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Research Article

Demystifying Electromagnetic Compatibility in Modern Aircraft Systems

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Abstract:

Electromagnetic compatibility in modern aircraft systems is an integration-driven engineering discipline whose importance grows directly with the electrification of onboard architectures. As aviation transitions toward more-electric configurations, the density of switching power electronics rises sharply, multiplying broadband interference sources across airframes that simultaneously demand higher functional reliability from safety-critical avionics, navigation, and flight control systems. This article examines electromagnetic interference mechanisms, source characteristics, functional degradation effects, margin quantification, the gap between equipment-level and system-level qualification, common misconceptions, and design principles applicable across engineering disciplines. Evidence drawn from documented failure events, controlled susceptibility testing, cable resonance characterization, and hybrid power system validation shows that passing qualification tests does not, on its own, prevent installed-system EMC problems, and that adequate compatibility margins must be engineered proactively through integrated, multidisciplinary design decisions made from the earliest stages of aircraft development.

1. Introduction: The Critical Role of EMC in Aircraft Systems

1.1 EMC as an Integration-Driven Engineering Discipline

Electromagnetic compatibility in aircraft systems is fundamentally an integration-driven engineering challenge rather than a standalone compliance activity. Modern aircraft rely on tightly coupled electrical, electronic, and structural systems that share common power sources, grounding networks, and physical space. As aircraft electrification advances, the number of electric power sources onboard increases correspondingly, which directly raises the risk of EMC-related failures across interconnected electronic equipment [1]. Electromagnetic interactions under these conditions are inevitable and must be actively managed to preserve functional integrity across all operating conditions. All electronic systems must coexist across diverse frequency bands while maintaining required safety margins throughout the aircraft's operational envelope—a constraint that grows more demanding as power electronics density continues to rise [2].

1.2 The Business Case for Proactive EMC Management

As aircraft architectures evolve toward higher levels of electrification, power density, and functional integration, EMC directly influences system reliability, certification risk, safety assurance, and operational performance. In the context of electrified propulsion, power electronics play a crucial role in electricity generation but simultaneously cause substantial electromagnetic disturbances that scatter inside the aircraft, entering cables and electronic systems [1]. Inverter switching behavior is a particularly significant contributor: because the rise and fall time of inverter switches can be as short as several tens of nanoseconds, the inverter generates electromagnetic energy extending up to several hundreds of MHz, creating broadband interference across safety-critical systems [1]. Signal transmission reliability of cable harnesses under such conditions is essential to both aircraft engine performance and flight safety, particularly as aircraft operate in increasingly complex electromagnetic environments [2].For HIRF compliance, an aircraft's critical electronic systems must be able to withstand electromagnetic disturbances up to 40 GHz during normal operation [1]. The FAA mandates that all aspects of electrical wiring, installations, and aircraft-level systems satisfy these requirements before an aircraft is considered safe for operation. Engineers must balance competing requirements including cable shielding, routing optimization, and inverter switching characteristics as early as possible in the design cycle, since late-stage changes can compromise motor efficiency or add prohibitive weight [1]. Addressing EMC issues after integration is orders of magnitude more costly than resolving them at the circuit or architecture level [3].

1.3 Scope

This article adopts a technical explanatory approach accessible to non-EMC specialists while maintaining engineering rigor. The subsequent sections cover the physical mechanisms of electromagnetic interference, EMI sources in aircraft electrical systems, functional impacts and performance degradation, emissions and susceptibility margin analysis, equipment-level versus system-level EMC considerations, common misconceptions and practical guidance, and design principles for multidisciplinary teams [2].

2. Electromagnetic Interference: Understanding the Energy-Coupling Phenomenon

2.1 Fundamental Definition

EMI is the coupling of electromagnetic (EM) energy between an EM energy source and a victim system through one or more coupling mechanisms. In the aircraft environment, EMI coupling occurs through conducted paths—power lines, signal lines, grounding systems, and common impedance networks or through radiated paths from wires, equipment enclosures, or structural members acting as unintentional antennas [4]. Capacitive coupling, inductive coupling, and common-mode coupling arise when electric and magnetic fields of one conductor interact with another, with current flowing through shared return paths or ground reference planes. Experiments with wireless systems on spacecraft confirm that these coupling mechanisms are not theoretical abstractions: when a new electromagnetic source is activated, the performance of a co-located receiving system degrades in a frequency-selective, path-dependent manner that begins immediately upon source activation [5]. EMI is often due to transients caused by switching-type electronics that have wide-band spectral content far beyond the operating frequencies of the equipment that caused the EMI in the first place [5].

