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Perspective

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Developing Electromagnetic Compatible Commercial Aircraft Engine Cable Harnesses: Trends and Prospects

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Abstract: Advancements in electrified and intelligent technologies require commercial aircraft engines to function reliably and durably in electromagnetic (EM) environments. To mitigate EM disturbances to signal transmissions in commercial aircraft engine cable harnesses, this paper proposes a framework that illustrates the prospects aligned with the systems engineering trend for developing EM compatible cable harnesses using integrated multidisciplinary modelling. Extracting empirical engineering experience, the framework begins by comprehensively identifying intrinsic and external factors and their interacting relationships influencing the induced EM responses in aircraft engine cable harnesses. Subsequently, this framework proposes promising mechanism-based modelling for respectively analyzing the three intrinsic factors, including parameterization-based geometry-topology modelling, heterogeneous material constitutive modelling, and cable harness nonlinear shielding, as well as three external factors, including coupling mechanisms with airborne interface loadings, coupling mechanisms with EM excitations, and numerical analysis techniques for evaluating induced EM responses. This framework outperforms conventional empirical experience-based single-aspect-oriented approaches with more sufficient mechanism-based justification, highlights the trends and prospects of analyzing EM responses from multidisciplinary perspectives, and ensures the function and performance reliability of newly developed commercial aircraft engines, which contributes to flight safety and competency in global aviation market competition.

Keywords: electromagnetic responses; cable harnesses; parameterization-based geometry-topology modelling; heterogeneous material constitutive modelling; multidisciplinary framework

1. Introduction

Commercial aircraft engine cable harnesses transmit electrical power and electronic signals among engine equipment and instruments for intercommunications, and they are widely considered as the “nerves” of commercial aircraft engines. In fact, a commercial aircraft engine is known for its highly complex design and manufacturing, high reliability requirements, extreme operating conditions, high asset value, and high operational cost [1–3]. It is commonly believed that the development of commercial aircraft engines must relentlessly overcome emerging and latent technical risks and remarkably improve overall system goals based on smooth reconciliations of conflicting disciplinary goals. Engineering developments in aircraft engines have been widely studied in the areas of aerodynamics [4–7], thermodynamics and heat transfer [8–11], materials [12–15], and structural integrity [16–18]. In contrast, studies on electromagnetic (EM) interference to electric equipment installed inside an aircraft engine, which are of considerable concern for airworthiness certification and operation safety of commercial aircraft engines, have received much less attention. In commercial aviation, the main external

EM interference during regular flight services originates from lightning strikes and high-intensity radiated fields (HIRF), the effects of which require accurate simulation, measurement, and certification [19–21]. Specifically, HIRF interference and lightning strikes are highly likely to result in signal distortions and malfunctions in electric systems via airborne cable harnesses, i.e., cable harnesses that are installed and grounded on aircraft engines, usually with curved branch paths, and use engine casings as conducting grounds. Overall, the induced EM effects on aerial electronic systems may result in disastrous flight accidents. Consequently, it is imperative that HIRF and lightning interferences, their transmissions within, and their impacts on airborne electric and electronic systems are comprehensively modelled and analyzed when a commercial aircraft engine is developed.

Conventional approaches for developing EM compatible aircraft engine cable harnesses rely heavily on engineers' personal engineering experience, which easily leads to overdesign and/or defects against EM disturbance. There has been research progress that contributes to solving the complex EM issue in cables. For instance, Andrieu et al. proposed a modelling method for assessing the EM disturbance emitted by a cable bundle with reduced complexity [22]. Baklezos et al. evaluated the electric fields resulting from spacecraft transmission lines versus distance at low frequencies [23]. Camara et al. investigated high-voltage direct current submarine cables and their EM properties in the time domain [24]. Zhu et al. conducted studies on transmission line EM excitation at low frequencies [25]. However, these methods are single-aspect-oriented and cannot be directly applied to the multidisciplinary development processes of commercial aircraft engine cable harnesses. In addition, aircraft engine cable harnesses in airborne scenarios, i.e., grounded onto conductive 3D curved engine casings of finite size, are considerably more complex than commonly assumed in the literature. All these technical difficulties indicate that a solution to conduct an integrated cable harness design and EM response analysis from a multidisciplinary perspective is necessary.

