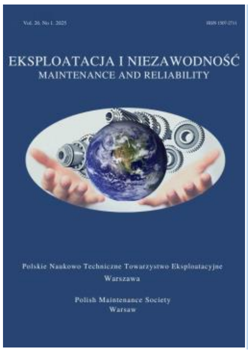

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Tests of pulse interference from lightning discharges occurring in unmanned aerial vehicle housings made of carbon fibers.

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Highlights

- The carbon fiber structure causes additional signal interference.
- A carbon fiber casing does not provide good protection against the effects of LEMP.
- The signal inside the housing for low frequencies is amplified.
- The impact signal passing through the carbon fiber undergoes significant dispersion.

Abstract

The Aim of the study was to determine the effect of a carbon fiber enclosure on overvoltages induced in unmanned aerial vehicle (UAV) circuits. Carbon fiber reinforced polymer (CFRP) is characterized by a heterogeneous structure and a thorough analysis of its impact on the LEMP (Lightning ElectroMagnetic Pulse) protection of UAVs is crucial for the further development of such machines. These overvoltages are the result of an impulsive electromagnetic wave (EMP), a consequence of flashes. The shorter the distance, the greater the amplitude of the EMP and the greater the value of the surges. Their maximum value determines the safe limit within which an object can move. This distance can be reduced by using shielding or an enclosure that can absorb or dissipate EMP. The tested object was placed in the middle between a large capacitor plates, which ensured the uniformity of the field. This article presents new results of tests on the CFRP shielding effectiveness against the electrical component of atmospheric discharge. using described below method, an increase in the signal amplitude inside the box was achieved in relation to the input signal, thus strengthening it instead of suppressing it.

Keywords
electric field, lightning strike, electronic immunity of drones, aircraft

1. Introduction

Large unmanned aerial vehicles commonly referred to as drones can be treated like airplanes. Drones used for entertainment are not being referred to here. Those are small (from those which can fit in the palm of your hand to one meter in diameter) structures. They are the most common, but it should not be forgotten that there are much larger machines. From air quality monitoring vehicles, to specialized survey drones, to unmanned military aircraft that can reach a considerable size [1]. All of these devices fall under a common classification of "UAV" objects. The wingspan of such machines can be as high as 12 meters and their weight exceeds half a ton. An example is the well-known Bayraktar TB2 , whose fuselage is made of carbon fiber, Kevlar and hybrid composites [2]. In both cases different structures use different materials from aluminum to polymers, especially when the structure (or parts of it) is 3D printed [3]. FDM, Polyjet, SLA, SLS and other techniques can be used for this purpose [4]. Additive manufacturing (AM) is a technique that makes it possible to reduce production costs for low volume

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manufacturing production, as it does not require special molds, production lines or programming of equipment. It is also possible to quickly check the quality of the manufactured products [4]. However these structures (especially small drones) are based solely on plastics, which are known to be non-conductive. This means that it is necessary to design such a structure and equip it with additional shielding to protect the sensitive drone electronics from the effects of electromagnetic fields (EMF). An example of such electromagnetic shielding applied to a small drone based on a plastic structure is shown in Figure 1. It is no coincidence that lightweight metal alloys, such as duralumin or aerospace aluminum alloys, have been used primarily for years. In recent years, much attention has been paid to composite coatings consisting of a combination of plastic (polymer) and embedded carbon fiber "reinforcement". The structure of interwoven carbon fibers not only provides greater strength but also the electrical conductivity of such a coating. Therefore, it can be successfully used as a kind of equivalent to a Faraday cage [5]

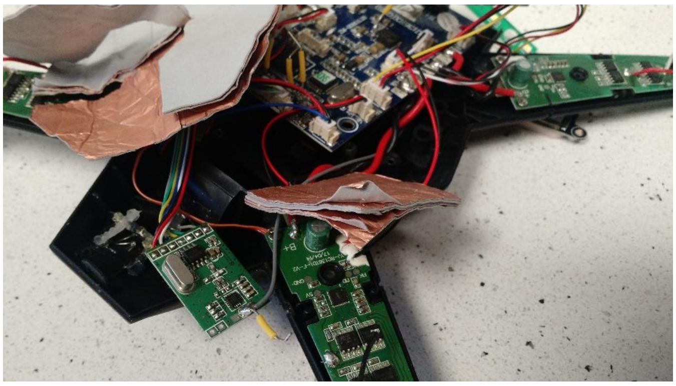

Figure 1. Example of EMF shieling in a UAV.