2.2 The Source-Path-Victim Model

The source-path-victim model defines the source as any system that emits electromagnetic energy, intentionally or otherwise; the coupling path as the physical structure that propagates that energy; and the victim as any system whose function is adversely affected by the energy. This three-element framework is practically useful because it identifies three independent points of intervention. Effective EMC design addresses all three: minimizing emissions at the source through filtering, shielding, and circuit design; attenuating coupling through cable design, routing, separation, and grounding; and hardening the victim through filtering and robust circuit design [4]. In civil aviation radio communication environments, interference sources have been shown to couple indirectly into protected frequency bands through intermodulation, where signals from two separate transmitters combine to produce spurious energy in an entirely different band—such as illegal FM broadcasts at 98.675 MHz and 101.25 MHz producing a detectable intermodulation product at 117.45 MHz within the protected civil aviation communication band [6]. EMC solutions do not require eliminating all electromagnetic energy—they require maintaining adequate margin between exposure levels and susceptibility thresholds under all operating conditions.

2.3 Frequency Domain Considerations

Electromagnetic interference is inherently a frequency-domain phenomenon, with different coupling mechanisms dominating at different frequencies. At lower frequencies, conducted coupling through power and ground networks dominates, with magnetic field coupling being primary. At higher frequencies, radiated coupling becomes the main mode, and structures begin to behave like antennas, making resonance an important effect. The civil aviation communication band extends from 108 MHz to 137 MHz and is adjacent to the FM broadcast radio band (87 MHz to 108 MHz), a frequency range that is especially susceptible to cross-band interference and intermodulation products [6]. Aircraft systems are therefore required to maintain EMC across a very wide frequency range—from DC power systems through computer systems to microwave communications and radar—and the techniques used to reduce interference must address the particular frequency of the interference [5].

3. Electromagnetic Interference Sources in Aircraft Electrical Systems

3.1 Power Generation and Distribution Systems

Aircraft electrical systems contain numerous intentional and unintentional sources of electromagnetic emissions, with power generation and conversion equipment representing the most significant contributor. The global push toward More Electric Aircraft (MEA) has intensified this challenge considerably, as aviation electrification drives higher switching frequencies and greater power density in onboard power electronics, both of which directly worsen the electromagnetic environment [7]. Electric actuators—which perform multiple critical functions, including flight controls, landing gear controls, and engine actuation—rely on motor drive systems whose high-frequency switching actions are a primary source of broadband EMI. Wide-bandgap (WBG) semiconductor devices such as silicon carbide (SiC) and gallium nitride (GaN), increasingly adopted in MEA for their superior power density capability, tend to generate more severe conducted and radiated EMI challenges due to faster switching transitions. Generating high-frequency common-mode voltage that can accelerate motor insulation aging, induce bearing currents, and cause crosstalk between power and signal circuits [7]. In parallel, DC-DC buck converters used throughout aircraft power distribution systems generate switching noise across wide bandwidths, and without properly designed EMI filters, the signal-to-noise ratio of the power rail degrades in a manner that directly compromises downstream electronic system performance [8].

3.2 Avionics and Digital Systems

Digital avionics and computing systems contribute substantially to the aircraft electromagnetic environment through clock signals, data bus activity, display drivers, and high-speed memory interfaces. The conducted EMI frequency range of concern in standard DO-160G spans from 150 kHz to 152 MHz, while radiated EMI extends from 100 MHz to 6 GHz, illustrating the spectral breadth across which digital avionics must be managed [7]. Integrated Motor Drive (IMD) systems, increasingly adopted to reduce cable lengths and improve power density by achieving 10% to 20% volume reduction compared to conventional separated architectures, introduce new EMC challenges by placing drive electronics in direct proximity to sensitive signal circuits inside the motor housing, where interference reflected by the motor enclosure can damage sensitive components [7]. In buck converter implementations typical of avionics power supply subsystems, switching activity at elevated frequencies produces harmonic peaks that represent the dominant EMI source, and passive EMI filters operating across an appropriate design frequency range are necessary to achieve acceptable signal quality at load interfaces [8].

3.3 Communication and Navigation Systems and Structural Sources

Intentional RF transmitters, including VHF/UHF communication radios, HF systems, satellite communication terminals, and weather radar, represent controlled but powerful electromagnetic sources whose energy can couple into susceptible systems through antenna sidelobes, cable penetrations, and structural paths. Passive structural elements act as efficient coupling structures: cable harnesses behave as unintentional antennas, connectors and discontinuities create impedance mismatches, and structural joints generate intermodulation products through non-linear contact resistance. In aircraft with 270 V common bus architectures, the interaction between power converter switching behavior and cable harness geometry creates conducted EMI paths that directly threaten system compatibility unless differential-mode and common-mode filters are systematically co-designed to address both noise types simultaneously [8]. EMI sources must therefore be classified not only by equipment type but also by their spectral characteristics, power levels, and coupling potential within the specific installation environment, as the aggregate effect of simultaneously operating sources creates an electromagnetic environment far more complex than any individual emitter alone [7].

