Methods of Effectively Shielding Unmanned Aerial vehicles from Lightning Electromagnetic Pulses

Tomasz Kossowski

Rzeszow University of Technology, 2 W. Pola Street, 35-959 Rzeszów, Poland
t.kossowski@prz.edu.pl

Abstract: This article describes methods for the protection of unmanned aerial vehicles against electromagnetic pulses, from close-range lightning. These pulses are a real threat to all electrical equipment. The main problem is the inability to ground the enclosure of a device in the air. Studies have therefore been carried out on different shielding materials, different numbers of layers, different mutual arrangements of these materials and their connection to the drone's power supply. All these tests and results were carried out in the laboratory using a special surge generator, used for avionics testing. The measurements were made inside a 2x2x1m capacitor. The application of the results of the tests described can contribute to the understanding and better design of shielding for drones, showing how important this aspect is and how the materials used can be effectively used to protect sensitive electronic circuits. When analyzing possible solutions, it is important to keep in mind at all times, the specific application of protection in small UAVs, where the weight of additional components has a significant role and these objects are in the air. The results clearly showed the ability of the battery to absorb interference from the enclosure, provided that the connection is made to the negative pole. Through the positive pole, interference propagates much stronger. All the details are shown in the results herein, in the form of graphs.

Keywords: conductivity materials; electricity; lightning discharges; protection against thunderstorm

1 Introduction

The importance and use of unmanned aerial vehicles (UAVs) is growing. These machines are not only becoming larger and faster, but above all equipped with measuring devices capable of analyzing every aspect of our lives, such as air pollution, terrain (geodesy), searching for lost persons, monitoring forest fires, surveillance, thermal analysis of energy facilities, inspection of power grids, photovoltaic farms [1] [2] or wind turbines [3] [4]. The applications are numerous and growing. Related to this is the fact that these machines have to work in harsh weather conditions, often close to a storm front. In such a situation, electromagnetic pulses from lightning discharges (LEMP) are a threat to all electronic equipment. These are specific, very short pulses with a frequency of hundreds of kilohertz. They are both single and multiple pulses, which is a direct result of the nature of the discharge [5] [6].

When UAVs are used to survey and measure high-voltage power lines, there is a risk of propagation of an electromagnetic pulse from a ground cable carrying a surge current (in the event of a lightning strike on a nearby power pole) [7]. This can pose a direct threat to such a device if its enclosure is not designed to protect against EM interference. Unfortunately, due to weight reduction, most small and lightweight UAVs are not equipped with shielding, or they only protect interference-sensitive systems such as GPS modules (mainly against interference from the radio band) [8].

This study and the proposed electromagnetic shielding, are designed to protect the drone's sensitive electronics from the overall effect of EMPs, without separating them into components [8]. Only the one that can cause more damage is described, but both parts of the EM wave should be kept in mind at all times. Indeed, electromagnetic protection made in the form of screens of conductive materials is nothing new. The problem that will be addressed in these considerations is the impossibility of physically grounding the conductive enclosure [9]. The lack of such a connection means that the enclosure can become a source of EM waves inside it (induced due to the eddy currents generated on its surface) which can result in significant interference transfer to the interior and a lack of the intended level of electromagnetic protection [10]. It was therefore decided to test configurations to minimize the negative effects of the lack of earthing for applications in small flying devices such as UAVs. The aim was to increase their resistance to the effects of a near atmospheric discharge as a source of LEMP.

There are many studies related to electromagnetic shielding. Most focus on shielding primarily radio frequency interference or interference from strong radiation sources, but there is a lack of research related to the analysis of impulse interference from lightning [11] [12]. It can be said that the problem of these issues has been perfectly solved in the case of aircraft, but there a much higher level of protection is applied due to many factors (safety of life and health of people on board and on the ground, reliability and many others). In the case of aircraft, effective shielding is even more important, but its weight does not play such a major role. In the case of aircraft, the basic solution is to use aluminum as a skin, which provides conductivity of the discharge as well as effective shielding of the interior [13] [14]. However, these are design solutions for large machines. In the case of small drones, which are mostly made of composite materials or plastics, it is not possible to speak of any shielding. Alloy materials (such as aluminum, for example) are not used for the casing due to the high cost and higher weight compared to plastics. The lack of conductive surfaces, means that these devices are not immune to any interference. The greatest threat for them is posed by pulses of energy capable of inducing surges capable of damaging the machine's delicate semiconductor circuits. The direct impact of lightning on a UAV is not subject to any analysis, as in such a case no effective protection can be applied and such a case will end in damage to the machine [15]. In addition to typical conductive materials such as steel, aluminum or copper, it is possible to use carbon fiber composites (CFRP) as a conductive element [16]. However, such structures are not homogeneous and can allow significant EMP penetration into the enclosure. Other smaller-scale materials such as manganese-nickel [17] or nano-cells [18] have also been proposed, but these represent too much mass for small UAV applications. The bargaining gap in small drone research was decided to be investigated within the scope of this article with a particular focus on solving the problem of pulse absorption, from a conductive electromagnetic shield.

