft fuel system (this is especially true for fuel tanks located in the wings);
- compensation for the internal charge that accumulates due to the operation of turbines, electronics and the interaction of the aircraft body with cloud charges (their own charge can cause lightning discharges when flying through condensed clouds that carry positive charges);
- protection of electronics, crew and passengers from damage by electrical discharges;
- shielding of engines and radar systems;
- removal of the corona effect.

The cause of semi-artificial lightning can be the aircraft's own charge, accumulated on the skin and body of the aircraft. The compensation technologies are used to remove this phenomenon. The action of these technologies is based on the artificial generation of the opposite polarity charges. In this way, an equilibrium is achieved in the magnitude of the charges, and the machine does not have the potential of any pole. Protecting the aircraft from lightning and equipment failure on the aircraft also includes the layout of components. Fuel tanks are installed no closer than 0.5 meters to the wing edge, leaving enough space for the operation of the shielding system and protection equipment. The structural elements of the aircraft are combined into a common mass, which greatly facilitates the possible consequences when an electric lightning charge hits. The cabin body and cockpit are reliably protected by screens and are not electrically connected to the aircraft skin. Therefore, in the event of a lightning strike, passengers and crew remain unharmed, although it is possible to observe a flash or hear a sound from outside.

The equipment used in the aircraft must be described in terms of susceptibility to signals in the frequency and time domain. These levels are chosen as functions of the intensity of the environmental fields, their attenuation by the aircraft body and intersystem

interaction. In addition, the equipment must be qualified for acceptable levels of interference emission in the frequency and time domain. This allows to manage intersystem threat levels. However, this method is mainly limited by the need to minimize interference levels in the receiver channels of embedded radio communication systems.

The developer must select the appropriate specification requirements for the aircraft equipment in accordance with the requirements for the entire aircraft. It is important to ensure that the system integration project, the system installation project and the aircraft body project complement each other from an electromagnetic point of view and all of them are aimed at achieving a threat level below the equipment qualification levels in order to guarantee the ability of the aircraft systems to successfully withstand violations of the integrity of functional safety.

Work on standardization of electromagnetic compatibility requirements is carried out at the international, European and National levels. At the global level, the main burden is borne by ISO (International Organization for Standardization) and IEC (International Electrotechnical Commission), a division of which is CISPR (International Special Committee on Radio Interference – International Special Committee to Combat Radio Interference). At the European level, this work is carried out by ECS (European Committee for Standardization) and ECES (European Committee for Electrotechnical Standards) as well as EIST (European Institute for Standardization in the Field of Telecommunications).

Civil aircraft have been equipped with secure critical electronic systems in recent years. This work was coordinated by a number of international organizations in the field of aircraft equipment (EUROCAE [16], CAE, EEHWG), which made it possible to achieve a consistent set of environments for civil aircraft worldwide [17].

The most relevant and currently used EMC standards in the aerospace industry are RTCA DO160G (civilian), EUROCAE/ED 14G (civilian), MIL-STD461G (military) and NATO STANAG 4370 - AECTP.

In addition, for example, Airbus and Boeing support internal standards. In addition to general issues, such guidelines cover specific cases related to the internal combustion engine. Broadband emissions produced by jet engine igniters are widely considered, but specific EMI emissions have not yet been included.

Thus, when considering the issues of aircraft EMC, several main directions can be distinguished:

1. Protection of on-board equipment from the effects of ground-based devices.
2. Protection of radar and navigation equipment and communication channels from electromagnetic radiation.
3. Protection against direct and indirect lightning.
4. Ensuring the uninterrupted operation of the aircraft power supply system.

The last point is most acute in more or an all-electric aircraft, since an increasing number of electrical units are connected to the power supply systems, the operation of which depends on such parameters as the interval of operation, the nature of the load, power consumption, phase shift, operation during the electric start of the aircraft engine, operations related to the transition (switching) from power from one electricity sources to others, including switching from power or to power from external sources, etc.

5 EMC requirements on board an all-electric aircraft

All-electric aircraft are an aircraft with a single centralized power supply system that provides all the energy needs of the aircraft [18].

The possibility and expediency of creating aircraft with fully electrified equipment is currently due to:

• the development of power electronics and the development of high-power semiconductor converter devices and contactless solid-state switching and protective equipment based on them;

• the development of new magnetic materials and the creation on their basis of powerful sources of electric energy and motors of electromechanical drives of flight control systems, which are not inferior in their main characteristics to hydro- and pneumatic drives;

• significant successes in the field of microelectronics and microprocessor technology, which have opened up real prospects for the introduction of digital control systems for the electric power complex.

The experience of operating aircraft shows that in terms of versatility, reliability, ease of operation and unification of equipment, electric energy has significant advantages over other types of energy.

On an all-electric aircraft, electric energy is used to power the most energy-intensive systems that have traditionally used hydraulic and pneumatic energy for their operation (fig. 5). Such systems include:

1) the hydraulic system of the aircraft [19], which provides:

• chassis releasing/removing;
• opening/closing cargo hatches and doors;
• aircraft engine start-up system;
• steering surfaces control and wing mechanization, etc.

2) the systems that require air extraction from aircraft engines:

• air conditioning system in the cockpit and in passenger cabins;
• anti-bleaching system of the wing and air intake.

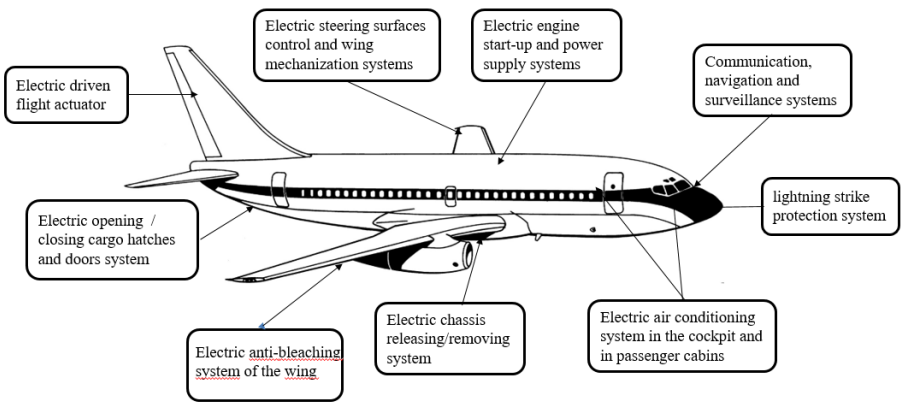

Fig. 5. Scheme of an all-electric aircraft systems.

For an electric aircraft, several more areas of research can be identified:

1. Ensuring the requirements of the EMC of the power supply system in terms of compliance with standards for the quality of electricity on the aircraft board.

2. Provision of the specified parameters of electromagnetic environmental inside the aircraft, taking into account the appearance of new electrical units with sharply variable load, as a result of which there is an imbalance of active and reactive power, causing the occurrence of higher harmonics, entailing deviations of almost all indicators of the quality of electricity in the power supply system.

3. Protection of the on-board cable network, including power, control, measuring, signal cables from induced currents.

4. Protection against the accumulation of additional static charges on the surface of the aircraft, taking into account the electromagnetic environmental created by electrical units.

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