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Assessing the shield termination approaches in aircraft wiring to withstand the lightning indirect effect

Uçak kablolamasında kullanılan kalkan sonlandırma yaklaşımlarının yıldırımın dolaylı etkilerine karşı değerlendirilmesi

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Assessing the Shield Termination Approaches in Aircraft Wiring to Withstand the Lightning Indirect Effect

Highlights

- *The effect of the shielding termination method on shield effectiveness is significant.*
- *Shielding of cables is a preferred method for protection from the indirect effects of lightning.*
- *The performances of different shield termination methods are analyzed against lightning.*
- *The performances of different shield termination methods have been tested against lightning.*

Graphical Abstract

The performances of different shield termination methods were investigated against the indirect effects of lightning, and the most successful method was found to be termination in 360˚ backshell.

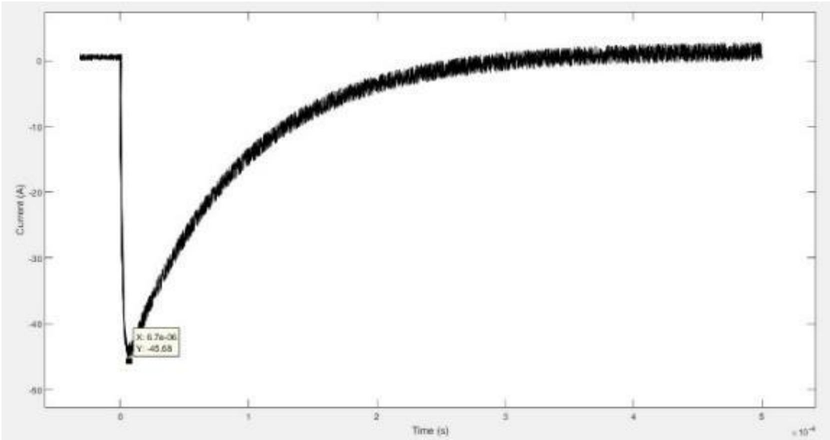

Figure. Current value induced in the cable when the shield is terminated in the 360˚ backshell

Aim

This study aims to examine the performance of different shield termination methods against the indirect effects of lightning and to determine the most successful shield termination method.

Design & Methodology

The most preferred shield termination methods in practice were determined and test setups were prepared. The lightning indirect effects test was applied to the prepared test setups in accordance with the standard, and the results were evaluated.

Originality

Investigation of the performance of the shield termination methods against the cable bundle test, different from the performance according to the frequency.

Findings

The most successful shield termination method against lightning effects is double-sided termination with 360˚ backshell.

Conclusion

The performance of the cable termination methods preferred for electromagnetic compatibility engineering is also successful against the indirect effects of lightning in the same order.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Assessing the Shield Termination Approaches in Aircraft Wiring to Against the Lightning Indirect Effects

(Bu çalışma 5. Uluslararası Mühendislik Bilimleri ve Multidisipliner Yaklaşımlar Kongresinde sunulmuştur. / This study was presented at the 5th International Congress of Engineering Sciences and Multidisciplinary Approaches.)

Araştırma Makalesi / Research Article

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ABSTRACT

Lightning is a natural phenomenon where high voltages and currents suddenly discharge. It can be caused by clouds themselves, clouds between them, or clouds near the earth. Aircraft are at risk of being struck by lightning and there is currently no way to prevent this from happening. Instead, efforts are being made to protect by reducing the effects of lightning. Metal structures in aircraft form a Faraday cage which helps in preventing lightning currents from entering the aircraft. However, composite structures, which are becoming more prevalent in the aviation sector, are less efficient in doing so compared to metals. Additionally, openings such as windows in the aircraft can break the Faraday cage and allow strong electromagnetic fields to penetrate. Hence, all equipment used on board the aircraft must be adequately qualified and lightning-proof. The most popular technique used to reduce the indirect effects of lightning on electronics is cable shielding. In this study, various shielding termination techniques for their effectiveness against indirect effect of lightning examined and it is found that utilizing a 360˚ backshell termination technique provided to be highly effective, providing protection of nearly 3 dB. The results obtained from the experiments are compared with simulation results and previous studies.

Keywords: Lightning, aviation, shielding, aircraft, unmanned aerial vehicle, EMA3D.

Uçak Kablolamasında Kullanılan Kalkan Sonlandırma Yaklaşımlarının Yıldırımın Dolaylı Etkilerine Karşı Değerlendirilmesi

ÖZ

Yıldırım yüksek akım ve yüksek voltajın ani olarak boşaldığı bir doğa olayıdır. Bu doğa olayı bulutlar arasında, bulut içinde ya da bulut ile yeryüzü arasında olacak şekilde meydana gelebilmektedir. Hava araçlarına da yıldırım çarpma riski vardır. Günümüzde yıldırım çarpmasını önleyici bir sistem mevcut değildir bunun için yıldırımın etkileri azaltılmaya çalışılmaktadır. Uçaklarda kullanılan metalik malzemeler Faraday kafesi etkisi göstererek yıldırımdan kaynaklanan elektromanyetik alanların uçak içerisine girişine izin vermemektedir fakat günümüzde daha sık kullanılmaya başlayan kompozit yapılar bu konuda metallere kıyasla daha kötü performans göstermektedir. Ayrıca uçak üzerinde bulunan pencere, kapı gibi süreksizlikler Faraday kafesi üzerinde boşluklar yaratmakta ve elektromanyetik alanların uçak içerisine girişine olanak sağlamaktadır. Bu sebeple uçak üzerinde kullanılan ekipmanların yıldırımın dolaylı etkilerine karşı kalifiye olması gerekmektedir. Ekipmanları yıldırımın dolaylı etkilerine karşı korumada en sık tercih edilen metot kabloların kalkanlanmasıdır. Kalkanın koruma etkisini ve sonlandırma metotlarının bu korumaya katkısını anlamak oldukça önemlidir. Bu çalışmada, yıldırımın dolaylı etkisine karşı çeşitli ekranlama sonlandırma teknikleri incelenmiş ve 360˚ arka kabuk sonlandırma tekniğinin kullanılmasının yaklaşık 3 dB koruma sağlayarak oldukça etkili olduğu bulunmuştur. Deneylerden elde edilen sonuçlar benzetim sonuçları ve önceki çalışmalar ile karşılaştırılmış ve elde edilen sonuçların birbiri ile tutarlı olduğu görülmüştür.