Carbon fibers are widely used in the aerospace industry to reduce the weight of structural components, improve fuel efficiency, reduce emissions and also increase the carrying capacity of aircraft [6,7]. Since drones (in some cases) have to fly in adverse conditions, including during a thunderstorms, the material used for the fuselage of the machine should also protect it against the electromagnetic field of nearby lightning strike. Some structures, including those used in the military, have a carbon fiber reinforced plastic hull and this material has been tested for shielding effectiveness against near lightning impulse.

Therefore, the aim of the work was to verify the simulation data and theoretical results in a practical measurement system, where real samples were tested. No studies on such cases have been found for relatively small (up to 1 meter diameter) UAV applications. So far, no one has analyzed the threats resulting from LEMP to UAVs of this sizes and the impact of those impulses on proper operation. Nevertheless, such research can be found in reference to other objects, such as Electronic Security Systems of Intelligent Buildings [15]. Therefore, it was decided to propose and perform the research described later in the work as an innovative approach to the safety and reliability of drones. Thanks to the attempt to test real materials in simulated conditions, it was possible to obtain data that has not been published so far, but which could help in the future in creating mathematical models to analyze the impact of LEMP on small UAVs.

Carbon fiber reinforced plastics (CFRP) are particularly suitable for the niche application of UAVs [1,8]. The main reason for this is the high production costs. The technology offers a range of possibilities in terms of structure formation and type. This affects the physical properties, especially the strength. A number of factors are important for strength of the coating, such as [8,9]:

- number of layers
- arrangement of the fibers (parallel/crossed/angled)
- curing of the polymer under different external conditions
- type of polymer filling the carbon fiber mesh
- pressure during polymerization

The presence of carbon fibers embedded in a polymer matrix determines the electrical conductivity properties of Carbon fibers reinforced polymer. These fibers form a percolation network that facilitates the flow of electric current through the CFRP. To enhanced electrical conductivity, the conductive fillers such as carbon black can be added to the polymer matrix. That's provide improved EMI shielding performance. The shielding effectiveness of CFRP depends on several factors such as the EM field frequency, the thickness and orientation of the CFRP layers and material conductivity. Both laboratory tests, mainly based on the ASTM D4935 standard or the MIL-STD-285 standard, which was later replaced by the IEEE 299.1 standard [11-13], and simulation models based on the physical properties of CFRP [14,15] confirm the satisfactory properties of LEMP shielding. However, these investigation do not appear to be sufficient. In the laboratory tests, the samples tested were in the form of plates placed between electrodes and the simulation models assumed relatively large objects (planes). To simulate the effects of electromagnetic pulse from close CG (cloud to ground) flashes on a smaller UAV with a CFRP fuselage, as accurately as possible, it would be preferable to make a box from carbon fiber material. In addition, in the IEEE 299.1 standard it is important to use a suitable discharge component (electric or magnetic), depending on the size of the object under test. It was decided to develop a different test method, that would better reflect the effectiveness of the protection of relatively small CFRP hull, against the electrical component of a near CG lightning strike.

The used method allows the observation of phenomenon that have not been observed in others works [10-15, 27-31]. Indeed, under certain conditions, the CFRP hull may not behave as a shield against electromagnetic pulse [10, 11, 15, 27-31] but on the contrary as an amplifier that increases the probability of damage to the drone`s sensitive electronic circuits.

2. Methodology

The theory of electromagnetic shielding is based on the shielding of an electromagnetic plane wave in the far field range (the distance between the incident and shielding barrier is greater than λ/2π where λ is the wavelength).