4. Functional Impact of EMI on Aircraft Systems

4.1 Beyond Binary Failures: Performance Degradation

The effects of EMI on aircraft systems extend well beyond outright component failure. Based on wide-ranging historical experience from documented aerospace and military programs, EMI frequently produces degraded performance rather than catastrophic failure. NASA's survey of EMI incidents involving spacecraft electronic systems found many examples where EMI affected spacecraft, aircraft, and military and commercial planes; the most serious spacecraft incidents appeared to be caused by EMI lowering the electromagnetic compatibility margin of a system below the operational limit without causing a direct electrical hardware failure [9]. The effect of HIRF EMI on airborne navigation systems is to cause GNSS receivers to see an effective degradation in signal carrier-to-noise density ratio (C/N_0). Degraded C/N_0 leads to increased dilution of precision (DOP), which leads to loss of satellite lock, which ultimately leads to loss of position accuracy—all without a single hardware fault occurring [10]. This specific, reproducible, and reversible degradation pattern is one reason EMC cannot be sensibly specified in terms of pass/fail criteria alone.

4.2 Operational Context Dependency

EMI-induced effects are highly context-dependent and may only manifest under specific operational scenarios, making them particularly difficult to detect during standard qualification testing. The NASA record of documented anomalies confirms this pattern repeatedly: the UH-60 Blackhawk helicopter experienced uncommanded stabilator movements specifically when flying near high-power radio transmitters, and between 1981 and 1987 five Blackhawk helicopters crashed because they flew too close to such emitters, killing or injuring all on board [9]. The AH-64 Apache helicopter similarly exhibited susceptibility only when exposed to low-level emitters such as commercial microwave, television, and airport radar systems during operational missions—conditions not fully replicated during initial qualification. In GNSS receiver testing conducted under DO-160G Section 20, Class G conditions, signal loss events were concentrated in the 12–18 GHz frequency range, with failures at 13.183 GHz under horizontal polarization and at 14.125 GHz under vertical polarization proving both repeatable and reversible—appearing when the electromagnetic field was applied and recovering after its removal, with observable data drift during the recovery transient [10]. This reproducible, frequency-specific, and configuration-dependent behavior exemplifies the operational context dependency that makes comprehensive EMC test coverage practically impossible.

4.3 Safety and Certification Implications

From a system engineering perspective, EMC must be evaluated in terms of functional robustness across the full range of foreseeable operational environments. The safety consequences of inadequate EMC design are well documented: the F-16 fly-by-wire flight control system, which is inherently unstable and fully dependent on its flight computer, crashed when exposed to HIRF from a Voice of America transmitter, and this specific incident became one of the primary drivers for the FAA's institution of the HIRF certification program [9]. Equipment-level shielding effectiveness measurements on airborne GNSS enclosures show that in the 3–10 GHz range, structural resonances cause sharp shielding effectiveness fluctuations, and above 10 GHz, overall shielding performance degrades further, leaving receivers vulnerable to interference-induced failure—a finding validated through anechoic chamber testing aligned with regulatory standards [10]. Demonstrating compliance therefore requires not only meeting defined test limits but also confirming that adequate EMC design margins are maintained across worst-case combinations of loading, configuration, environmental stressors, and simultaneous system operation.

5. Emissions, Susceptibility, and EMC Margin Analysis

5.1 Emissions and Susceptibility in Integrated Aircraft Systems

EMC performance is characterized by two complementary quantities: emissions, which represent the electromagnetic energy generated by a system as measured conducted or radiated quantities, and susceptibility, which defines the system's tolerance to external electromagnetic stress through threshold levels that cause functional degradation. Neither concept alone determines compatibility—EMC is achieved only when sufficient margin exists between expected electromagnetic exposure and functional susceptibility thresholds. In aircraft EMC testing, this distinction is operationalized through a structured sequence of trials that examine both how much electromagnetic energy a system produces and how well it withstands externally applied fields [11]. Immunity testing within this framework evaluates how equipment handles voltage dips, surges, lightning effects, magnetic fields, radiated fields, and high-intensity radiated fields, while emissions testing verifies that conducted and radiated output remains below limits that would affect neighboring systems. The bandwidth of emissions must stay below an appropriate limit to function compatibly around other devices, and this requirement applies across both narrowband intentional transmissions and broadband unintentional ones [11].

5.2 The Source-Path-Victim Framework and Quantifying EMC Margin

The EMC margin quantifies the safety buffer between normal operation and interference. A technically rigorous framework expands the source-path-victim model into a quantitative expression:

EMC Margin = Susceptibility Threshold − (Source Emission + Path Coupling + Uncertainty)