Kelimeler: Yıldırım, havacılık, kalkanlama, uçak, insansız hava aracı, EMA3D.

1. INTRODUCTION

According to literature, commercial passenger aircraft are struck by lightning at least once a year [1,2]. Reports also indicate that fighter planes may encounter lightning strikes on multiple occasions throughout their service life, with some instances of being struck twice [3]. A lightning strike on an aircraft, initiates the formation of two distinct conduction lightning channels. These channels manifest as a positive leader and a negative leader [4]. The high voltage and current generated by the

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lightning strike can have various effects on the aircraft, which can be categorized into two types: direct (physical) and indirect (electromagnetic). Direct effects include structural damage to the aircraft, such as combustion, boiling, and fragmentation caused by high-pressure shock waves and high currents. On the other hand, indirect effects are the result of interference from electric and magnetic fields generated by the lightning currents circulating on the aircraft surface and affecting the devices inside the aircraft. As pointed out in [5], the aircraft must continue to meet its operational requirements and make a safe landing even after being struck by lightning.

In particular, the use of composite in the aviation industry has increased with the increase in studies on unmanned aerial vehicles [6] and the expansion of the usage areas [7] of unmanned aerial vehicles. The use of composites in aircraft requires additional precautions against the indirect effects of lightning as well as the direct effects of lightning. In addition, the certification of military unmanned aerial vehicles is expected by the end user.

The aviation industry has long dealt with indirect lightning due to its impact on safety. As a result, it is included in lightning certification for aircraft environments [4], [8], at various levels such as equipment [9], sub-system, and aircraft [10], [11].

During the late 1980s, Onera seized the opportunity to conduct an in-flight experiment on the C160 Aircraft [12], sponsored by the French Defense Agency. During this experiment, EM field surface sensors were strategically positioned on the aircraft's exterior, while backdoor sensors were discreetly placed behind a carbon composite door. Remarkably, the observed bidirectional waveforms during the experiment were unexpected, catching the researchers by surprise. Nevertheless, through in-depth analysis, the origins of these phenomena were unveiled by conducting calculations on the redistribution of currents using a simplified 3D model that accurately represents the outer surface of the aircraft [13]. Additionally, the phenomenon of backdoor electromagnetic (EM) coupling was confirmed through the application of the theory of scattering by small loaded apertures [14].

During the 1990s, the European Union initiated two noteworthy projects in collaboration with academic, laboratory, and industry partners. These projects were dedicated to investigating indirect lightning and its impacts. One of these projects was the FULMEN EU project. It played a pivotal role in establishing the initial groundwork for 3D modeling of aircraft, encompassing their interiors and wiring. For more detailed information on these endeavors, references [15] and [16] can be consulted.

The focus of this presentation is on cable shielding, which is the passive protection. Shielded cables are an application derived from the principles of electromagnetic (EM) shielding theory [17]. Active protection, on the other hand, primarily revolves around safeguarding equipment inputs using nonlinear devices that are activated by induced currents. However, this paper does not delve into that topic as it is highly dependent on the specific functional signals requiring protection. Furthermore, this article does not address the distinct issue of protecting fuel tanks, which also arises from indirect lightning concerns. For a comprehensive understanding of this specific problem, readers can refer to [18]. Since this problem poses potential risks to the mechanical structure, it is discussed alongside direct lightning effects.

The performance of the shield is heavily influenced by the method used to terminate the shielding. Studies in the literature [19-27] have investigated the impact of various shielding termination methods on performance. Additionally, extensive research has been conducted on EM coupling in cables. Notably, studies have involved measuring currents on low-impedance cables of the Rafale Fighter and the NH90. These measurements were performed while injecting a lightning waveform onto both aircraft in a coaxial-return test configuration [9], [28], [29]. The primary aim of these studies was to determine the effectiveness of different shield termination methods in providing protection against the indirect effects of lightning.

Unlike previous literature, this study directly employed the single stroke test, which is one of the methods for measuring the indirect effects of lightning. Furthermore, this study demonstrates the effectiveness of the shield termination methods favored by EMC engineering in protecting against the indirect effects of lightning. In addition, simulations were conducted to analyze the impact of direct lightning strikes on both shielded and unshielded cables.

Result were compared with the success of shielding termination methods in the literature. Thus, the consistency of the precautions taken for electromagnetic compatibility (EMC) with lightning protection measures was discussed, and an idea was gained about the termination methods that can be preferred in applications on aircraft.

This study aims to evaluate various shielding termination methods to determine their effectiveness against the indirect effects of lightning. The study is carried out using both experimental and simulation methods. First, the lightning effects were simulated using the EMA3D program. The simulation results provided valuable insights into the expected impacts of lightning on the test setup. Then, test setups were developed to conduct experimental analysis. The experimental analysis results were compared against the simulation results to confirm the consistency between the two methods.

It is worth noting that the consistency between the simulation and test results is a crucial aspect of the study. Without this consistency, it would be challenging to draw meaningful conclusions from the results obtained. The fact that the simulation and test results match is a strong indication that the study's findings are reliable and can be used to inform real-world applications.

The results obtained can be used to guide the development of best practices for protecting aircraft against the indirect effects of lightning.