The remainder of this article will describe in detail the materials used in the tests and the variants of their combination. An experimental test rig will also be described, allowing measurements to be made using repetitive lightning strikes under laboratory conditions.

2 Research Method and Screening Materials

The fundamental question sought to be answered was how to provide the best form of shielding without the possibility of grounding the shield. The use of classical earthing is not possible with flying objects. How then to solve the problem of impulses and over-voltages appearing on the screen protecting sensitive electronic systems? The simplest of the solutions used is a single-layer screen that is connected to the ground field. This is a common and quite effective solution. The aim of this study was to find a solution with greater effectiveness in particular against the effects of LEMPs, i.e. pulses with low and medium frequencies, but with high energy. It was decided to propose double-layer shielding with one and two different types of material: copper and aluminum. Both of these materials are commonly used for shielding (along with steel). Steel was rejected due to its high weight, which is important for UAVs. Aluminum is lightweight and copper provides the greatest electrical conductivity, so it was decided to test these two materials [19] [20]. It was still to be considered whether connecting to a ground point would actually give the best result, or whether it should be solved in a different way. A detailed list of options for the proposed tests is presented in the materials subsection. The aim of the research is therefore to find both the optimal configuration of materials and their connections to each other and to the drone components. All the time, the lowest possible mass should be kept in mind, so only thin films can be used. The tests were carried out by placing samples inside a capacitor measuring 2x2x1 m. This ensured the uniformity of the field in its central part, because the samples were more than ten times smaller (0.15x0.15x0.15 m). The source of the surge pulses was a generator used to test avionics components. The waveforms used were used in accordance with international standards. A real object – a UAV – was used to detect signals inside the capacitor. It was important to use a working device, especially in terms of connecting the shielding to its power supply system. The tests were carried out while maintaining safe peak overvoltage values so as not to damage the machine during the tests. This ensured the reliability of the results. A detailed description of both the measuring station and the materials used for the tests is described later in this chapter.

2.1 Measurement Setup

To carry out the experiments, a test rig was built consisting of the following components:

- High-voltage surge pulse generator - MIG0618SS
- Two 2x2m steel plates as capacitor covers (covers 1m apart)
- A non-conductive stand inside the capacitor, allowing the samples to be placed in the central part
- Digital oscilloscope for recording waveforms - Rigol 1054Z
- Measurement cabling - coaxial cables (attenuation 0.1 dB/m @ 50 MHz)
- Small UAV

A schematic diagram of the test stand is presented in Figure 1.

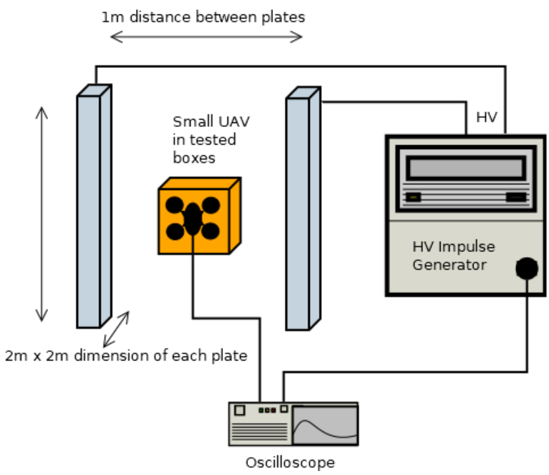


Figure 1
Measurement equipment setup

The dimensions of the capacitor covers were selected with an allowance to ensure a homogeneous electric field in the central part. Due to the large dimensions and the fact that the capacitor (including its electrical insulation) is placed on the floor, there is a risk of inhomogeneity at its edges. In order to ensure a homogeneous shock signal for the test objects (15x15x15 cm), the central part provided a sufficient level of homogeneity of the electric field strength [21]. This was proven by experimental measurements of the field distribution inside the constructed capacitor, as described in another scientific paper [22] and the results of these measurements are shown in Figure 2.

The generator MIG0618SS (single-stroke voltage impulse with the waveshape of 6.4/69 μs for open circuit condition) generator allows a reproducible waveform conforming to international standards to be obtained, every time, allowing tests to be carried out under the same conditions throughout a series of measurements [23-25]. This is very important so that each of the analyzed and tested cases is measured with the same parameters. The results collected in an unchanging measurement system are meaningful and real and with a reduced impact of type A uncertainty.