To overcome the limitations of traditional single-aspect-oriented research methods for EM response analysis and for developing EM compatible engine cable harnesses, this paper proposes a framework that points out the trends and prospects from the view of multidisciplinary modelling that opportunely accommodates disparate models originating from the areas of electromagnetics, optics, material, geometry, and numerical analysis, which is a systematic solution to EM robustness problems encountered in airborne cable harnesses by combining systems engineering approaches with conventional EM analysis and engineering approaches. Specifically, this framework identifies the intrinsic and external factors and their relationships influencing the induced EM responses in aircraft engine cable harnesses and points out the prospects for conducting EM analysis and optimizing airborne cable harness designs before proceeding to manufacturing, which significantly reduces the time and economic costs of product development cycles and improves product quality, leading to an increase in the competency of aviation companies in global market competition.

This paper is organized as follows: Section 1 presents the background and significance of developing EM compatible aircraft engine cable harnesses. Section 2 proposes a framework that identifies the intrinsic and external factors and their interaction relationships that influence the induced EM responses in airborne cable harnesses based on practical engineering experience. Section 3 elaborates on mechanism-based modelling and the integration of intrinsic factors for designing EM compatible cable harnesses. Section 4 presents the three external factors whose coupling mechanism with the cable harnesses influences the induced EM responses and therefore the optimization of cable harness designs. Finally, Section 5 concludes the paper with closing remarks.

2. Multidisciplinary Framework for Identifying Factors Influencing EM Compatible Cable Harness Development

The foundation for developing commercial aircraft engine cable harnesses capable of functioning reliably in complex EM environments is to capture the corresponding EM responses via EM mechanism analysis. The theoretical core of electromagnetics is the well-known Maxwell equations shown by (1) that govern the transmission and induction processes of intercorrelated electric and magnetic fields.

$$\begin{cases} \nabla \times \boldsymbol{E} = -\dfrac{\partial \boldsymbol{B}}{\partial t} \\ \nabla \times \boldsymbol{H} = \boldsymbol{J} + \dfrac{\partial \boldsymbol{D}}{\partial t} \\ \nabla \cdot \boldsymbol{D} = \rho_v \\ \nabla \cdot \boldsymbol{B} = 0 \end{cases} \tag{1}$$

where $\boldsymbol{E}$-electric field intensity, $\boldsymbol{B}$-magnetic flux density, $\boldsymbol{H}$-magnetic field intensity, $\boldsymbol{J}$-volume electric current density, $\boldsymbol{D}$-electrical flux density, and ρ_v-volume electric charge density. In particular, the Ampere equation and Faraday equation describe conversions between electric and magnetic fields, indicating that processes relevant to electromagnetic compatibility (EMC) analysis are multidisciplinary in nature, which calls for an integrated multidisciplinary approach that outperforms conventional single-aspect-oriented engineering practices.

The author's research team has revealed that airborne cable harness EM responses reflect the nonlinear coupling effects of multidisciplinary factors including EM excitations, interface loadings, cable harness materials and structures [26]. Extracting empirical engineering experience accumulated from practical commercial aircraft engine development processes along with looking ahead of the EM technology trends, the author proposes a multidisciplinary framework that identifies the factors influencing the induced EM responses in cable harnesses from multiple aspects instead of one single aspect, and the relationships among these factors successfully identified by the proposed framework are shown in Figure 1. Specifically, these factors can be further divided into two categories: those that are intrinsic to cable harness designs and those external to cable harness designs. The three intrinsic factors include cable harness topology and geometry, cable material properties, and cable harness nonlinear shielding. The three external factors include connecting interface loadings from airborne equipment in the engines, EM excitations from the environment, and numerical analysis techniques. As illustrated in Figure 1, all these factors are synthesized together to ensure that the newly developed aircraft engine cable harnesses are EM compatible and can function reliably under EM disturbance. The trends of investigating the coupling mechanism from the influential intrinsic and external factors are presented in the following sections respectively.