Each term accounts for measured or predicted electromagnetic energy at the source, attenuation or amplification through coupling mechanisms expressed in decibels, the degradation threshold of the victim system, and tolerances arising from measurement uncertainty, environmental variation, and aging effects. Research on cable resonance behavior in EMC test environments demonstrates concretely how coupling path characteristics dominate the margin equation. For a single-end grounded cable system with a length of 1.8 m—the standard length adopted in automotive and component-level EMC testing per CISPR-25—the primary resonant frequency can be estimated as approximately 41 MHz using the quarter-wavelength formula, and measured resonance peaks in practice fall between 30 MHz and 41 MHz, confirming satisfactory agreement with the analytical prediction while also illustrating how parasitic capacitance and grounding configuration shift the actual coupling frequency below the theoretical estimate [12]. This frequency-specific coupling amplification directly degrades the effective EMC margin at resonance frequencies, irrespective of whether the source emission or victim susceptibility characteristics have changed.
Robust EMC design addresses this by reducing emissions at the source through filtering, shielding, circuit design, and PCB layout; attenuating coupling paths through cable shielding, separation, grounding, and structural design; increasing system tolerance through input filtering, differential signaling, and robust design practices; and maintaining adequate margin depending on criticality and uncertainty. Transfer impedance of cable screens is a directly measurable coupling path parameter: varying the transfer impedance by a factor of two produces 6 dB variations in conducted current emission results, confirming that cable shield quality is a primary determinant of coupling path attenuation and therefore of the achievable EMC margin in integrated system configurations [12]. Modern aircraft EMC testing employs reverberation chambers and open area test sites to evaluate these margins under conditions that realistically represent the electromagnetic environment experienced in operation [11].

6. Equipment-Level versus System-Level EMC

6.1 Equipment-Level Qualification

Equipment-level EMC qualification verifies that individual components meet defined emission and susceptibility limits under controlled test conditions, typically per DO-160G or equivalent standards. This approach establishes baseline performance for individual systems, enables modular qualification and supplier accountability, provides repeatable test conditions for design verification, and supports technology reuse across multiple aircraft programs. The DO-160G standard defines environmental conditions and test procedures for airborne equipment across a structured set of categories, with Section 22 specifically addressing lightning-induced transient susceptibility—a critical qualification requirement for flight-critical systems including guidance, radars, communications, engine control, and heat and air controls [13]. Standard equipment-level tests encompass conducted emissions on power and signal interfaces, radiated emissions in controlled environments, conducted susceptibility to power transients and ripple, radiated susceptibility to RF fields and HIRF, as well as lightning indirect effects and electrostatic discharge. For lightning protection specifically, DO-160G Section 22 defines protection levels from Level 1 through Level 4, with the most severe Category A and Category B zone environments requiring Level 3 or Level 4 protection for flight control avionics located in environmentally uncontrolled areas of the aircraft [13].

6.2 Limitations of Equipment-Level Testing

Equipment-level testing does not fully represent the electromagnetic behavior of integrated aircraft systems. At the system level, multiple compliant subsystems operate simultaneously and share power distribution networks with common impedances that create coupling paths, grounding structures where potential differences generate ground loops, physical space where proximity enables field coupling, and cable routing where shared bundles create crosstalk opportunities. Aircraft electromagnetic environments are also strongly dependent on operational state. During service, systems experience dynamically changing combinations of loading, switching activity, mode transitions, and concurrent subsystem operation across the full flight cycle—conditions that can alter both emission characteristics and susceptibility margins relative to standardized laboratory configurations. Compliance under controlled equipment-level test conditions does not, by itself, guarantee robust electromagnetic behavior in the installed aircraft environment. System-level EMC assessment must therefore account for installation-specific coupling paths, aggregate source behavior, and operational variability in addition to equipment-level qualification results.

6.3 System-Level EMC Behavior and Integration

One of the most challenging aspects of aircraft EMC is that equipment passing all certification tests in isolation may still contribute to interference when installed in the aircraft. Installation-dependent behavior introduces interference paths not observable during standalone equipment testing, including cable shields grounded at multiple points creating ground loops, long cable runs acting as efficient antennas at particular frequencies, structural resonances amplifying coupling at unpredictable frequencies, and common-mode currents flowing through unintended return paths. The consequence of inadequate system-level consideration is severe. For example, if RS-485 communication interfaces used in fly-by-wire flight control systems or full authority digital engine control systems are degraded or damaged by indirect lightning effects not adequately characterized at the equipment level, closed-loop feedback for flight control systems can be compromised, and engine condition monitoring functions may be disrupted in service [13]. Effective aircraft EMC programs therefore complement equipment-level qualification with system-level EMC testing of integrated configurations, installation reviews verifying cable routing and grounding, comprehensive ground testing before first flight, and flight testing across the operational envelope—increasingly supported by modeling and simulation to identify potential issues early in development [13].

7. Common Misconceptions about EMC in Aircraft Programs

7.1 Misconception 1: "EMC is the Responsibility of Specialists Only"

A persistent misconception is that EMC is solely the responsibility of specialists or test organizations. EMC performance is strongly influenced by design decisions made across multiple engineering disciplines, often long before formal testing occurs. The EMC design of the Flap and Slat Electronic Control Unit (FSECU)—the core component of an aircraft's High Lift System—illustrates this directly: EMC outcomes are determined by decisions spanning chassis design, interface circuit layout, grounding topology, and printed wiring board configuration, all of which involve mechanical, electrical, and systems engineers simultaneously [14]. When the FSECU's switch closes or opens during flap and slat actuation, it produces large dI/dt and dV/dt transients that generate broadband high-frequency disturbances, and the logic circuit simultaneously acts as both a disturbance source and a sensitive victim—a duality that only integrated, multidisciplinary design awareness can address effectively [14]. Treating EMC as a downstream activity increases the likelihood of late-stage mitigation and program risk, because by the time testing occurs, the fundamental architecture and installation are largely fixed.