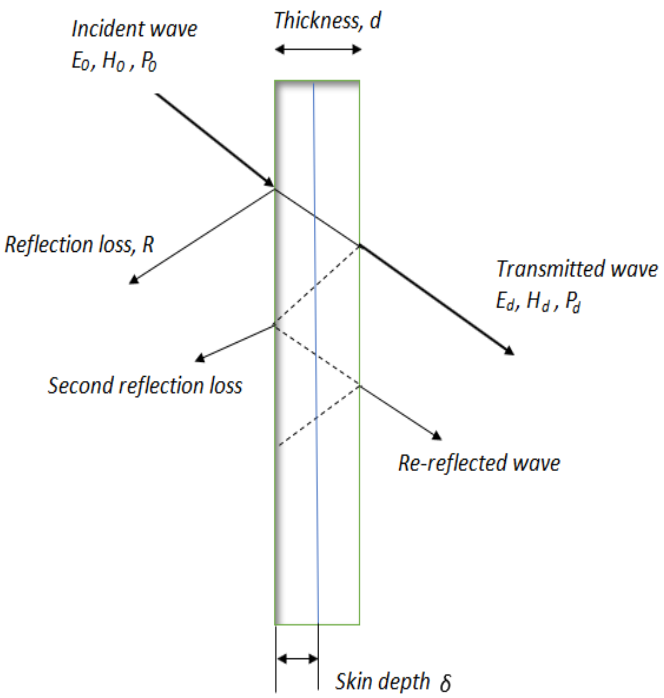

Figure 2. Conceptual model of the shielding effectiveness (SE) for conductive material [10,11].

If the intrinsic impedance of the barrier is lower than the impedance of the wave propagation medium, the charges in the material start to behave like an antenna. They start oscillating, inducing superficial alternating current. This current generates a contracting electric field, that weakens or even cancels out the original incident field and appears as reflected power with minimal energy loss. The prerequisite for reflections to occur is the presence of electrons or holes which are the charge carriers. This means, that the material must be highly conductive. The degree of impedance mismatching between the shielding material (η_m) and the wave propagation medium (η_0) determines the magnitude of the reflection loss (SE_{Ref})[11,12].

$$SE_{Ref} = 20log_{10}\left(\frac{(\eta_m+\eta_0)^2}{4\eta_m\eta_0}\right) \tag{1}$$

Assuming that $\eta_m << \eta_0$, the SE_{Ref} can be obtained from the equation:

$$SE_{Ref} = 20log_{10}\left(\frac{\eta_0}{4\eta_m}\right) \tag{2}$$

The impedance η, can be calculated from:

$$\eta = \sqrt{\frac{j\omega\mu}{\sigma+j\omega\varepsilon}} \tag{3}$$

where: ω – pulsation in rad/sec, μ – magnetic permeability, ε – permittivity, σ – electrical conductivity. For air η0 = 377Ω

As the electrical conductivity of the material decreases, the part of the wave that penetrates the material increases and the part of the reflected wave decreases.

The second type of loos is the „absorption loss", and is proportional to the penetration depth or skin depth of the material:

$$\delta = \frac{1}{\sqrt{\pi f\mu\sigma}} \tag{4}$$

Where: f is the frequency, δ is the depth of the material at which the electromagnetic field drops exponentially to 1/e of the incident value.

The absorption loss can be obtained from:

$$SE_{Abs} = 20\log_{10}\left(e^{-\frac{d}{\delta}}\right) \tag{5}$$

The third part of the attenuation of the electromagnetic wave is „multiple reflection". If the skin depth is significantly smaller than the thickness of the shield, this mechanism can be neglected in the SE calculation, otherwise it can be calculated from equation (5):

$$SE_{MuR} = 20\log_{10}\left|1-\frac{(\eta_m-\eta_0)^2}{(\eta_m+\eta_0)^2}e^{-\frac{2d}{\delta}}\right| \tag{6}$$

The remaining part of the electromagnetic radiation is transmitted through the shielding material.

The shielding effectiveness (SE) can be obtained from:

$$SE_{all} = 20\log_{10}\frac{E_{in}}{E_{out}} = 20\log_{10}\frac{H_{in}}{H_{out}} \quad (7)$$

Where E is the electric field and H is the magnetic field strength and subscript „in" and „out" indicates the transmitted values, respectively.

The complex structure of carbon-fiber composites (CFRP), the fact that two electrically dissimilar materials are combined, and the irregular arrangement of the carbon fibers makes the analysis of the electromagnetic field effects on this material very difficult. The analysis is additionally complicated by the anisotropic properties of the carbon fibers, resulting from their internal structure.