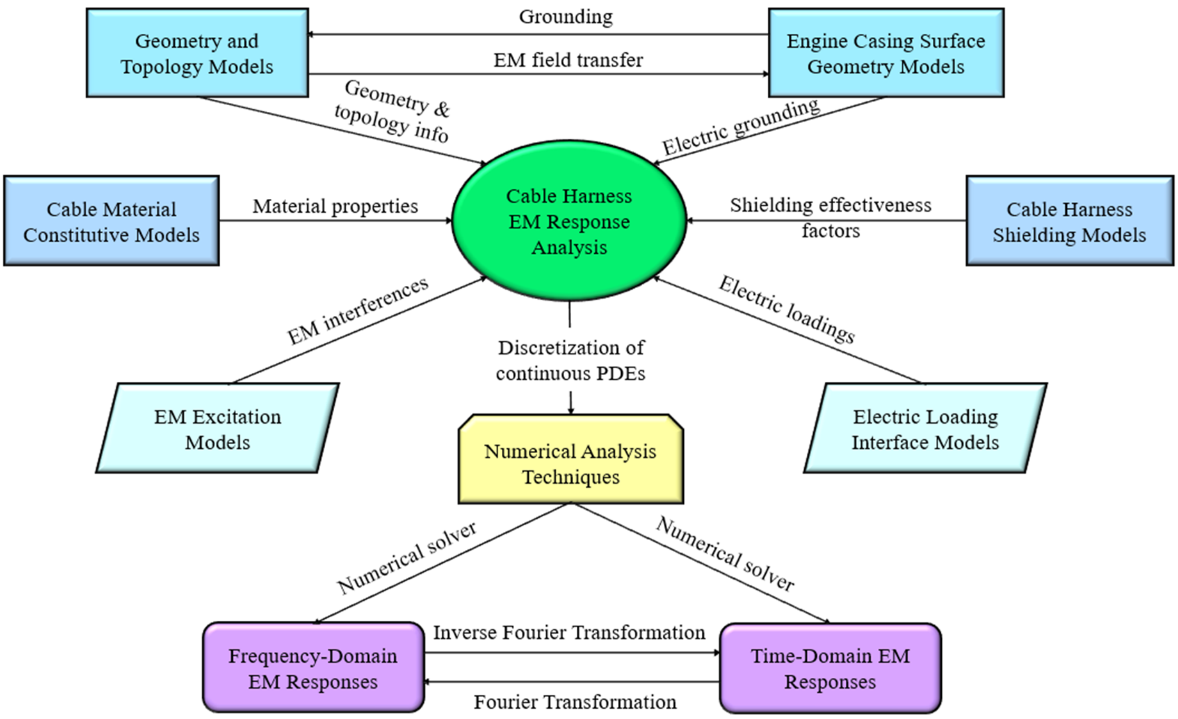

Figure 1. Multidisciplinary framework identifying critical intrinsic and external factors that influence EM response analysis and design finalization of EM compatible aircraft engine cable harnesses.

3. Intrinsic Factors Influencing Induced EM Responses

Cable harnesses are the "nerves" of commercial aircraft engines: numerous cable harnesses with multiple branches are connected to the electronic engine controller, various types of sensors providing control and monitoring signals, solenoid valves, alternators, and other airborne electrical and electronic equipment and systems in commercial aircraft engines. As outlined in the previous section, this section elaborates on three intrinsic mechanism-based factors for designing integrated EM compatible airborne cable harnesses.

3.1. Parameterization-Based Geometry-Topology for Airborne Cable Harnesses

As illustrated in Figure 2, where a multi-branched cable harness is grounded on a curved engine casing surface of finite size, the author suggests establishing EM coupling analysis models in a parameterized space and expressing external EM fields in Frenet Coordinates on every curved cable branch path, where the three axes of Frenet Coordinates are formed by the tangent unit vector, normal unit vector, and bi-normal unit vector of the curved cable path, respectively. Specifically, a cable path $\vec{C}$, which represents the geometry of an airborne cable path on an engine casing, is mathematically expressed as

$$\vec{C}(u) = \sum_{i=0}^{n} N_{i,p}(u) P_i \tag{2}$$

where the parameter $u \in [0,1]$, P_i are the control points, $n+1$ is the total number of control points, $N_{i,p}$ is the weight matrix defining the weight of the corresponding control point P_i. For an airborne cable path, the model defines P_0 as the source terminal point and P_n as the load destination terminal point. The connections among cable-path terminal points form the topological model of an airborne cable harness.