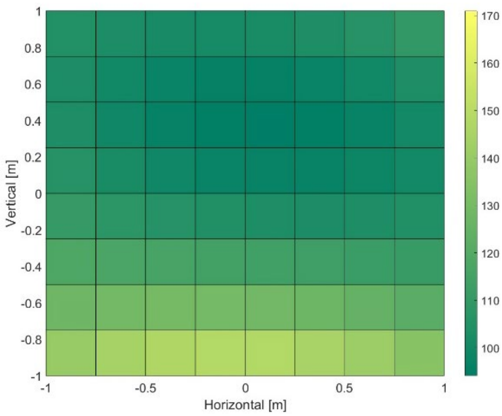


Figure 2
The amplitude [V/m] of the electric field between the capacitor covers – measured by Maschek ESM-100 meter [22]

To determine the induced voltage in a conductor of length *l* based on the lightning current, we can use Faraday's Law (formula 1) and the Biot-Savart Law [26] [27].

$$U = -\frac{d\Phi}{dt} \tag{1}$$

where: U is the induced voltage, Φ is the magnetic flux, $d\Phi/dt$ is the rate of change of the magnetic flux.

The Biot-Savart Law (formula 2) allows us to calculate the magnetic field B at a distance r from a current-carrying conductor:

$$B(r) = \frac{\mu_0 I}{2\pi r} \tag{2}$$

where: *B(r)* is the magnetic field at a distance *r* from the conductor, μ_0 is the magnetic permeability of free space (≈$4\pi\times10^{-7}$ H/m), *I* is the lightning current, *r* is the distance from the conductor.

The magnetic flux *Φ* through a conductor of length *l* can be expressed as:

$$\Phi = B \cdot A = B \cdot l \cdot d \tag{3}$$

where: *A* is the area through which the magnetic flux passes, *l* is the length of the conductor, *d* is the distance between the conductor and the source of the magnetic field.

Assuming the magnetic field changes over time with a rate *dB/dt*, we can express the induced voltage as [26] [28]:

$$U = -l \cdot d \cdot \frac{d}{dt}\left(\frac{\mu_0 I}{2\pi r}\right) \tag{4}$$

The above discussion focuses on the magnetic component for several reasons. Firstly, its shielding is definitely more difficult, secondly it is the dominant component inducing over-voltages in the drone's conductors, thirdly it is part of the component of the LEMP pulse generated inside the capacitor covers. This is because the forcing pulse is a short duration pulse. Thus, we are dealing with an impulsive electromagnetic wave and not a static field of purely electrical nature. Of course, the electrical component and its value in the drone's circuits are equally important, as they can cause significant voltage differences between sensitive components, resulting in damage (such as punctures and burnout of semiconductor structures). This study and the proposed electromagnetic shielding are designed to protect the drone's sensitive electronics from the overall effect of EMP, without separating them into components. Only the one that can cause more damage is described, but both parts of the EM wave should be kept in mind at all times. Indeed, electromagnetic protection made in the form of screens of conductive materials is nothing new [16-18, 29]. The problem that will be addressed in these considerations is the impossibility of physically grounding the conductive enclosure. The lack of such a connection means that the enclosure can become a source of EM waves inside it (induced due to the eddy currents generated on its surface) which can result in significant interference transfer to the interior and a lack of the intended level of electromagnetic protection.

It was therefore decided to test configurations to minimize the negative effects of the lack of earthing for applications in small flying devices such as UAVs. The aim was to increase their resistance to the effects of a near atmospheric discharge as a source of LEMP.

2.2 Materials

Two primary materials used for electromagnetic shielding in industry were selected for the study: aluminum and copper. Of course, there is nothing revealing about this, but the aim of the research was not to select a material, but a combination of them, along with the way the shielding layers are connected both to each other and to the drone's components.

For the construction of the shields, the materials used were [30] [31]:

- Aluminum foil with a thickness of 25 μm
- Copper foil with a thickness of 35 μm

These two materials resulted in enclosures made as follows:

A. One layer of aluminum
B. One layer of copper
C. Two layers of aluminum - possible configurations: interconnected, separated from each other, any layer connected to any circuit of the drone (explanation later)
D. Two layers of copper - possible configurations: as before
E. Inner layer made of aluminum and outer layer made of copper - possible configurations: as before
F. Inner layer made of copper and outer layer made of aluminum - possible configurations: as before

The results obtained for configurations A and B did not give any significant results so the results are not presented in this work. On the other hand, the two layers with different configurations and different connections gave different results for the surge pulses. It was decided to connect the individual shielding layers to the positive and negative terminals of the lithium-ion battery (7.4V) powering the UAV. Connecting different layers (C, D, E and F) in each variant was considered in this case:

- Connecting the inner and outer layers to the positive pole
- Connection of the inner and outer layers to the negative pole
- Connection of the inner layer to the negative pole
- Connection of the inner layer to the positive pole

Tests were carried out for all the configurations discussed, but only the most important and representative results obtained during the tests have been collected and presented in the graphs. Several systems of the drone were each tested, such as the motor winding, the motor controller (ESC), the communication to the RF antenna, the power supply to the electronics (3.3 V) and the main power line feeding the drone's components, where surge propagation could cause the most damage due to the number of components fed from it.