In measurements to determine the shielding effectiveness of CFRP, the SE_{MuR} is irrelevant. If the mechanism of multiple reflections is disregarded and it is assumed that the polymer composite is non-magnetic and the CFRP is an electrically conductive material, the following expression is obtained (the Simon formalism) [11,12]:

$$SE = 50 + 10\log_{10}\frac{1}{\rho f} + \sqrt{\frac{2.89d^2 f}{\rho}} \quad (8)$$

Where: f – frequency in MHz, d – thickness of the material in cm, ρ – volume resistivity expression in Ωcm.

Early, most SE assessment methods were based on MIL-STD-285 [16]. This standard dealt with attenuation measurements for shielded enclosures within frequency range of 100 kHz to 10 GHz. It specified the required equipment and antenna configuration. The measurement devise is located outside the tested enclosure, whilst the signal source is located inside. MIL-STD-285 was later (in October 1997) replaced by IEEE-STD-299 [12,17], which describes methods for measuring the shielding effectiveness of enclosures. The smallest linear dimension of such an enclosure must be at least 0.1 m. The method distinguishes between three measurement ranges:

- low range - from 9 kHz (50 Hz) to 20 MHz – for the magnetic component (H),
- resonant range - from 20 MHz to 300 MHz – for the electrical component (E),
- high range - from 300 MHz to 18 GHz (100 GHz) – for the plane wave power (P).

Depending on the frequency range, specific measuring instruments must be used. At low frequencies, the magnetic field is measured with a small loop antenna (0.3 meters in diameter, electromagnetically shielded against electric field). Same antenna is used to generate the magnetic field. For high frequencies, dipoles, biconical antennas, horns, yagis, log periodic, or other linear type antenna which can generate a continuous wave field (CW).

This article uses a completely different, original method to test the effectiveness of protection against LEMP, based on authors previous research. The research site has already been described in detail [19, 20]. In this article, it is presented in Figure 3. In this case, to estimate the degree of protection, the difference in levels of the output signal measured in the center between the capacitor plates and the output signal measured inside the box (at the central point between the capacitor plates), using a multi-band antenna was used.

The main objective of the research was to verify whether carbon fibers materials can be safely used (in terms of protection from pulsed electromagnetic field caused by CG flashes) for the manufacture of a relatively small UAV enclosure. The available knowledge on this topic, does not give a clear answer, therefore the authors decided to review these results, approaching the topic in a slightly different way than other researchers have done so far. They focused on analyzing the impact of lightning, i.e. frequencies in the range of 100-500 kHz. The above limitations are due to the normative shock pulses used in testing aircraft avionics for lightning resistance. The most important standard used in this work is RTCA/DO-160 [18]. Surge pulses are also described in other international standards such as: EN 62305 [19], EN 61000 [20], MIL - STD - 461 F [21]. Among others, surge pulses of 1.2/50 μs, 6.4/69 μs, and 40/120 μs (respectively, the rise/fall time of the surge slope) are used to perform this type of tests [11,19,21-23]. Ensuring the repeatability of the surge pulse was ensured by the use of a Swiss MIG0618SS lightning surge generator designed and calibrated for aircraft tests. This allows the system to be tested with the two waveforms mentioned. Theoretical assumptions and analyzed studies by other researchers [13-15,24] indicate that the conductive carbon (and carbon black) layer in the polymer structure should attenuate the EMP wave satisfactorily. However, the question arises whether, the relationship is not completely reversed in confined spaces and at certain frequencies, and resulting in pulse amplification instead of attenuation (through at least the superposition of reflected waves).

In previous paper, the authors have shown that UAVs exposed to the indirect effects of lightning strikes at a short distance (up to 1 km) from an object are exposed to strong LEMP (Lightning ElectroMagnetic Pulse), which in most cases leads to damage to sensitive electronic components [25]. However, they investigated screenless machines based on plastic housings such as ABS. Thus, the authors decided to solve the issue of drones with carbon fiber housings, which they had not dealt with before. This material has completely different properties than the commonly used "plastic" and its properties need to be verified.