In Chapter 2, the lightning environment is defined, and appropriate safety margins are presented. Chapter 3 presents the shielding termination methods used in practice and explains their differences. In Chapter 4, the simulation study and its results are given. Chapter 5 gives the explanation, test configuration, and test setup of the conducted experiment. In Chapter 6, all the results are evaluated and compared with the literature.

2. LIGHTNING ENVIROMENT

As a result of lightning attachment to the aircraft, physical and electromagnetic effects occur on the aircraft. Physical effects mainly cause structural damage, such as melting, puncture, and boiling. Electromagnetic effects, on the other hand, occur due to the circulation of lightning currents on the aircraft’s surface and the interference of electromagnetic fields to aircraft avionics.

While the specific characteristics of lightning injection current may vary across different events, certain typical signatures can be observed consistently. To ensure consistency and compliance, the establishment of normalization standards has been crucial. These standards define generic waveforms that systems must adhere to, as outlined in references [8], [10], and [30]. By following these defined waveforms, systems can maintain the expected level of uniformity and adherence to the set standards.

Notably, the RTCA [9] and EUROCAE [31] have defined the waveform sequences depicted in Figure 1 as the standardized representations for aircraft. These waveforms serve as a reference for ensuring conformity within the aviation industry. In addition, these standard waveforms are used not only in the aviation industry, but also in the industry. For example, lightning tests are also carried out on transformers and transformers are designed to resist these effects [32].

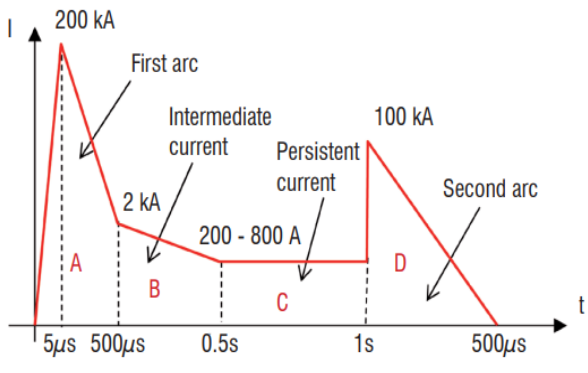

Figure 1. Lightning Waveform, as defined in RTCA DO-160 [9]

In Figure 1, the primary standardized waveform sequence is depicted, consisting of four consecutive elementary waveforms. Every waveform in this sequence is characterized by a notable action integral, which is a prominent feature. The action integral, derived from integrating the square of the current waveform, holds a close association with the energy of the signal. A significant action integral indicates either high current amplitudes or a prolonged duration of the waveform, signifying its persistence over time.

The indirect lightning environment is investigated in Chapter 22 of RTCA DO-160G [9], specifically under the damage resistance and functional failure tests. The standard provides "Pin Injection" and "Cable Bundle" tests for damage resistance and functional failure, respectively.

In damage resistance tests, the level and waveform determined are directly applied to the designated pin on the Device Under Test (DUT) connector. This method demonstrates the damage resistance tolerance of the equipment's interfaces [9].

Functional failure tests require applying the determined level to the cable bundle using an induction probe. This method shows the equipment's resistance to the electromagnetic (EM) environment created by the external lightning environment [9].

There are various waveforms that are standardized for different test levels and requirements. These waveforms are called standard waveforms, and they are derived from direct lightning waveforms. The data obtained from experimental observations of the internal effects of lightning directly attached to the aircraft was used to standardize these waveforms.

Table 1 and Table 2 display the waveforms that should be used, and the required levels are specified in the RTCA DO-160G standard.

Table 1. RTCA DO-160 Table 22-1.2, cable bundle test requirement [9]

Waveform Set	Test Type	Test Levels	Test Waveform Nos.
C (unshielded, aperture coupling)	Single Stroke	Table 22-3	2, 3
D (unshielded, aperture and resistance coupling)	Single Stroke	Table 22-3	2, 3, 4
E (shielded aperture coupling)	Single Stroke	Table 22-3	1, 3
F (shielded, aperture and resistance coupling)	Single Stroke	Table 22-3	3, 5A
G (unshielded, aperture coupling)	Single Stroke	Table 22-3	2, 3
	Multiple Stroke	Table 22-4	2, 3
H (unshielded, aperture and resistance coupling)	Single Stroke	Table 22-3	2, 3, 4
	Multiple Stroke	Table 22-4	2, 3, 4
J (shielded, aperture coupling)	Single Stroke	Table 22-3	1, 3
	Multiple Stroke	Table 22-4	1, 3
K (shielded, aperture and resistance coupling)	Single Stroke	Table 22-3	3, 5A
	Multiple Stroke	Table 22-4	3, 5A
L	Multiple Burst	Table 22-5	3
M	Multiple Burst	Table 22-5	6

Table 2. RTCA DO-160 Table 22-3, test and limit levels for cable bundles single stroke tests [9]

Level	Waveforms				
	2/1	2/1	3/3	4/1 Note 3	4/5A
	V_L/I_T	V_T/I_L	V_T/I_L	V_T/I_L	V_L/I_T
1	50/100	50/100	100/20	50/100	50/150
2	125/250	125/250	250/50	125/250	125/400
3	300/600	300/600	600/120	300/600	300/1000
4	750/1500	750/1500	1500/300	750/1500	750/2000
5	1600/3200	1600/3200	3200/640	1600/3200	1600/5000

Figure 2 shows the properties of the waveform (Current Waveform 1) to be used in this study.

Every equipment manufacturer needs to test their equipment at the appropriate level, taking into account its position on the aircraft (including the route of the cables), and show that it functions normally under these test levels.