The type of discharge (positive and negative polarity of the stroke) was also studied, as 90% of cloud-to-ground discharges have negative polarity [32] [33]. Therefore, it is this group of discharges that should be the focus of the study, as due to the maximum flight altitude of the UAV, it will not be in the immediate vicinity of clouds and therefore there is no validity to consider other types of discharges in particular clouds. The polarity of the shock pulse is critical to the induced surges in the drone's circuits, particularly in semiconductor systems. Interference propagation will be greater if the polarization is in the direction of conduction. The behavior and magnitude of interference will therefore be different from that of motors or power systems. It should also be noted that the susceptibility to interference induction itself will be less in electronic systems than in wiring, antennas or motor windings, due to the length of the conductor [33-35].

3 Results

The results of the experiments are divided by the different types of materials and their combinations. These are a selection of results from all that have been tested (as detailed in the previous section). Each graph consists of two parts. The first (a) shows the recorded pulses (surges) in the UAV for different shielding configurations. The second part (b) shows the same signals integrally timed, for a better depiction of the total interference energy that entered through a given type of shielding. This solution allows a better representation of the difference between the different results, as in the form of pulses (a) the graphs partially overlap and are not well readable. Figure 3 shows the results for two layers made of aluminum.

Figure 4 shows analogous results for two layers made of copper. The value of the interference induced in the circuits is almost twice as low. The interference suppression time is also shorter, as can be clearly seen in the time characteristics (Figure 4a), and this translates directly into the value of the pulse energy over its entire duration.

Figures 5 and 6 show how effective a combination of one layer of copper and one layer of aluminum is at screening. In the first variant (Figure 5), the inner layer was aluminum and in the second (Figure 6), it was copper.

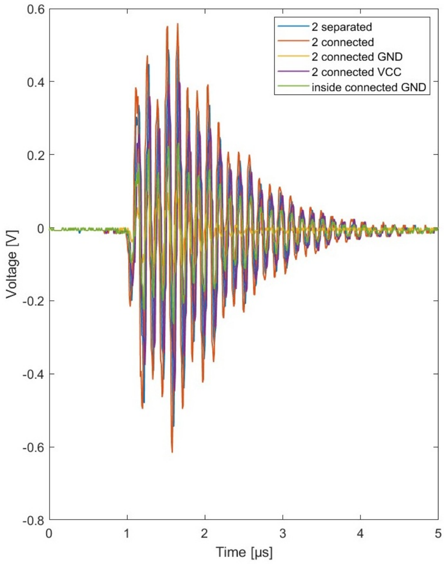


Figure 3a

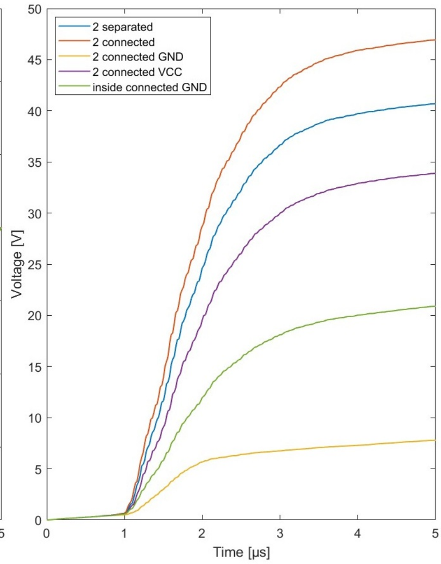


Figure 3b

Results for two layers of aluminum: (a) – signals in power supply (b) – integral of this signals