The mathematical model of the pulse is described using Maxwell's equations for the electrical component of the electromagnetic wave. The basic function describing the EMF variables is the dependence of the current on the distance relative to the channel based on the DCR or LCS model. In the literature, the MTLE model, described by the following formulas, is most commonly found [24,26].

$$i(z',t) = e^{\frac{-z'}{\lambda}} i\left(0, t - \frac{z'}{v}\right) \tag{9}$$

$$\rho(z',t) = e^{\frac{-z'}{\lambda}} \frac{i\left(0, t - \frac{z'}{v}\right)}{v} + \frac{c^{\frac{-z'}{\lambda}} Q(z',t)}{\lambda} \tag{10}$$

$$Q(z',t) = \int_{\frac{z'}{v}}^{t} i\left(0, \tau - \frac{z'}{v}\right) d\tau, \tag{11}$$

Where: $v = v_f = const, H = const, \lambda = const, t \geq \frac{z'}{v_f}$

$$E_Z(z,t) = \frac{1}{2\pi\varepsilon_0} \int_0^{h(t)} \left[\frac{2z'^2 - r^2}{R^5(z')} \int_{\frac{z'}{v_f} + \frac{R(z')}{c}}^{t} I\left(z', \tau - \frac{R(z')}{c}\right) d\tau + \frac{2z'^2 - r^2}{cR^4(z')} I\left(z', t - \frac{R(z')}{c}\right) - \frac{r^2}{c^2 R^3(z')} \frac{\partial I\left(z', t - \frac{R(z')}{c}\right)}{\partial t} \right] dz - \frac{r^2}{2\pi\varepsilon_0 c^2 R^3(h(t))} I\left(h(t), \frac{h(t)}{v_f}\right) \frac{dh(t)}{dt} \tag{12}$$

Where: $h(t)$ – height of the channel "seen" by the observer in time t, r – distance of the observer from the discharge channel in a straight line, $R(z')$ – distance of the observation point P from the specific point along the channel, z` - height of any point in the discharge channel measured from the ground, υ_f – speed of the current wave front, c- speed of light, ε_0 -permittivity in vacuum.

A carbon fiber housing with the following parameters was used for the testing:

- thickness: 2 mm
- number of layers: 5
- filling material: epidian
- grammage: 220 g/m^2

The above material (Figure 3) was used to build a cube with a wall dimensions of 20 cm. The choice of such shape was necessary due to the size of the measuring antenna placed inside the cube. An analysis of the field distribution inside the cube showed no significant differences between measurements for different positions of the antenna inside it. Thus, the influence of the size of the DUT on the changes in pulses measured with respect to other relatively small dimensions of the housing (e.g.: the target drone enclosure) can be rejected. It was shown that at each position of the measuring antenna, the recorded signal is unchanged for the same forcing conditions.

Figure 3. Carbon-fiber composite – structure of the tested material.

The test stand was prepared on the basis of the previously mentioned MIG0618SS shock pulse generator, which is a source of repetitive 6.4/69 µs and 40/120 µs pulses up to 3400 V. Scheme of setup was shown in figure 4. The recording device was a Rigol 1054Z digital oscilloscope (1 GSa/s sampling at 50 MHz bandwidth) connected to the measurement antenna via shielded coaxial cables with 0.1 dB/m attenuation at 50 MHz. The measurement sample was placed inside a capacitor with parallel plates dimensions of 2 m x 2 m (height x width) each. The distance between the facings was 1 m. These large dimensions (compared to the dimensions of a cube) made it possible to maintain a homogeneous electric field inside the capacitor. The measuring element was a multi-band antenna, with maximum gain for the following frequency ranges:

- Low frequency (LF) - 30-300 kHz
- Medium frequency (MF) - 0.3-3 MHz
- High frequency (HV) - 3-30 MHz
- Very high freqency (VHV) - 30-300 MHz