Test levels go up to Level 5, with Level 1 being the Protected Environment that takes into account the shielding effect of the aircraft structure. The protected environment is not clearly defined, but it is considered to be areas that are electromagnetically closed and away from openings where the aircraft structure's shielding effect is sufficient.

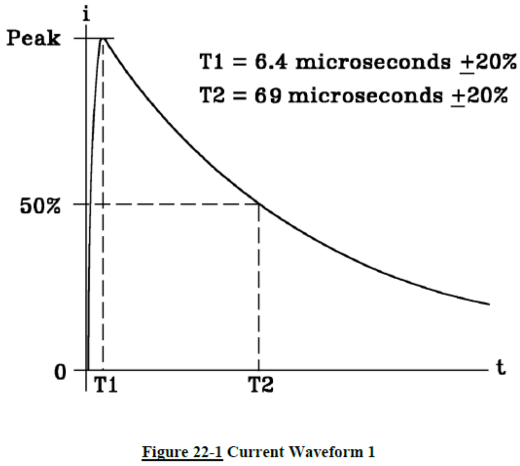

Figure 2. RTCA DO-120 Section 22, current waveform 1 (WF1) [9]

To prove the qualification, it is necessary to demonstrate that the margin levels set forth in FAA Aircraft Circular 20-136B [33] have been met. If the margin levels are inadequate, the equipment must be modified to achieve the required level. Figure 2 illustrates the margin adequacy level in the AC 20-136B standard. For a more detailed understanding, refer to the RTCA DO-160G [12] and AC 20-136B [33] standards.

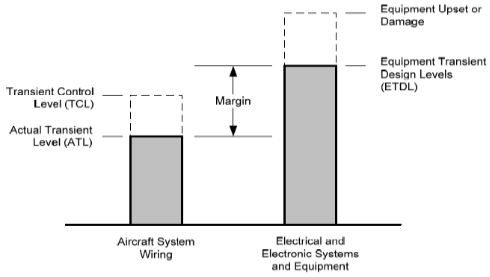

Figure 3. AC 20-136B Figure 1, relationships among transient levels [33]

In this study, we use Current Waveform 1 (WF1), Level 1. WF1 is susceptible to interference from openings or inductive coupling, and is derived from direct lightning Component A. It has a lower-level current waveform that is similar in shape to Component A.

3. SHIELDING TERMINATION METHODS

Ensuring cable shielding is of paramount importance as it serves as a vital safeguard against unintended radiation and electromagnetic (EM) interference, shielding electronic systems from potential disruptions and external influences. There is widespread recognition that proper shield termination greatly affects the effectiveness of shielding [22 - 26], although there may be some disagreement on the exact methods.

The aircraft's cable network is not only extensive but also omnipresent. Its electromagnetic compatibility (EMC) largely depends on the design of the harness, as cited in references [34] and [35].

Today, the idea of using electrical energy instead of fuel in airplanes is coming to the fore [36]. This situation makes it necessary to shield the cables passing high current and take special precautions. As it is known, the more current passing through a cable, the more emissions it makes will be.

It is unclear to what extent parameters such as termination geometry and material affect shielding performance. This study does not aim to explore the effect of termination on shielding effectiveness. As previously stated, the focus of this research is on determining which termination method provides the best protection against lightning indirect effects.

The recommended approach for terminating shields in cables is to use a double-sided 360˚ backshell. However, there may be situations in which this is not feasible, and alternative methods can be employed. Type of termination methods are given in [37-39]. Figure 4 outlines these methods and provides a general evaluation of their effectiveness in terms of electromagnetic compatibility (EMC) engineering. In addition, there are different methods than the termination methods given here. In particular, the termination methods used in power lines can be quite different from the methods mentioned here. Readers can refer to reference [40] for details of screen termination on power lines.

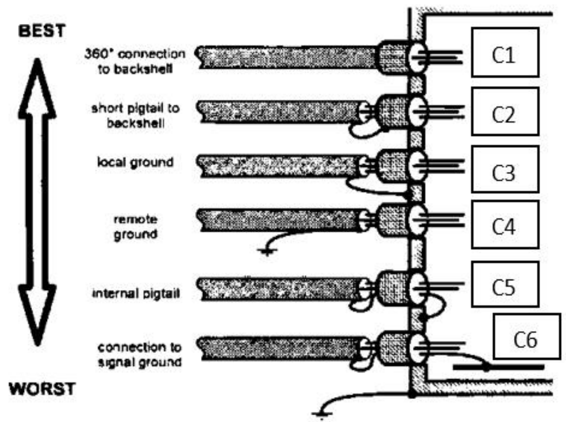

Figure 4. General evaluation of different shield termination methods in terms of EMC engineering

C1 is the termination method in the backshell with 360˚. In this configuration, the shield is transferred to the backshell by contacting the shield from all directions at 360˚ without any discontinuity in the shielding.

C2 is one of the most preferred applications in connectors that do not have an EMI backshell but are conductive. The shield is transferred to the pigtail with the solder sleeve method, as close as possible to the connector, usually 10 cm or less, and the transfer to the connector is provided with the help of the pigtail.

In C3, C4, C5, and C6 configurations, the shield is transferred to the pigtail with the solder sleeve method as close as possible to the connector, but the pigtail terminations are made at different points.

In C3, the pigtail is terminated on the chassis of the equipment. If the pigtail is kept short enough and the connection is made correctly, it is expected to achieve approximately the same level of shielding effectiveness as C2.

In C4, the pigtail is terminated on the aircraft structure, not the equipment. Here, the pigtail is expected to be kept as short as possible.

In C5, the pigtail is passed through the connector with the signal cables and terminated inside the equipment. In this method, the currents on the shield may cause interference with the nearby signal cables during the connector transition.

In C6, the pigtail passes through the same connector as the signal cables and is terminated at the ground plane inside the equipment. Here, with the currents on the shield flowing to the ground plane inside the equipment, the ground plane may be polluted, and the signal reference of the equipment may be distorted. This method should be avoided.