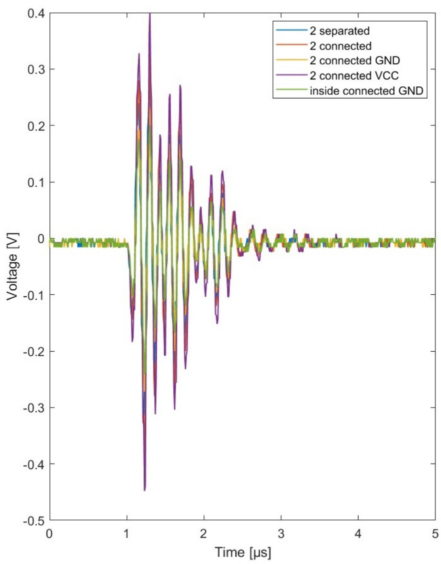


Figure 4a

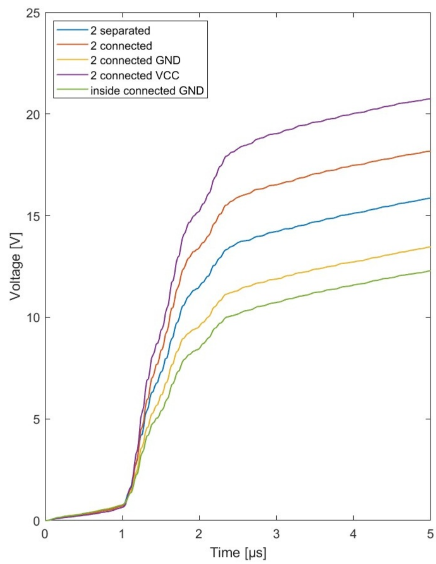
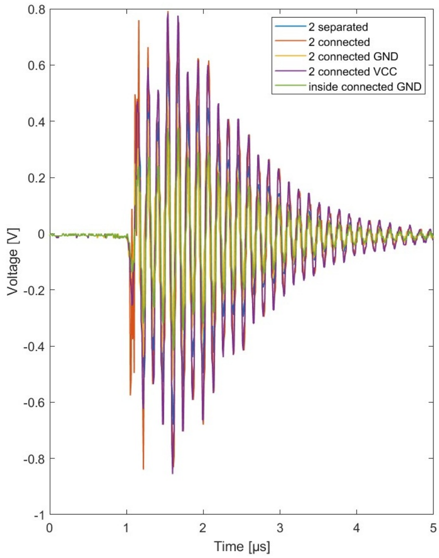


Figure 4b

Results for two layers of copper: (a) – signals in power supply (b) – integral of this signals



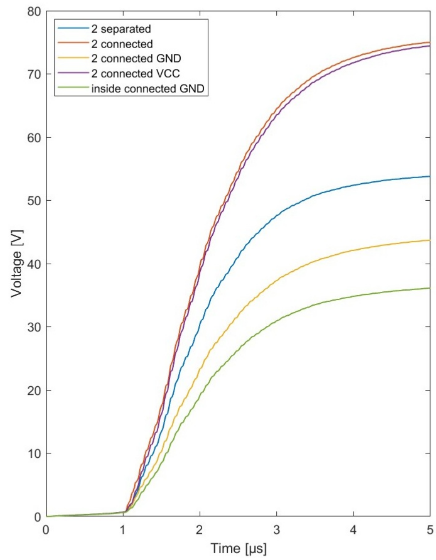
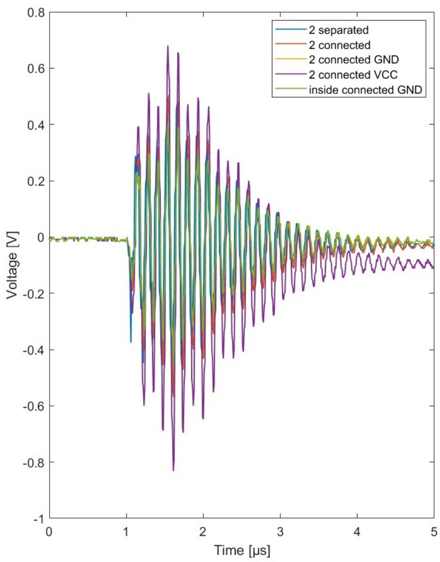


Figure 5a Figure 5b

Results for aluminum (inside) and copper (outside): (a) – signals in power supply (b) – integral of this signals



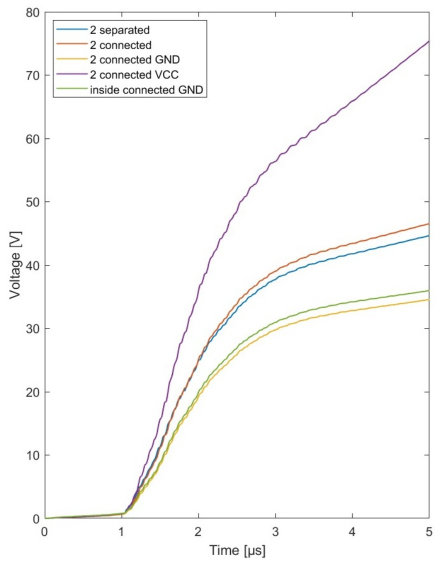


Figure 6a Figure 6b

Results for copper (inside) and aluminum (outside): (a) – signals in power supply (b) – integral of this signals

The results are not particularly satisfactory and it is clear that combining different materials did not give a gain in shielding efficiency. The order of the materials in the EM wave path is also not very important. Both of these forfeits do not represent a good solution compared to the results for two layers made of copper. The following conclusions can be drawn from the above diagrams:

- There is no best solution when simultaneously considering changing the types of materials in the different layers and their connection to each other and to the drone's power supply
- Solutions where both layers or only the inner layer is connected to the ground give (alternate) the best results in terms of reducing the variance of the surges induced in the UAV circuits
- Connection to the positive battery terminal causes the greatest propagation of disturbances, which even amplifies them throughout the system.
- Previous studies related to the connection or separation of individual shielding layers have also been confirmed, that connected layers provide worse protection than those galvanically separated

Based on these results, one of two solutions should be considered: combining both layers (irrespective of material) to the mass or only the inner layer. In order to find the optimal solution, it is still necessary to compare each of the material combination options for these cases.