7.2 Misconception 2: "Compliance Guarantees Robustness"

Passing defined EMC tests demonstrates conformity to specific controlled conditions, but it does not eliminate all potential interference mechanisms encountered in real operational environments. EMC evaluation criteria for complex airborne platforms such as UAVs can be divided into two fundamentally different categories: system or equipment performance evaluation criteria based on deterministic electromagnetic environment characteristics and statistical analysis evaluation criteria based on stochastic environmental characteristics—and qualification testing typically addresses only the former [15]. The operational electromagnetic environment is subject to the effects of high-power ground-based wireless systems and other wireless equipment that no laboratory test can effectively replicate. A technically sound EMC program therefore accounts for the incompleteness of the test coverage by stressing strong design: allowing for a margin beyond the minimum specified level of performance, accounting for the physical mechanisms of coupling rather than just numerical limits, and verifying performance in the operational environment.

7.3 Misconception 3: "Shielding Solves All EMC Problems"

While shielding is an important EMC tool, it is not a universal solution. Effective shielding of airborne equipment requires complete enclosures with well-designed seams and penetrations, proper grounding and bonding at all shield terminations, and attention to apertures and connector penetrations. In UAV and aircraft systems, statistics indicate that 60% of all electromagnetic interference occurring on an aircraft is attributable to electromagnetic coupling between cables—a coupling mechanism that shielding alone, without complementary grounding, routing separation, and filter design, cannot adequately suppress [15]. Over-reliance on shielding leads to increased weight and cost, maintenance challenges in accessing shielded equipment, and false confidence when shielding is improperly implemented. A balanced approach uses multiple mitigation techniques simultaneously: source suppression, filtering, grounding, physical separation, and shielding applied selectively where appropriate [14].

7.4 Misconception 4: "Digital Systems Are Immune to EMI"

Digital systems, including the logic circuits within flight-critical units such as the FSECU, are particularly susceptible to EMI despite their inherent noise margins. The logic circuit within the FSECU not only produces conducted disturbance in public power lines and wires but also generates radiation disturbance, confirming that high-speed digital switching is simultaneously a source and a victim of interference [14]. Modern high-speed digital systems with GHz clock rates have shorter rise times and higher harmonic content, making them both more emissive and more susceptible than slower legacy systems. The rise time challenge is governed by the relationship $f_{max} \approx 0.5/t_{rise}$, meaning that faster transitions directly extend the emission bandwidth into frequency regions occupied by critical aircraft communication and navigation services.

8. Engineering Principles for Multidisciplinary Teams

8.1 Primary Control Variables for EMC

Many routine engineering decisions act as primary control variables for electromagnetic coupling in aircraft systems. Avionic systems contain a large number of onboard frequency-generating systems, including frequency synthesizers, digital circuits, telemetry, and switching power supplies, and effective frequency management begins with a comprehensive tracking system that catalogs all frequencies, their significant harmonics, signal rates, rise and fall times, and power levels—information that enables designers to avoid incompatibilities among components based on their existing frequency allocations [16]. Cable routing and separation constitute the most fundamental control variable: physical separation between power and signal cables, avoidance of parallel routing of sensitive and noisy cables, and minimization of loop areas all reduce inductive coupling. Grounding topology is equally critical, requiring careful choices between single-point and multi-point strategies, star grounding for sensitive analog systems, and deliberate measures to avoid ground loops and minimize ground impedance [16]. Shielding and bonding, interface definition through differential signaling and balanced interfaces, and filtering with transient suppression at equipment boundaries complete the set of primary control variables—all of which are determined by engineers across mechanical, electrical, and systems disciplines rather than by EMC specialists alone.

8.2 Design-for-EMC Principles

Early awareness of EMC principles allows non-EMC engineers to make design choices that inherently reduce interference potential. Effective shielding of line replaceable units and harnesses requires enclosures with shielding effectiveness starting at 60 dB and ranging up to more than 100 dB depending on system criticality, achieved through proper enclosure material selection, effective PCB layout, ensuring resistance continuity across enclosure joints, effective gasketing between mating surfaces, and properly terminating cable shields [16]. Apertures and seams are especially critical because they allow leakage of electromagnetic energy—the larger the aperture or seam, the lower the shielding effectiveness of the enclosure design. At the source level, spread-spectrum techniques offer a complementary design principle: by modulating the switching frequency of power electronics, narrowband harmonic energy concentrated at the switching frequency and its multiples is dispersed across a wider spectral range, reducing peak emission levels. Experimental studies of inductive-resonant wireless power transfer systems demonstrate that the baseline system efficiency without spread spectrum is 76.7%, and that when peak switching frequency deviation is kept below 6 kHz, the resulting drop in efficiency remains below 1% for all modulation waveforms—confirming that spread-spectrum design can be applied with minimal performance penalty when parameters are selected carefully [17]. Furthermore, for a given efficiency reduction, the multi-frequency technique provides equal or slightly higher emission reduction coefficients compared to sine modulation, while ramp modulation outperforms both by 1–3 dB, making it the preferred waveform choice when the modulation index exceeds 2.5 [17].