Grounding is another aspect that geometrically influences the transmission and change of EM fields. Instead of treating the ground as a 2D flat plane of infinite size, as is commonly practiced in the literature, the author suggests overcoming such restrictions and grounding cable harnesses onto engine casings that are represented by a 3D curved surface of finite size. Similarly, the surface of an engine casing is parameterized into a periodic bounded surface, and is expressed as follows:

$$S(v,w) = \sum_{k=0}^{h} \sum_{j=0}^{m} N_{k,s}(v) N_{j,q}(w) P_{k,j} \tag{3}$$

where parameters $v, w \in [0,1]$, $P_{k,j}$ are the control point matrices, $N_{k,s}$ and $N_{j,q}$ are the basis functions for v and w respectively.

As presented in Section 2, classical Maxwell's equations are formed in 3D Cartesian Coordinates. However, it is of increasing interest to conduct EM coupling analysis for airborne cable harnesses in parameterized spaces. As presented in Figure 2, the author suggests expressing the EM fields in every cable path in the Frenet Coordinates $\{\xi, \eta, \zeta\}$. The three axes of the Frenet Coordinates are the tangent, normal, and bi-normal directions of the cable path curve, respectively. The proposed Frenet Coordinates map EM fields from 3D Cartesian coordinates into the newly formed parameterized space as follows:

$$\begin{cases} E(x,y,z) \to E(\xi,\eta,\zeta) \\ H(x,y,z) \to H(\xi,\eta,\zeta) \end{cases} \tag{4}$$

Clearly, mapping EM excitations into the proposed parametric spaces facilitates the analysis of EM responses along the tangential and perpendicular directions of the cable path. Topology models of complex multi-branched airborne cable harnesses characterize the topological constraints among multiple cable branches and affect the induced EM field intensities and propagation modes in the cable harnesses.

Note that, although mathematically Frenet Coordinates may become ill-defined when the cable path curvature approaches zero, such cases are hardly encountered by aircraft engine cable harnesses because the 3D space in commercial aircraft engines is packed and limited for cable harness installation and grounding, making cable harnesses almost impossible to have space-consuming 3D straight cable path designs; besides, cable harness mechanical stress and strain design requirements do not allow cable paths in the 3D space to be designed without curvatures. Hence, the proposed Frenet Coordinates not only help electromagnetic response analysis but may also serve as an approach for optimizing cable paths geometrically.

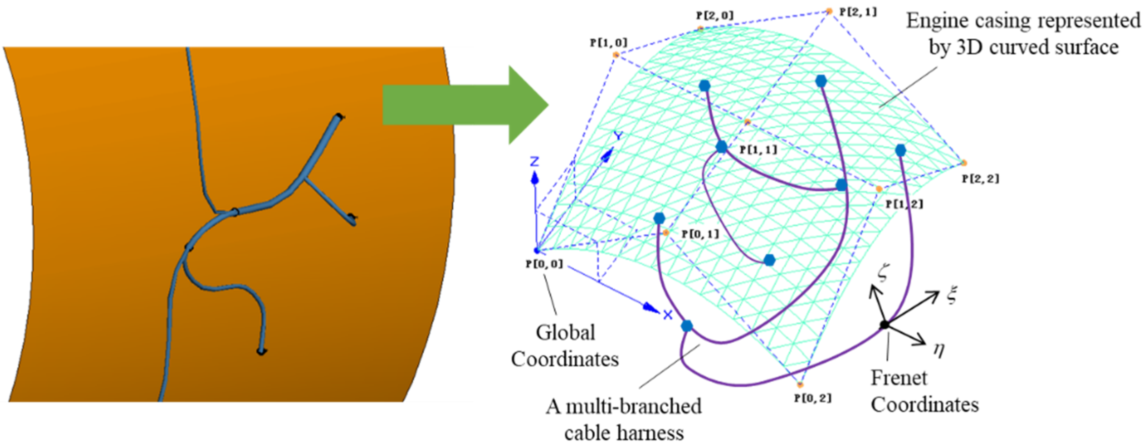

Figure 2. Airborne cable harness geometry-topology models in the parameterized space.