Figure 7 summarizes a comparison of all material confluences for a negatively polarized shock pulse. The variant chosen was the one shown to transmit one of the smallest values of interference in the above-presented winks. As mentioned, there is no single ideal solution, as for different material configurations the best solution alternated between connecting the two layers together to ground and only the inner layer to ground. The second variant was therefore chosen, i.e. separating the layers and connecting the inner one to ground. The results are summarized in Figure 7. Aluminum and Copper layer (description in figures) means that both of layers are consist of the same material. In this figures all configuration consist of two layers.

It is clear from the results, that the most favorable solution is to realize the shielding with two layers of copper, galvanically separated from each other, where the inner layer is connected to ground (the negative terminal of the battery). Such a connection ensures that the resulting surges and impulses are absorbed, acting as a capacitor. In addition, some UAVs are equipped with filters on the power supply (to reduce impulse interference from BLDC motors) to further help reduce emerging interference from LEMPs.

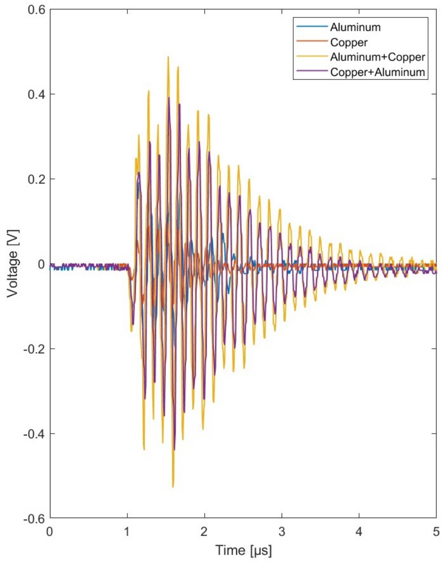


Figure 7a

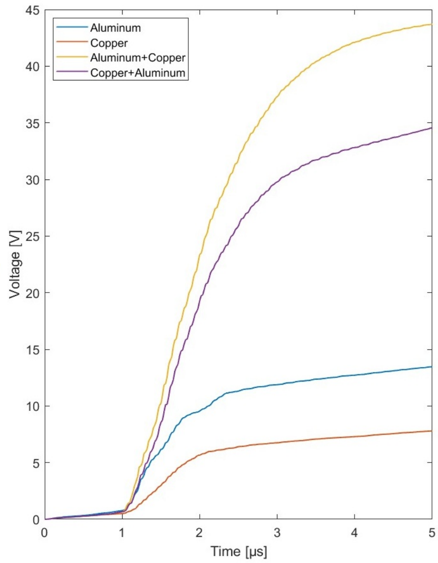


Figure 7b

Results for all configurations of materials: (a) – signals in power supply (b) – integral of this signals

Conclusions

This article focuses on the specific case study of protecting UAVs, from the effects of LEMP. The most relevant threat is an electromagnetic pulse propagating from a cloud-to-ground (CG) discharge with negative polarity. The magnitude of the field strength is distance-dependent and, as proven in earlier studies, a distance of up to several hundred meters, between the drone and the lightning channel, can pose a threat. It is caused by the value of the surges induced in the UAV circuits. It is not possible to give a definite value without specific data, as a random variable is the value of the discharge current, which can range from a few dozen to even a few hundred amperes. However, protection in the form of electromagnetic shielding is important. In the research, a number of different combinations of two shielding layers (the number is derived from previous research) of different and identical metals were proposed.

All combinations are described and the results of the experiments are presented. The most effective solution turned out to be to make the shielding from two layers of copper, where the layers are separated from each other and the inner layer is connected to the negative terminal of the battery (ground point). Connecting the layers to the power supply significantly increased the values of interference propagating through the circuits. It also confirmed previous results that galvanic separation of the layers works better than connecting them together. Experiments with different types of materials did not yield any expected results. The results for these considerations represent inferior protection by LEMP, as presented in the graphs. The most significant conclusion of the presented research is that, for effective protection of UAVs from LEMP, the best solution is to design an electromagnetic shield consisting of two layers of copper, where the inner one is connected to ground. This solution reduces the value of the resulting overvoltages and protects the machine from damage in the event of a close lightning discharge.

The test results presented can be summarized as:

- The connection of the shields to the positive battery terminal results in significant interference propagation in the machine circuits
- Connecting the shields to the negative battery terminal allows the greatest reduction in surges
- The connection of both layers or only the inner layer provides the best results
- The use of both copper layers offers greater protection against LEMP than the use of different types of material (regardless of configuration)
- Galvanically separated layers protect better than interconnected layers
- The polarization of the surge pulse does not bring about significant changes in measured surge values, confirming the validity of the assumptions

Further work on the development of shielding for small UAVs, due to LEMP exposure, should focus on recommending other materials. One possibility is to use conductive plastics, for the construction of enclosures, performing both mechanical and electrical tasks (electromagnetic shielding).