8.3 Integration-Driven Approach

Viewing EMC as an integration attribute rather than a specialized afterthought allows multidisciplinary teams to improve system robustness, reduce reliance on late-stage corrective actions, accelerate certification, and improve operational reliability across the full operational envelope. Recommended practices include EMC considerations in design reviews from conceptual design forward, cross-functional collaboration between EMC specialists and design teams, early identification and mitigation of high-risk coupling paths, and verification of EMC design rules during installation and integration. The gasketing approach for enclosure seam treatment illustrates this integration principle concretely: beryllium copper gaskets offer the highest attenuation across the widest frequency range and are preferred over close-spaced fasteners alone because they compensate for mechanical variations and joint unevenness—a design detail that requires simultaneous input from mechanical, structural, and EMC engineers to implement effectively [16].

9. Future Outlook

The electromagnetic compatibility landscape of aviation is being reshaped by increasing aircraft electrification, higher power density, and tighter system integration. As more-electric architectures continue to replace hydraulic and pneumatic functions with electrically driven alternatives, the density of switching power electronics onboard will increase correspondingly, multiplying broadband interference sources across airframes that simultaneously demand higher reliability from safety-critical digital systems [18]. Distributed electric propulsion represents a further increase in EMC complexity. NASA’s review of DEP architectures shows that electrically driven propulsors distributed across the airframe create coupling pathways spanning much greater physical distances than those in conventional aircraft installations [19]. This expands the challenge from managing localized equipment behavior to controlling electromagnetic interactions across the full aircraft system. Future aircraft platforms including hybrid-electric and highly integrated transport concepts will require EMC design methods that address the aircraft as a coupled electromagnetic system rather than as a collection of independently qualified equipment. Treating EMC as an integration attribute from conceptual design forward, rather than as a compliance activity appended to development, will be essential to achieving the reliability and safety required of next-generation aircraft.

Table 1: *Representative Frequency-Domain EMC Examples in Civil Aviation Communications [5, 6]*

Frequency Range	Representative EMC Phenomenon
98.675 MHz and 101.25 MHz (FM sources)	Intermodulation product generated at 117.45 MHz
Civil aviation communication band	108 MHz to 137 MHz

Table 2: Frequency Ranges and Emission Profiles of Onboard EMI Sources [7, 8]

EMI Source	Frequency Range	Emission Type	Key Parameter
WBG inverter (SiC/GaN)	100 kHz – >100 MHz	Conducted + Radiated	Switch rise time: tens of ns
Buck converter	150 kHz – 152 MHz (DO-160G)	Conducted	Switching frequency harmonics
High-speed digital (FSECU)	100 MHz – 6 GHz (DO-160G)	Radiated	Clock harmonics, data transitions
Cable harness resonances	30 – 300 MHz	Radiated	Quarter-wave resonance at installation length
Common bus (270 V DC)	Broadband	Conducted	Converter switching interaction

Table 3: *Primary EMC Engineering Parameters for Multidisciplinary Aircraft Teams [16, 17]*

Design Parameter	Value
Required LRU shielding effectiveness range	60 dB to over 100 dB
Baseline wireless power transfer system efficiency (no spread spectrum)	76.7%
Peak frequency deviation threshold for spread-spectrum	Below 6 kHz
Ramp modulation advantage over sine modulation	1–3 dB