The most significant difference between the C5 and C6 is the effect they have on the signal plane of the equipment rather than the shielding effectiveness. Unless the equipment manufacturer specifies explicitly, the C5 and C6 applications will not be applied. Even when the equipment manufacturer uses one of these methods, it is generally accepted by the manufacturer to use C1 for shielding termination.

In addition to the configurations outlined above, it may be necessary to leave the shield on the equipment side as a dead-end, either for practical reasons or at the equipment manufacturer's request. However, it is important to note that in order to provide effective shielding, the shield must still be terminated from at least one side.

When using the pigtail method, it's generally accepted that the pigtail length should not exceed 6 inches.

To ensure proper shielding termination, it is important to consider the electrical bonding value of the shield. According to MIL-STD-464D, the bonding value between the shield and equipment should be 15 milliohms or less, which includes the cumulative effect of the connector and auxiliary interfaces [5]. These can be achieved whether 360˚ termination is used, but it is not very possible to achieve the shielding at a different point from the equipment, such as "remote ground" applications. Therefore, in practice, the resistance value between the shield and the termination point is expected to be less than 2.5 milliohms. In addition, the resistance value of the connection between the equipment and the aircraft surface should be less than 2.5 milliohms [5],

[41]. Although the value of 2.5 milliohms lacks scientific backing, it is a longstanding and widely recognized value within the aviation industry [5]. It is expected that Metal-to-Metal connections will have a bonding value of less than 2.5 milliohms.

4. SIMULATION STUDY

As specified in the standard, the biexponential waveform is considered a practical and convenient mathematical model that effectively captures the essence of various fundamental waveforms. This is because it closely resembles waveforms produced by actual current sources, which often rely on capacitive discharges [9, 28, 29]. The choice of the biexponential waveform as a model is rooted in its ability to accurately represent the characteristics of actual current sources in a straightforward manner.

Biexponential waveform is defined:

$$I(t) = I_0(e^{-\alpha t} - e^{-\beta}) \quad (1)$$

where α and β are constant number and I_0 is Ampere.

Please note that while the exponential waveform is commonly used for approximating the pulse, it is not the only option available. One example of a waveform that can be used as an alternative to the biexponential waveform is employed to address the issue of having a non-zero derivative at time zero, although not representing a physically realistic scenario, can pose challenges in the modeling process. In order to overcome this limitation, alternative waveforms can be employed [42].

Developing appropriate electromagnetic models for intricate structures is a demanding and time-consuming process. At present, there are only a few widely utilized software programs available for simulating the electromagnetic fields generated by lightning on aircraft.

In 2008, Airbus Apra M accomplished a significant milestone by successfully modeling aircraft made with carbon fiber reinforced polymer (CFRP). This achievement was made possible through the utilization of finite difference time domain theory in combination with the EADS IW tool and Innovation Working Group. The study conducted by Airbus Apra M involved a comprehensive analysis of the lightning-induced effects on CFRP aircraft, leading to the formulation of valuable recommendations for mitigating the indirect consequences of lightning [43].

The research presented in reference [44] involved an analysis of the regional electromagnetic field and surface current distribution of a carbon fabric composite aircraft. Furthermore, simulation software was employed to investigate cable coupling at different locations within the nacelle.

Reference [45] discusses the use of EMA3D, an electromagnetic simulation software, to examine the electromagnetic environment of airborne equipment during lightning events. The simulations conducted in the study also focused on exploring inductive currents in crucial cables.

In a study described in reference [46], the simulation of the electromagnetic field resulting from a lightning strike on an aircraft's engine is presented. The study employs the transmission-line matrix (TLM) theory to analyze both the induced and the surface current within the cables which are located in the engine. In order to achieve a precise depiction of the entire turboprop engine, the study incorporates the real-world distributions of internal cables and components into the model. This ensures an accurate representation that closely mirrors the physical configuration of the engine.

In this study, a cable with and without a 360˚ shield was simulated on the F-16 model in the EMA3D program. Direct lightning Component A was applied to the aircraft for the analysis to reflect reality.

The lightning entry point is designed to resemble the nose of the aircraft, while the exit point is located on the aircraft's right wing. For an overview of the model and the location of the cable, please refer to Figure 5 and Figure 6. The entry and exit points are chosen to simulate the worst-case scenario by allowing lightning current to pass through the area where the cable is located. It should be noted that since this study is focused on comparing the condition of shielded and unshielded cables, there is no need to perform a worst-case analysis or test. Based on the simulation, the shielding effectiveness and expected current values induced in the cable during the test can be estimated theoretically.

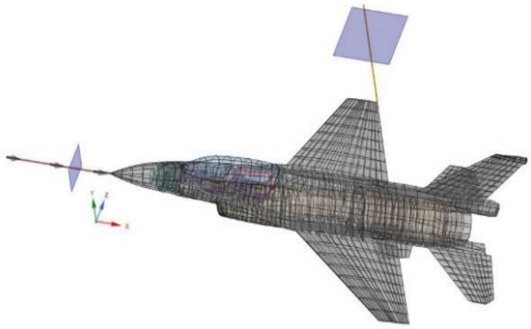

Figure 5. In the EMA3D program, the F16 model and lightning attach/de-attach points

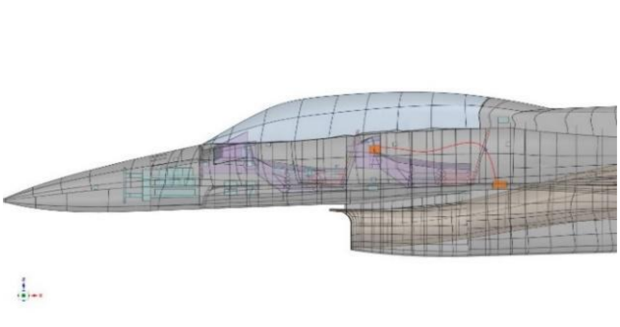

Figure 6. Close-up view of the modeled cable in the EMA3D program

As previously mentioned, the cable was modelled with a length of approximately 3 meters both with and without a shield. In the shielded state, the shields were terminated on both sides with a value of 2.5 milliohms to simulate the 360˚ termination method. Please find the results obtained in Figures 7 through 10 below.