3.2. Heterogeneous Material Constitutive Models for Cable Branch Cross Sections

In multiphysics systems, constitutive relationship models characterize the manner and extent to which a specific material responds to loading. In the case of EM response analysis, constitutive models correlate the magnetic flux density with the magnetic field intensity and the current density with the electric field intensity via the electrical conductivity and permeability of the material. As shown by the example in Figure 3, an aircraft engine cable harness cross section is composed of diverse conducting and insulation materials of different sizes, with each color representing a different type of material, and multi-branched cable harness cross sections usually consist of complex heterogeneous conductor-insulating medium-shielding structures, making the EM response analysis difficult and challenging.

Specifically, the constitutive relations originating from material properties are shown by Equations (5)–(7), where ε is the medium permittivity, μ is the medium permeability, and σ is the medium conductivity. Taking these influencing factors into consideration, the author proposes to analyze the constitutive relationships of the EM responses of various cable conduction materials and insulation layer materials, the nonlinear constitutive relationships of cable materials in EM environments, and the isotropic and anisotropic material constitutive relationships in cable harnesses. Additionally, the author proposes to analyze the influence of differences in cable cross sections and insulation thickness of the metal conductor branch in the cable harnesses on the response of the EM refractive index, electrical conductivity, and permeability of cables and establish an integrated constitutive model library for analyzing the EM responses in aircraft engine cable harnesses. Note that, the material parameters ε, μ, and σ, may be treated as frequency-independent for simplicity or frequency-dependent for necessary accuracy based on the external excitation frequencies of interest. In fact, it is the Research and Development (R&D) engineers' job to capture external EM requirements including the frequency ranges of EM excitations and carefully decides if these material parameters may be considered as frequency-independent.

$$\boldsymbol{B} = \mu \boldsymbol{H} \tag{5}$$

$$\boldsymbol{D} = \varepsilon \boldsymbol{E} \tag{6}$$

$$\boldsymbol{J} = \sigma \boldsymbol{E} \tag{7}$$

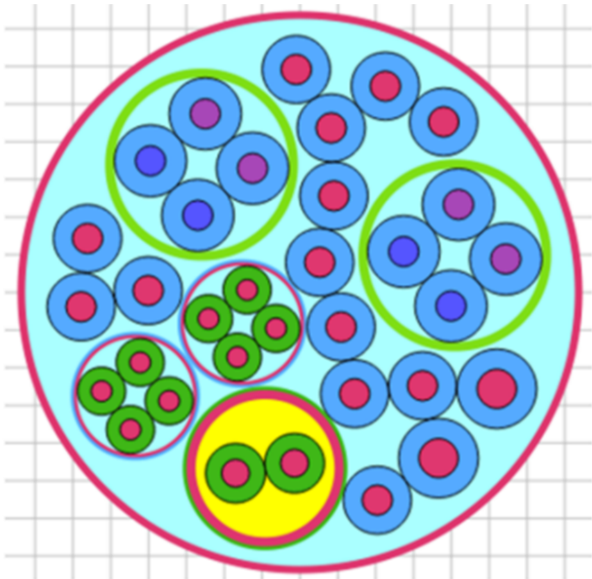

Figure 3. Complex heterogeneous conductor-insulating medium structures in cable branch cross sections.

3.3. Cable Harness Nonlinear Shielding

Compared to those installed in other complex industrial vehicles, commercial aircraft engine cable harnesses are more likely to be exposed to EM noises because the nacelles housing the aircraft engine cable harnesses generally have limited shielding effectiveness. Therefore, despite the increased weight brought by harness shielding, aircraft engine cable harnesses are equipped with an overall layer of harness shielding covering every branch of the cable harnesses.

Two multi-branched aircraft engine cable harnesses, one with harness shielding and the other without harness shielding, are used as a comparison example for illustration, with the other features of the two cable harnesses being identical. When the two are exposed to the same EM excitation, their respective induced EM responses are shown by the blue and red lines in Figure 4, with the blue line representing the responses from the cable harness without harness shielding and the red line, which is much lower than and has different peaks from the blue line, representing that from the cable harness equipped with harness shielding. As shown by the blue and red lines in Figure 4, the induced EM responses in the cable harness are reduced nonlinearly on average when the cable harness is equipped with an overall layer of harness shielding enclosing the entire cable harness. Cable harness shielding is also used to change the resonance frequencies of the airborne cable harness such that the induced peaks do not appear at the engine working frequencies. Shielding design parameters, such as optical coverage and weave angles, all influence the shielding effectiveness for the airborne cable harnesses in different extents. Hence, it is significant to evaluate the effectiveness and contribution of different shielding parameter combinations before finalizing the design of EM compatible cable harnesses. In addition to the harness shielding design parameters, shielding termination, i.e., how the shielding is connected at cable harness terminals, and transfer impedance are also two factors that should be considered during EM compatible cable harness development processes.