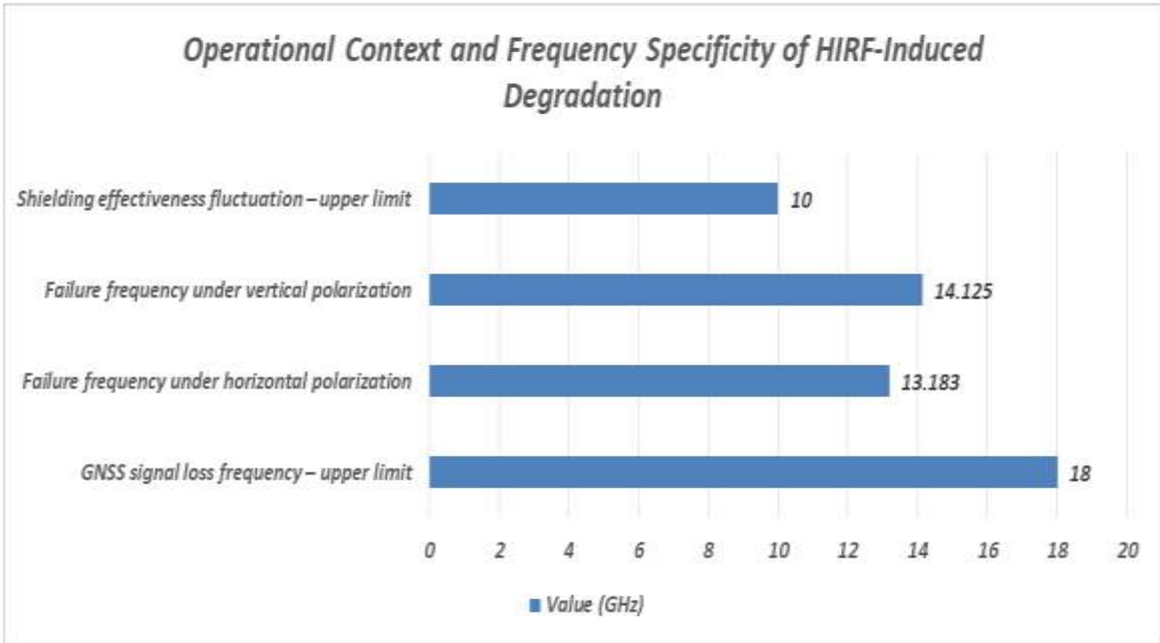

Figure 1: *Operational Context and Frequency Specificity of HIRF-Induced Degradation [9, 10]*

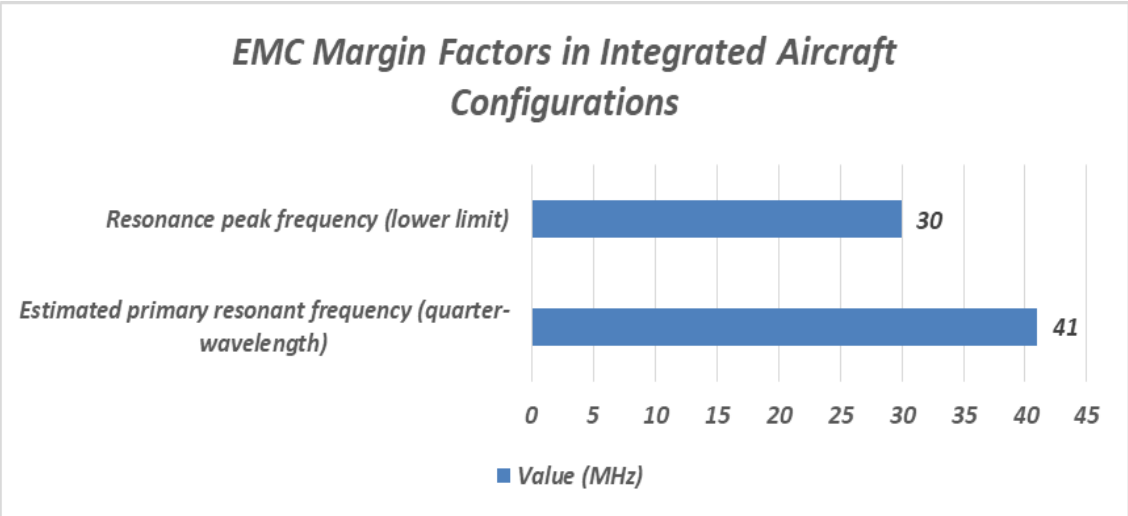

Figure 2: *EMC Margin Factors in Integrated Aircraft Configurations [9, 10]*

10. Conclusions

Electromagnetic compatibility in aircraft systems cannot be achieved through compliance activities alone—it must be designed into the architecture from the earliest conceptual decisions and maintained as a system-level integration attribute throughout development. The evidence presented across all sections consistently demonstrates that interference most commonly manifests as subtle functional degradation rather than catastrophic failure, that compliant equipment can still contribute to system-level incompatibilities when installed in an integrated aircraft, and that the physical mechanisms of coupling operate independently of whether formal test limits have been satisfied. As aircraft electrification advances toward distributed propulsion, high-voltage power distribution, and dense power electronics architectures, the electromagnetic environment onboard will grow more complex, and the consequences of inadequate margin more severe. Addressing these challenges demands proactive early coordination between systems, wiring, mechanical, and EMC engineers, early identification of high-risk coupling paths, design margins that exceed minimum test requirements, and validation frameworks capable of representing realistic operational electromagnetic environments.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
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interests or personal relationships that could have appeared to influence the work reported in this paper

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References

[1] K. de Langhe, "Addressing electromagnetic compatibility in the context of aircraft electrification," SAE International, SAE-MA-06835, 2022. https://www.sae.org/articles/addressing-electromagnetic-compatibility-context-aircraft-electrification-sae-ma-06835

[2] B. Wang, Y. Zhang, X. Li, and J. Liu, "An integrated approach for electromagnetic compatible commercial aircraft engine cable harnessing," Chinese Journal of Aeronautics, vol. 35, no. 6, pp. 1–12, 2022. https://doi.org/10.1016/j.cja.2022.01.013