Acknowledgements

This work was funded by the Ministry of Science and Higher Education of the Republic of Poland to maintain the research potential of the disciplines of automation, electronics, electrical engineering, and space technologies.

References

[1] Rexhepi, V., Gjukaj, A., Assessing the Impact of Integrating Photovoltaic Systems and Wind Turbines, on Power System Stability and Performance Parameters. Acta Polytechnica Hungarica, 21(11), 2024

[2] Vojtek, M., Mastny, P., Moravek, J., Drapela, J., Vrana, M., Dvoracek, J., Recent Challenges Regarding the Verification of Photovoltaic Inverters Properties and their Compliance with Technical Requirements. Acta Polytechnica Hungarica 20(11), 63-82, 2023

[3] Syed Agha Hassnain Mohsan, Nawaf Qasem Hamood Othman, Yanlong Li, Mohammed H. Alsharif, Muhammad Asghar Khan, Unmanned aerial vehicles (UAVs): practical aspects, applications, open challenges, security issues, and future trends, Intelligent Service Robotics, Vol. 16, pp. 109-137, 2023

[4] Sachi Nandan Mohanty, J. V. R. Ravindra, G. Surya Narayana, Chinmaya Ranjan Pattnaik, Y. Mohamed Sirajudeen, Drone Technology: Future Trends and Practical Applications, John Wiley & Sons, Inc., Hoboken, NJ, USA, 2023

[5] Tomasz Kisielewicz, Carlo Mazzetti, Giovanni Battista Lo Piparo, Bolesław Kuca, Zdobysław Flisowski, Lightning electromagnetic pulse (LEMP) influence on the electrical apparatus protection, Proceedings of the International Conference on Lightning Protection (ICLP), Rzeszów, Poland, September 2018, pp. 123-130

[6] Smith J., Brown A., Johnson C., LEMP from Lightning Discharges Observed by JLDN, Proceedings of the IEEE International Symposium on Electromagnetic Compatibility (EMC), Tokyo, Japan, August 2019, pp. 45-52

[7] Leon Colqui, J. S., Ribeiro de Moura, R. A., De Oliveira Schroeder, M. A., Filho, J. P., Kurokawa, S., The impact of transmission line modeling on lightning overvoltage. Energies, 16(3), 1343. 2023

[8] Permata, D., Gurning, M. C., Martin, Y., Sitorus, H. B., Muda, M. A., Sinaga, H. H., Electromagnetic interference shielding in unmanned aerial vehicle against lightning strike. TELKOMNIKA (Telecommunication Computing Electronics and Control), 17(2), 915-919. 2019

[9] R. Rashid and S. A. A. Gilani, Electromagnetic Pulse (EMP): A Study of General Trends, Simulation Analysis of E1 HEMP Coupling and Protection Strategies, 2021 International Conference on Cyber Warfare and Security (ICCWS), Islamabad, Pakistan, 2021, pp. 106-111, doi: 10.1109/ICCWS53234.2021.9703034

[10] Zhangang Yang, Yuhao Wei, Xudong Shi, Analysis of Cable Shielding and Influencing Factors for Indirect Effects of Lightning on Aircraft, Proceedings of: Aerospace, Volume 11, Issue 8, Tianjin, China, August 2024 p. 674

[11] Wu Zhaofeng, Xu Yanlin, Liu Peiguo, Zha Song, Review and prospect of electromagnetic protection technology development, Proceedings of the High Power Laser and Particle Beams, Volume 36, Issue 4, February 2024

[12] M. Fernando, V. Cooray, Propagation effects on the electric field time derivatives generated by return strokes in lightning flashes, Journal of Atmospheric and Solar-Terrestrial Physics 69 (12) (2007) 1388-1396

[13] R. P. d. S. Barradas, G. V. S. Rocha, J. R. S. Muniz, U. H. Bezerra, M. V. A. Nunes, J. S. e. Silva, Methodology for analysis of electric distribution network criticality due to direct lightning discharges, Energies 13 (2020) 1580. doi:10.3390/en13071580

[14] G. Shukun, C. Erwei, C. Yazhou, W. Yuming, Research on ultrawideband electromagnetic pulse irradiation effect and protection method of unmanned

aerial vehicle, in: Journal of Physics: Conference Series, Vol. 1325, IOP Publishing, 2019

[15] A. O. Belousov, Y. S. Zhechev, E. B. Chernikova, A. V. Nosov, T. R. Gazizov, Uavs protection and countermeasures in a complex electromagnetic environment, Complexity, 2022