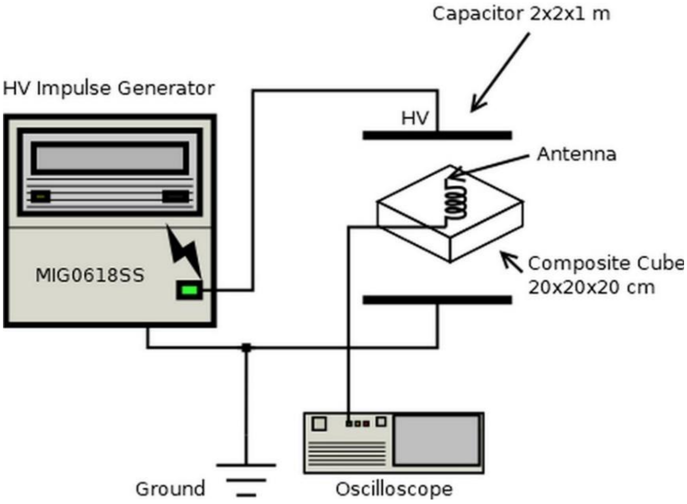

Figure 4. Setup of the testing equipment.

Due to the shape of the pulses which simulate lightning (double exponential), interference was only recorded in the LF and MF ranges. To verify the correctness of the assumptions, the pulse waveforms were also checked using the HV and UHV bands. However, the assumptions were confirmed in practice, and at high frequencies the recorded signals were very low (higher harmonics of the low-frequency fundamental components, which make no appreciable difference).

3. Data analysis

The experimental tests were carried out according to the presented test bench description. The most important anomalies are shown in the following figures. They are the result of the unexpected behavior of the tested material at certain EMF wavelengths compared to other researchers results [10-16, 27-31]. In Figures 5 and 6, it can be observed that the LEMP is attenuated more slowly inside the cube than outside. This has to do with the internal reflections inside the cube. The effect is significantly greater with an antenna in the range 300-3000 kHz (MF). In the range of 30-300 kHz (LF), i.e. at lower frequencies, the wave inside the cube has an even greater amplitude than outside.

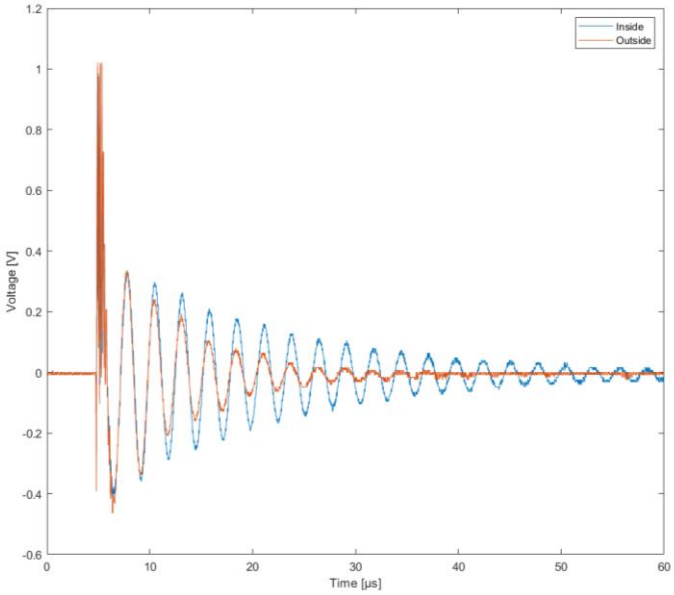

Figure 5. Testing at 2.5 kV/m with shape 40/120µs MEDIUM (medium frequency antenna).

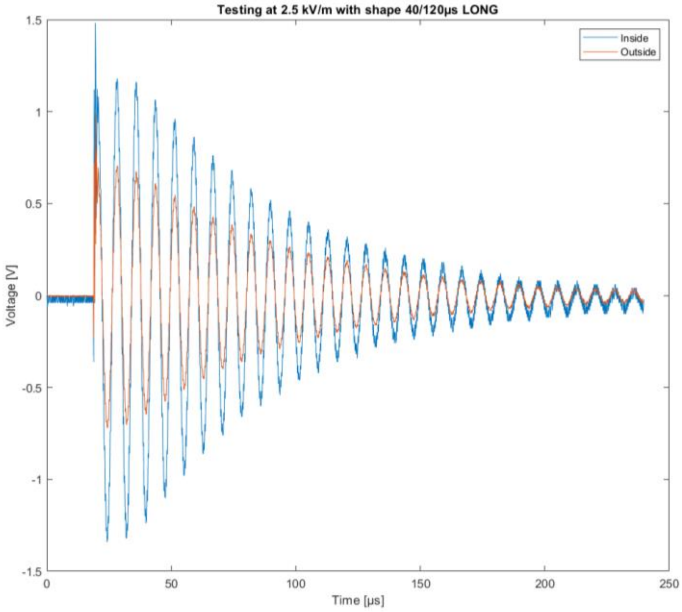

Figure 6. Testing at 2.5 kV/m with shape 40/120µs LONG (long frequency antenna).