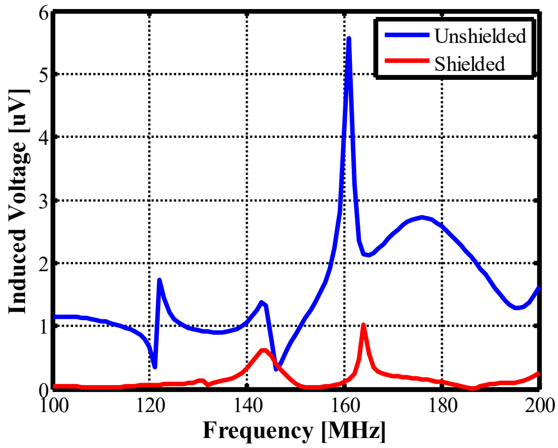

Figure 4. Cable harness shielding nonlinear effects on induced EM response in aircraft engine cable harnesses, where the induced EM responses in shielded cable harnesses are not only significantly lower in magnitude but also have resonant frequencies different from unshielded cable harnesses.

4. External Factors Influencing Induced EM Responses

In addition to the factors intrinsic to the cable harnesses presented in the previous section, there are factors external to the cable harnesses that also influence the induced EM responses. The most significant external influential factors include the interface loadings connected by airborne cable harnesses, EM excitations from external environments, and numerical analysis techniques for conducting EM analysis.

This section specifically illustrates the prospects of these three factors in each subsection by presenting their interactions with cable harnesses.

4.1. Coupling Mechanisms with Airborne Interface Loadings

Airborne cable harnesses transmit data and commands unidirectionally or bidirectionally among numerous pieces of airborne electrical and electronic equipment, such as electronic controllers, sensors of various physical domains, and solenoid valves serving as actuators. As indicated by theoretical analysis methods such as transmission line theory, airborne loadings interconnected by airborne cable harnesses influence the induced EM responses in cable harnesses. As illustrated by the interface loading example in Figure 5, airborne interface loading connecting with aircraft engine cable harnesses can be complex in terms of components and series/parallel circuit connections. An illustrative representation of the loading impedance Z reflecting electric characteristics can be expressed as

$$Z = R + \frac{1}{j2\pi fC} + j2\pi fL \tag{8}$$

where $j = \sqrt{-1}$ is the imaginary number, f is the frequency, R is the resistance, L is the inductance, and C is the capacitance. Every piece of airborne interface loading has its own loading impedance reflecting its electric characteristics, making the EM analysis more complicated in engineering practice.