[3] L. Malburg and N. Moonen, "The changing electromagnetic environment onboard all-electric aircraft, an EMC perspective," in Proc. IEEE Int. Symp. on EMC, Signal & Power Integrity, and EMC Europe, 2021, pp. 1–6. https://doi.org/10.1109/EMC/SI/PI/EMCEUROPE52599.2021.9559208

[4] R. Perez, Ed., Handbook of Aerospace Electromagnetic Compatibility. Hoboken, NJ: Wiley-IEEE Press, 2019. https://doi.org/10.1002/9781119082880

[5] X. Wang, Y. Liu, Z. Chen, and H. Zhang, "Research on electromagnetic compatibility prediction and test verification of spacecraft wireless system," Journal of Physics: Conference Series, vol. 2336, no. 1, p. 012012, 2022. https://doi.org/10.1088/1742-6596/2336/1/012012

[6] M. Zhou, Y. Li, X. Wang, and J. Chen, "Identifying sources of interference in civil aviation radio communication," EURASIP Journal on Advances in Signal Processing, 2024. https://doi.org/10.1186/s13634-024-01185-5

[7] Z. Wang, X. Zhang, Y. Li, and H. Zhao, "A review of EMI research of high power density motor drive systems for electric actuator," Actuators, vol. 12, no. 11, p. 411, 2023. https://doi.org/10.3390/act12110411

[8] D. R. A. Shirley, K. Ramash Kumar, and P. Sivakumar, "Reduction of electromagnetic interference using EMI filter in a buck converter," Journal of Physics: Conference Series, vol. 2325, no. 1, p. 012014, 2022. https://doi.org/10.1088/1742-6596/2325/1/012014

[9] R. D. Leach and M. B. Alexander, "Electronic systems failures and anomalies attributed to electromagnetic interference," NASA Technical Report NASA-RP-1374, 1995. https://ntrs.nasa.gov/api/citations/19960009442/downloads/19960009442.pdf

[10] H. Chen, X. Li, C. Zhou, and Y. Wang, "Study on the shielding effectiveness of airborne navigation equipment enclosures under high-intensity radiated fields (HIRF)," Processes, vol. 13, no. 12, p. 3782, Nov. 2025. https://doi.org/10.3390/pr13123782

[11] E. J. Borgstrom, "An overview of the EMC requirements in RTCA/DO-160D," in Proc. 17th IEEE/AIAA Digital Avionics Systems Conference (DASC), 1998, pp. F41/1–F41/8. https://doi.org/10.1109/DASC.1998.741472

[12] H. H. Zhong and F. X. Wu, "Cable resonance in automotive component EMC tests," Signal Integrity Journal, Sep. 2025. https://www.signalintegrityjournal.com/articles/4073-cable-resonance-in-automotive-component-emc-tests

[13] D. Ramos Somolinos, C. Morales Blanco, and J. Cidras, "Coupling analysis under lightning indirect effects for cable bundles with different ground plates in unmanned aerial vehicles," in Proc. IEEE Int. Symp. on EMC, Signal & Power Integrity, and EMC Europe, 2021. https://doi.org/10.1109/EMC/SI/PI/EMCEUROPE52599.2021.9559199

[14] B. Han, "The EMC design of flap and slat electronic control unit," Journal of Physics: Conference Series, vol. 2437, no. 1, p. 012119, 2022. https://doi.org/10.1088/1742-6596/2437/1/012119

[15] Y. Wu, X. Zhang, H. Li, and W. Chen, "Progress of electromagnetic compatibility design for unmanned aerial vehicles," MATEC Web of Conferences, vol. 336, p. 04008, 2020. https://doi.org/10.1051/matecconf/202033604008

[16] J. J. Ely, T. X. Nguyen, and R. H. Koppen, "Electromagnetic interference to flight navigation and communication systems: new strategies for the 21st century," NASA Technical Memorandum NASA/TM-2005-213606, 2005. https://doi.org/10.2514/6.2005-6361

[17] D. Stepins, J. Zakis, N. Ponomarenko, and G. Strazdins, "Suppression of radiated emissions from inductive-resonant wireless power transfer systems by using spread-spectrum technique," Electronics, vol. 11, no. 5, p. 730, 2022. https://doi.org/10.3390/electronics11050730

[18] A. Gębura, T. Stefaniuk, W. Barański, and J. Krawczyk, "Concepts and experiments on more electric aircraft power systems," Energies, vol. 18,

no. 7, p. 1653, Mar. 2025. https://doi.org/10.3390/en18071653

[19] H. D. Kim, G. V. Brown, and J. D. Moore, "A review of distributed electric propulsion concepts for air vehicle technology," NASA Technical Memorandum NASA/TM-2018-219749, 2018. https://ntrs.nasa.gov/api/citations/20180004729/downloads/20180004729.pdf