The calculations were performed using the Fast Fourier Transform (FFT) algorithm for spectral analysis of the investigated signal (Figure 7). It turned out to be identical for both ranges of the antenna measurements. The frequency distribution is therefore not random and is registered in the same way over a wide frequency range regardless of the maximum efficiency of the antenna. However, the difference becomes clear when the signal measured inside and outside the enclosure is compared. It is clear that the basic shape is the same at 95-100 kHz, which indicating the same frequency of the lightning strike. However, the character of the higher frequencies changes completely depending on whether the antenna is inside or outside. The signal energy in the interior is definitely higher, which translates into signal amplification due to reflections and harmonics. It should also be remembered that a pulse that passes through different media changes its characteristics over time. The discussion focuses on the dispersion of the pulse over time, caused by the different propagation speeds in air and carbon fiber housing. This phenomenon further affects the pulse properties.

An analogous analysis was also performed for the second shock pulse (6.4/69 μs). Due to the higher frequency of the signal, the LF antenna was abandoned. MF and VHF bands were used (for comparison). Figure 8 shows that for the same pulse, measured in different bands, the phenomenon of amplification inside does not occur as in the previous case. The attenuation inside is greater than outside - that is, completely opposite. This means that a pulse of shorter duration passes through the enclosure slightly attenuated (fundamental harmonic). On the other hand, higher harmonics (measured with a VHF antenna) are definitely more attenuated by the composite under test.

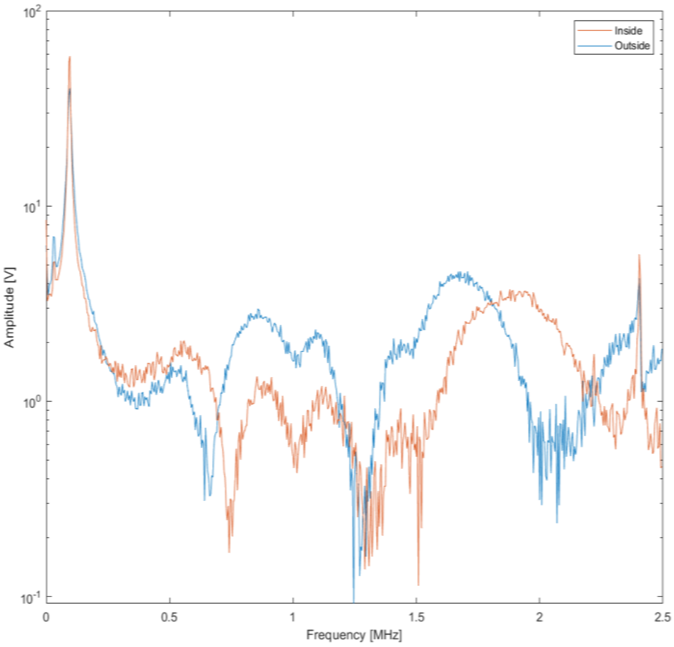

Figure 7. FFT of signal inside and outside the box.

Once it was established that a 40/120μs LEMP could be amplified, a further experiment was carried out. Figure 9 shows the variation of the measured pulse at different positions.