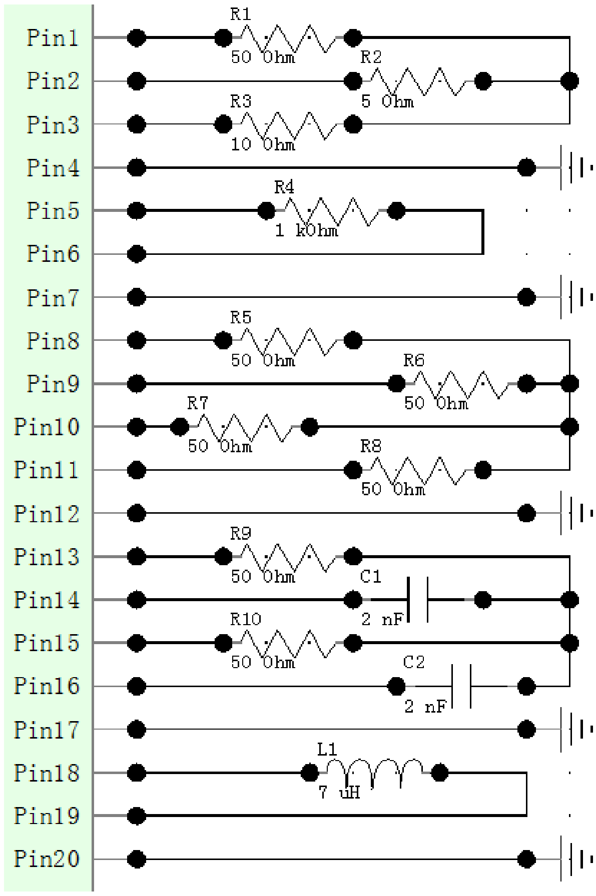

Figure 5. An example of an airborne interface loading connecting with aircraft engine cable harnesses, where the loading is comprised of several frequency dependent as well as frequency independent complex impedance components.

Clearly, some airborne electric loadings, such as temperature sensors whose core components are thermo-resistors, are of pure resistance and are therefore independent of frequencies; others are frequency-dependent, such as vibration sensors whose core components are capacitors. Note that the electric characteristics of the interface loading cannot be modified during the development of EM compatible cable harnesses, as the loading characteristics are the nature of airborne instruments and equipment. Hence, it is meaningful to analyze the coupling mechanisms between cable harnesses and connecting interface loadings while conducting EM analysis and optimizing aircraft engine cable harness designs.

4.2. Coupling Mechanisms with EM Excitations

External EM interference excitations induce currents and voltages in the cable harnesses, and these induced responses couple with the data and command signals transmitted in the cable harnesses. There are two common types of EM environments that commercial aircraft engines are expected to encounter during flight: lightning and HIRF. Lightning is a type of time-domain excitation that potentially strikes directly onto the nacelle which houses the airborne cable harnesses, as illustrated in Figure 6. Although lightning does not strike directly onto cable harnesses housed by the nacelle, lightning strikes introduce indirect effects of lightning (IEL) that cause disturbances to signal transmission in cable harnesses, because the nacelle is mostly made of low-conductivity materials. In addition to lightning magnitude and duration, lightning striking and exiting positions on the nacelle is another influencing factor that should be considered when modelling lightning environments. HIRF, on the other hand, is a type of frequency-domain excitation resulting from plane waves that are usually generated by antennae that function continuously to facilitate human activities. Therefore, it is necessary to model the coupling mechanisms between cable harnesses and EM excitations from external environments to promote the engine cable harness development processes.

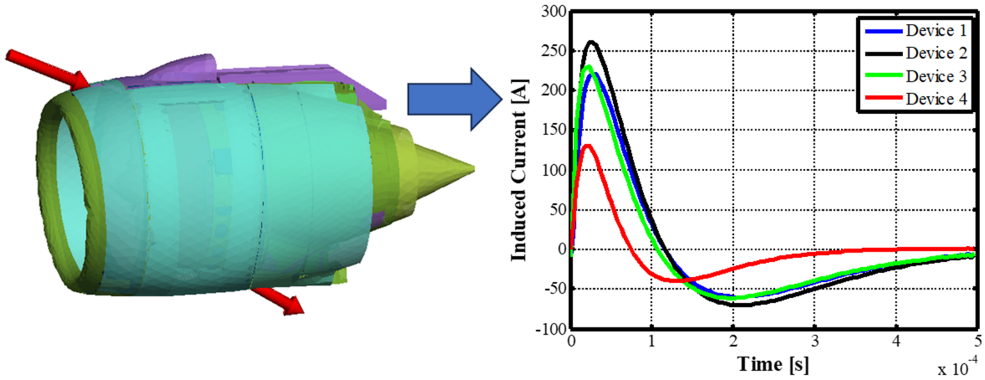

Figure 6. External EM excitations (lightning strikes in this example) induce EM responses in airborne cable harnesses.

4.3. Numerical Analysis Techniques for Evaluating Induced EM Responses

The numerical analysis technique is a less visible external factor influencing the EM response analysis. Figure 7 shows an example of the EM responses of a cable harness when it is exposed to HIRF excitations of the same magnitude but with two different wave indentation angles, $\theta = 0°$ and $\theta = 180°$ respectively. The EM responses analyzed using two conventional methods, namely, Multiconductor Transmission Line (MTL) theory and Method of Moments (MoM), are different as can be seen when comparing the blue line with the black line and the green line with the red line.