[16] E. Mikinka, M. Siwak, Recent advances in electromagnetic interference shielding properties of carbon-fibre-reinforced polymer composites, Journal of Materials Science: Materials in Electronics, Vol. 32, pp. 24585-24643, 2021

[17] Ming Yan, Martin Gosau, Reinhard E. Friedrich, Ralf Smeets, Yi Yang, Ling-ling Fu, Evolution of microstructure, electromagnetic shielding, and in vitro corrosion properties of Mg-Ni composites for cancer biomarker applications, Advanced Composites and Hybrid Materials, Vol. 8, article number 47, 2025

[18] Yang Shi, Mingjun Wu, Shengbo Ge, Jianzhang Li, Anoud Saud Alshammari, Jing Luo, Mohammed A. Amin, Hua Qiu, Jinxuan Jiang, Yazeed M. Asiri, Runzhou Huang, Hua Hou, Zeinhom M. El-Bahy, Zhanhu Guo, Chong Jia, Kaimeng Xu, Xiangmeng Chen, Advanced Functional Electromagnetic Shielding Materials: A Review Based on Micro-Nano Structure Interface Control of Biomass Cell Walls, Proceedings of the Nano-Micro Letters, Volume 17, Article 3, September 2024

[19] X. Y. Wang, S. Y. Liao, Y. J. Wan, P. L. Zhu, Y. G. Hu, T. Zhao, C. P. Wong, Electromagnetic interference shielding materials: recent progress, structure design, and future perspective, Journal of Materials Chemistry C 10 (1) (2022) 44-72

[20] S. J. Mostafavi Yazdi, A. Lisitski, S. Pack, H. R. Hiziroglu, J. Baqersad, Analysis of shielding effectiveness against electromagnetic interference (emi) for metal-coated polymeric materials, Polymers 15 (8) 2023

[21] Hartmann, J., Schür, M. T., Hardt, S. Manipulation and control of droplets on surfaces in a homogeneous electric field. Nature Communications, 13(1), 289, 2022

[22] Kossowski, T., Szczupak, P., Analysis of the electric field distribution in the parallel-plate capacitor designed for testing the immunity of electrical devices to lightning electromagnetic pulse. Przeglad Elektrotechniczny, 2024(2)

[23] RTCA DO-160. Environmental Conditions and Test Procedures for Airborne Equipment; Radio Technical Commission for 506 Aeronautics:Washington, DC, USA, 2010

[24] EN 61000-4-5:2014-10. Electromagnetic compatibility (EMC) – Part 4-5: Testing and measurement techniques – Surge immunity test. CENELEC, August 1, 2014

[25] EN 62305-1:2011. Lightning Protection—Part 1; BSI Standards Publication: London, UK, 2011

[26] Phillips, J. A., Sanny, J. Experimental evidence for the Biot–Savart law. The Physics Teacher, 61(7), 548-548, 2023

[27] Khadka, C. B. (2023) Biot-Savart law for determination of speed of particle beyond the speed of light. Indian Journal of Advanced Physics, 3(1), 1-5

[28] Chew, W., Tong, M. S., Bin, H. U., Integral equation methods for electromagnetic and elastic waves. Springer Nature, 2022

[29] A. Sharma, M. S. Babu, A. V. Kumar, R. Sarathi, V. Subramanian, Electromagnetic shielding efficiency of carbon fibre fabric-sandwiched epoxy–mwcnt nanocomposites, Bulletin of Materials Science 45 (1) 2022

[30] Acharya, S., Datar, S., Wideband (8-18 GHz) microwave absorption dominated electromagnetic interference (EMI) shielding composite using copper aluminum ferrite and reduced graphene oxide in polymer matrix. Journal of Applied Physics, 128(10), 2020

[31] Pandey, R., Tekumalla, S., Gupta, M. EMI shielding of metals, alloys, and composites. In Materials for potential EMI shielding applications (pp. 341-355) Elsevier, 2020

[32] T. Horvath: Supposed undistorted original distribution of lightning currents, Proc. of 20th International Conference on Lightning Protection, Interlaken, Switzerland, 24-28 September 1990

[33] Wang, S., Wada, Y., Hayashi, S., Ushio, T., Chandrasekar, V., Observation of electrical alignment signatures in an isolated thunderstorm by dual-polarized phased array weather radar and the relationship with intracloud lightning flash rate. Journal of Geophysical Research: Atmospheres, 129(19), e2023JD040681, 2024

[34] Wenrong, S., Jinxiu, B., Xu, Z., Rong, X., Lightning Characteristics Based on Date Observed with Shanghai Lightning Location System, China. Przeglad Elektrotechniczny, 88(11a), 152-156, 2012

[35] Mammadov, N., Piriyeva, N., Ismayilova, S., Research of lightning protection systems for wind electric installations. Przegląd Elektrotechniczny, 2024(9), 2024