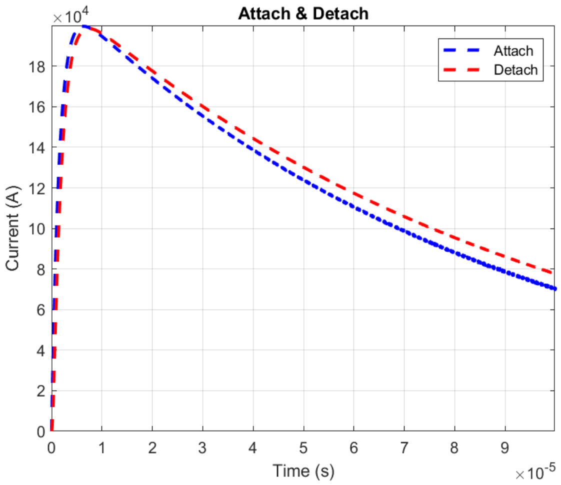

Figure 7. Levels of simulated lightning current (Component A) at attach and de-attach points

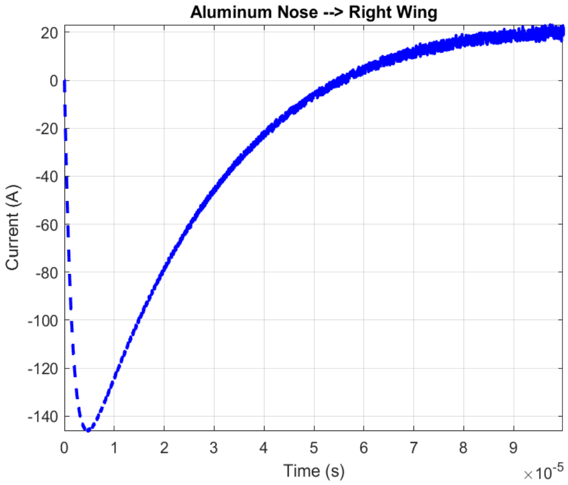

Figure 8. Induced current value on unshielded cable

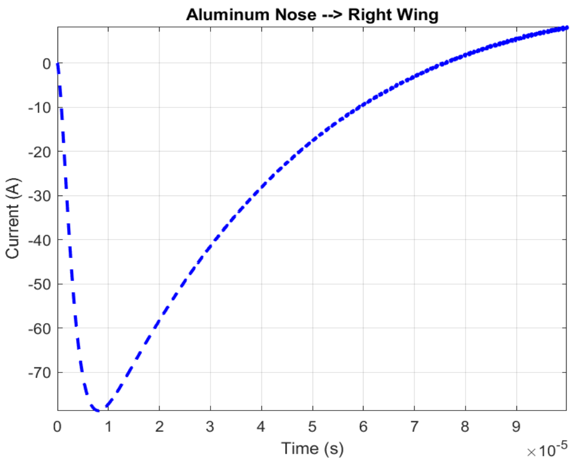

Figure 9. Induced current value on shielded cable

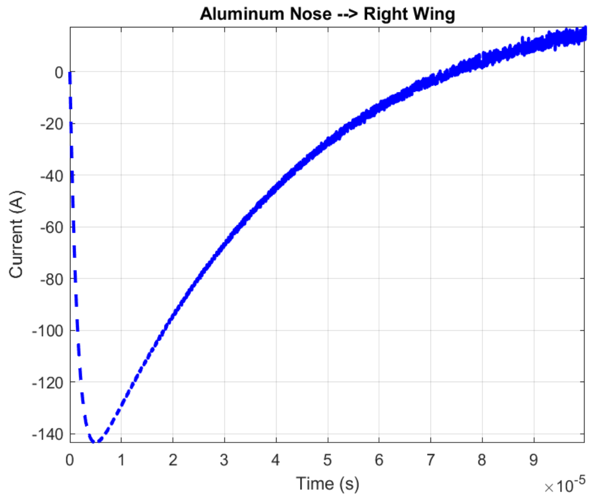

Figure 10. Induced current value on the shield

As anticipated from the analysis, the current levels induced on the shield in the shielded configuration with the unshielded cable were similar. Upon scrutiny of the analysis results, it is evident that the 360˚ shielding termination offers approximately 2.7 dB of protection when compared to the unshielded configuration.

5. EXPERIMENTAL STUDY

This study examines various termination methods using WF1-Level1. The current value on R_L is measured with a current probe, and the resulting induced levels on the cable are analyzed. The effects of shielding termination are also examined using the obtained values. Additionally, the pigtail method is explored, with different pigtail lengths and their effects being studied. Termination bonding values must comply with the standard and provide 2.5 milliohms. The configurations to be used are described in the following section.

5.1. Test Configurations

In this study, shielding effectiveness was tested using 6 different setups across 5 configurations. The shielding termination on the Box2 side was fixed and terminated in a 360˚ backshell (bck). On the Box1 side, different termination methods were used, as shown in Figure 4, to evaluate the shielding effectiveness. The resistance value between the ground plane inside the box and the box was less than 2.5 milliohms, and the bonding value between all connections and connection points was less than 2.5 milliohms. The figures below provide a detailed description of all configurations used in the study.