As confirmed by the example in Figure 7, the same EM scenario resulting in the same EM coupling effects may have different EM responses in the cable harness when R&D engineers use different numerical algorithm solvers, indicating that the numerical analysis technique, although less visible to engineers, is definitely another external factor that influences the induced EM response. One solution that the author suggests is to decouple the coupled Maxwell's equations, a system of primary partial differential equations, into independent electric/magnetic wave equations, i.e., quadratic partial differential equations. Linear and quadratic elemental functions are used to discretize the global continuous electric/magnetic field wave equation into a local continuum. To reflect the EM excitation characteristics of the airborne cable harness more realistically, the author suggests expressing the electric loadings in each cable in Frenet Coordinates. The electric and magnetic fields perpendicular to each other are studied to interpret the interactions between the electric loading characteristics connected to the airborne cable harnesses and the external EM excitations. The finite element method (FEM) analyzes the frequency-domain EM responses of cable harnesses, and the extended finite element time domain (FETD) method analyzes the time-domain EM responses of cable harnesses.

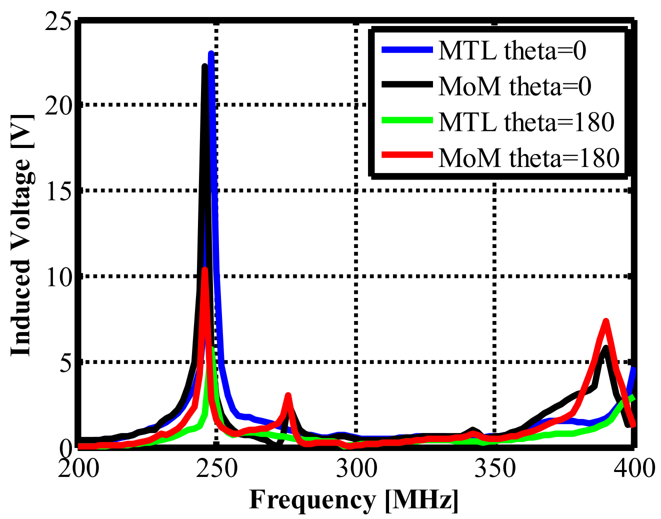

Figure 7. The induced EM responses analyzed using different numerical solver (Multiconductor Transmission Line theory shown by the blue and green lines and Method of Moments shown by the black and red lines in the example) confirm that numerical analysis technique is a less visible factor that also influences EM compatible cable harness development processes.

5. Conclusions

To meet the practical aviation industry requirements of developing commercial aircraft engines whose airborne cable harnesses are capable of transmitting electric signals reliably and durably in complex EM environments, this paper presents a framework that analyzes the trends and prospects on factors promoting the development of EM compatible cable harnesses for commercial aircraft engines. The proposed comprehensive framework successfully identifies the intrinsic and external factors influencing EM responses in airborne cable harnesses and their relationships and suggests various mechanism-based modelling and analysis aspects for the development of EM compatible aircraft engine cable harnesses.

The framework begins by identifying the influential factors intrinsic and external to cable harness designs for EM response analysis. Subsequently, the framework specifically presents suggestions on analyzing the influences and contribution of the three intrinsic factors, namely airborne cable harness geometry-topology parameterization, cable cross section heterogeneous material constitutive models, and cable harness shielding. In terms of external influential factors, this framework proposes to analyze the interaction mechanisms of the electric loading characteristics of airborne equipment with interconnecting cable harnesses for expressing signal transmissions, of the external EM environment with airborne cable harnesses, and proposes suggested methods for improving numerical analysis techniques. The proposed multidisciplinary framework reduces the risks of aircraft engine cable harness EM defects resulting from conventional single-aspect-oriented EM analysis approaches that usually fail to take the entire design view into consideration.

This paper provides researchers and engineers with trends and prospects for the development of EM compatible aircraft engine cable harnesses. It points out directions for R&D engineers and transfers them from traditional experience-based cable harness designs to the newly proposed mechanism-based designs methodology. The analysis of the trends and prospects presented in this paper is of significant engineering value and bridges the gap between mechanism analysis and engineering applications.

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Institutional Review Board Statement

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Informed Consent Statement

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Data Availability Statement

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Conflicts of Interest

The author declares no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the author used Paperpal to assist with language polishing and clarity improvements. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

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