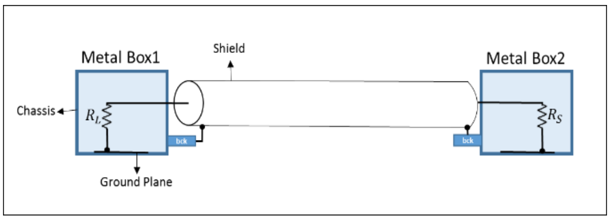

Figure 11. Configuration 1

With Configuration 1, given in Figure 11, the shield is terminated double-sided in a 360˚ backshell (bck). In terms of EMC, it is the most convenient way of shield termination. (See Figure 4, C1)

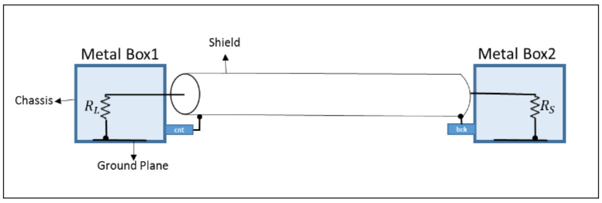

Figure 12. Configuration 2

With Configuration 2, given in Figure 12, the shield is terminated at the connector (cnt) with the help of a short pigtail on the Box1 side. The length of the pigtail is 5 cm. (See Figure 4, C2)

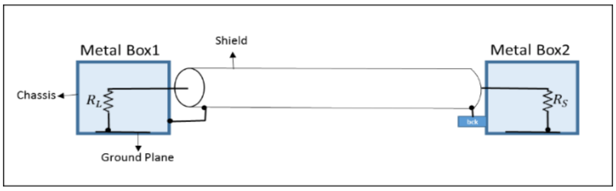

Figure 13. Configuration 3

With Configuration 3, given in Figure 13, the shield is terminated on the equipment's chassis with the help of pigtails on the Box1 side. The length of the pigtail is 7 cm. (See Figure 4, C3)

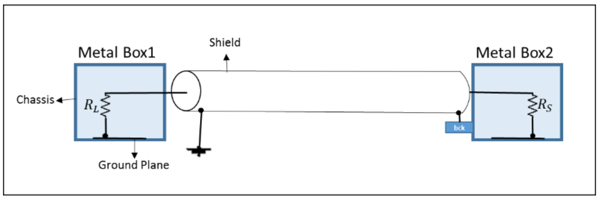

Figure 14. Configuration 4

With Configuration 4, given in Figure 14, the shield is terminated at a different point from the equipment with the help of a pigtail on the Box1 side. Here, two different lengths of pigtails were used to examine the effect of the length of the pigtail. Pigtails were tested as 15 cm and 25 cm, respectively. (See Figure 4, C4)

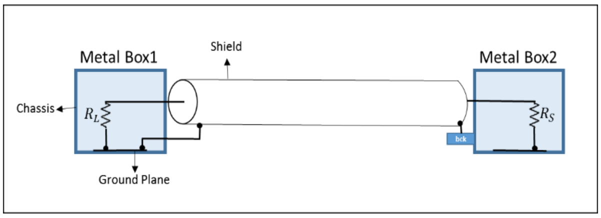

Figure 15. Configuration 5

With Configuration 5, given in Figure 15, the shield is terminated on the ground plane inside the equipment with the help of a pigtail on the Box1 side. It is considered the worst application in terms of EMC. (See Figure 4, C6)

To evaluate how shield termination affects shielding performance, tests can be conducted in various configurations. To ensure practicality, the most common situations were taken into account when determining the configurations.

5.1. Test Setup

The test setup was set up in accordance with the standard, as shown in the general setup schematic in Figure 16.

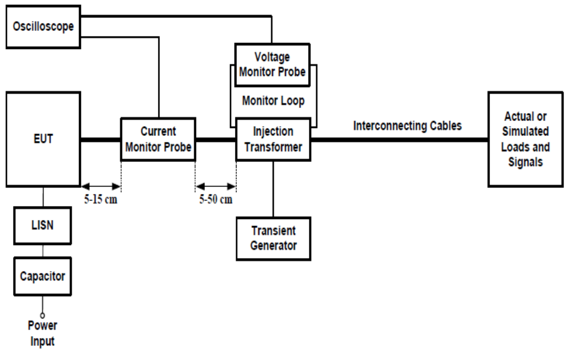

Figure 16. MIL-STD-461G, FIGURE CS117-10, Typical setup for bulk cable injection of lightning transients on complete interconnecting cable bundles

The current is measured using the current probe over the resistor R_L as shown in the configuration figures. To read the short circuit current, the resistance values of both R_L and R_S resistors are minimized. The cable is connected to the ground plane with resistance values less than 2.5 milliohms. Please note that this setup differs from the one provided earlier.

The data obtained as a result of the tests are given below from Figure 17 to Figure 22.

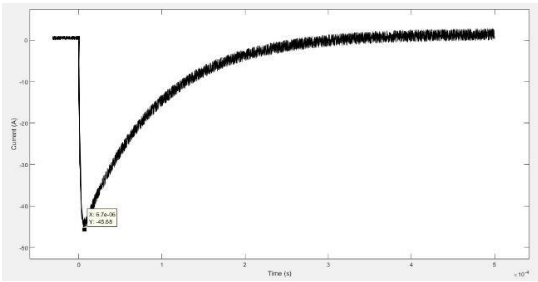

Figure 17. Termination in 360˚ Backshell (Configuration 1)

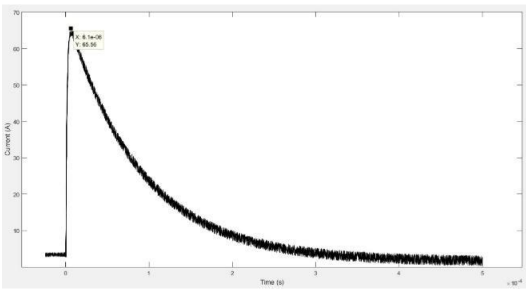

Figure 18. Termination at connector with pigtail (5 cm) (Configuration 2)

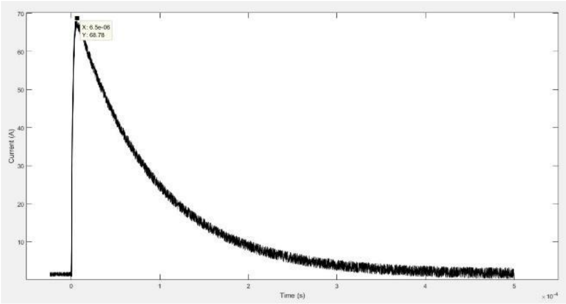

Figure 19. Termination on chassis with pigtail (7cm) (Configuration 3)

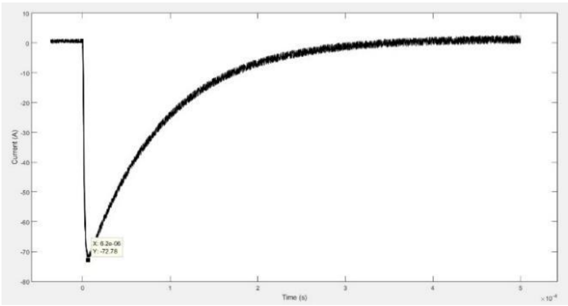

Figure 20. Termination at a separate point with pigtail (15 cm) (Configuration 4)

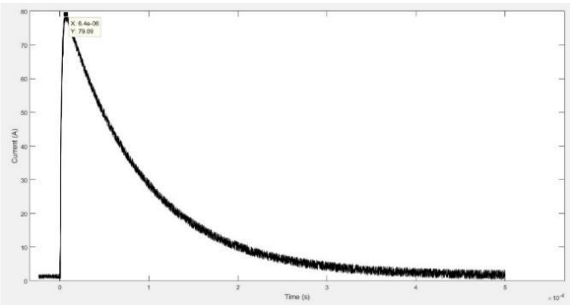

Figure 21. Termination at a separate point with pigtail (25 cm) (Configuration 4)

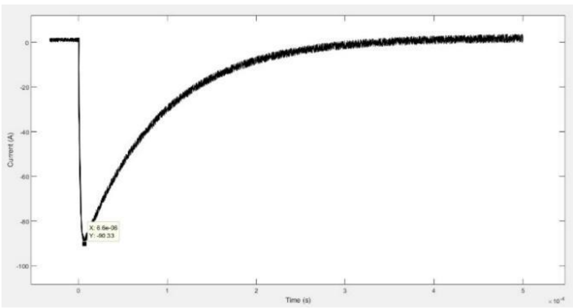

Figure 22. Termination inside the equipment with pigtail (15 cm) (Configuration 5)

Upon examination of the obtained data, it appears that the current levels on the cable are approximately 45A when the shield is terminated with a 360˚ backshell, 65A when the shield is terminated at the connector with a short pigtail, 68A when the shield is terminated on the equipment chassis with a short pigtail, 72A when the shield is terminated at a different point with a 15 cm pigtail, 79A when the shield is terminated at a different point with a 25 cm pigtail, and 90A when the shield is terminated at the ground plane inside the equipment with the help of pigtail.

The shielding values obtained are as follows: 3.46 dB, 1.87 dB, 1.67 dB, 1.42 dB, 1.02 dB, and 0.45 dB, respectively for the following termination methods: 360˚ backshell termination, connector termination, chassis termination, 15 cm pigtail termination, 25 cm pigtail termination, and internal equipment termination. These results are in line with the recommended shielding termination methods for EMC engineering.

6. RESULT AND DISCUSSION

This study was carried out using both experimental and simulation methods and the results obtained from the experiments were compared with the simulation results and previous studies. As a part of the study on evaluating various shielding termination techniques for their effectiveness against the indirect effect of lightning on electronics, the test and analysis results were examined. It was found that utilizing a 360˚ backshell termination technique proved to be highly effective, providing protection of nearly 3 dB. The results obtained from the experiment and simulation were consistent, further validating the effectiveness of the 360˚ backshell termination technique. Overall, this study highlights the importance of adequate protection against lightning strikes on aircraft and the need for qualified, lightning-proof equipment. In addition, simulation results are consistent with the experimental results. This consistency has given greater confidence in the accuracy and reliability of the simulation. Therefore, the simulation is now considered to be a valuable tool for predicting future outcomes and informing decision-making processes.

Furthermore, the effectiveness of shielding termination methods on the indirect effects of lightning was found to be comparable to the performance of shielding termination methods against radiated susceptibility, as previously documented in the literature [19-22], [38]. In this study, it has been found that the 360˚ backshell termination method is the most effective shielding method against the indirect effects of lightning. In contrast, ground plane termination inside the equipment has been found to be the least successful Shielding measures taken in terms of EMC have been found to be equally advantageous against the indirect effects of lightning as well. If the termination method used on the test rig cannot be applied to aircraft, it is recommended that a more effective termination method be employed. This study demonstrates that the shielding termination methods accepted in the relevant literature are equally effective in mitigating the indirect effects of lightning.

Conclusion, for both EMC engineering and protection against the indirect effects of lightning, the most effective method of shielding termination is the 360˚ backshell termination.

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Emre ATALAY was planned, performed the simulations and designed, planned the experiments, processed the experimental data, performed the analysis, wrote the manuscript and designed the figures.

Ahmet Turgut TUNCER participated in the planning and supervised the work, helped interpret the results, and collaborated on the manuscript.

All authors discussed the results, commented on the manuscript, and contributed to the final version of the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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