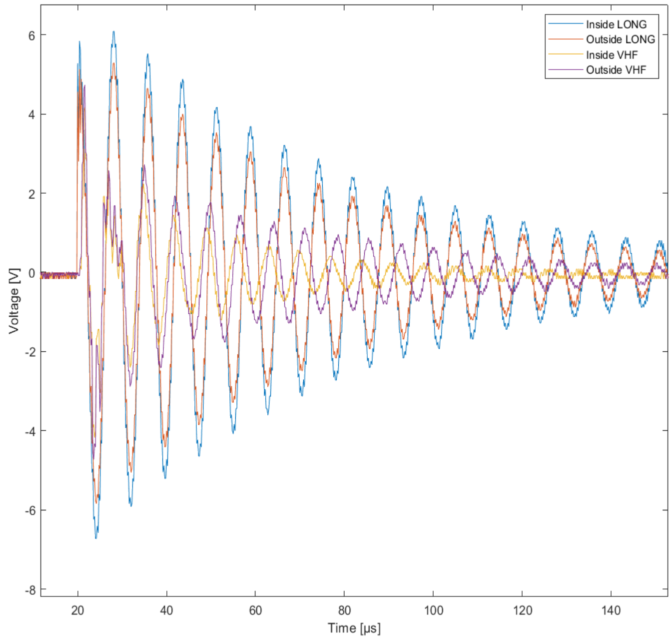

Figure 8. Testing at 2.5 kV/m with shape 6.4/69 μs in different frequency ranges.

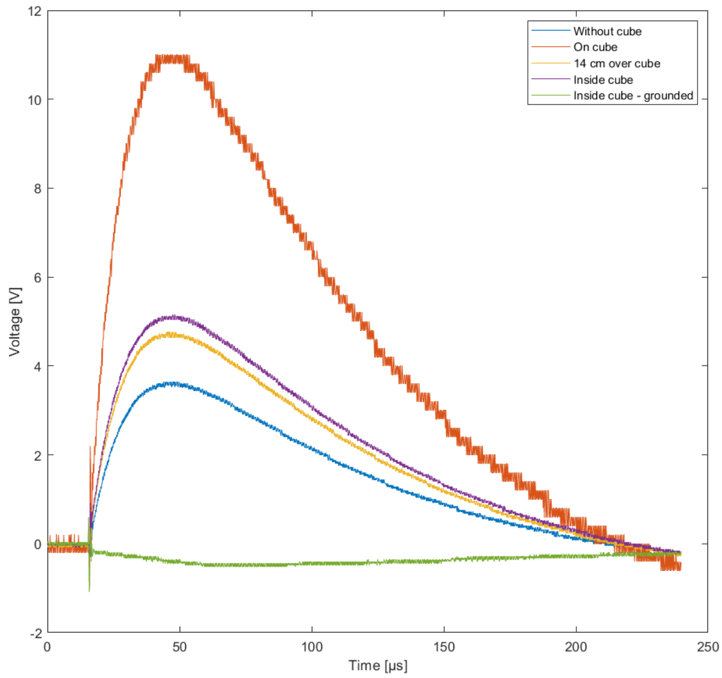

Figure 9. Electric field - 2.5 kV/m with shape 40/120μs.

It can be clearly seen that both the presence of the cube and its distance from the antenna are important for the observed values. However, the distance has no influence on the waveform of the surge pulse itself (the same applies to the voltage from the generator on the capacitor covers). The following conclusions can be drawn from the Figure 9:

- the amplitude is higher inside the cube than outside which indicates the amplification of the signal inside it,

- the amplitude is highest when the antenna is directly (through insulation) on one of the walls (the ceiling, perpendicular to the capacitor covers).
- the grounded enclosure has perfect shielding properties

The measurement results seem to contradict those obtained by other researchers. It should be noted, however, that the tests carried out by the authors used standardized lightning waveforms, which are in much lower frequencie ranges (up to several hundred kilohertz compared to several or a dozen or so gigahertz [10, 11, 15, 27-31]). The research presented in this article also shows that signals with higher frequencies, of the order of Megahertz, are effectively suppressed, which is consistent with the current knowledge.

4. Discussion

The shielding effectiveness of CFRP enclosures can be attributed to the absorption, reflection and multiple reflections of the electromagnetic waves by the layers. The absorption mechanism is due to the conductive nature of the carbon fibers. In this case, absorbed electromagnetic wave is converted into heat. The reflection mechanism is due to the impedance mismatch between the carbon fibers reinforced polymer material layer and the surrounding space, which causes EM wave to be reflected. The multi reflection mechanism is due to reflections between the CFRP layers. Its further enhance the shielding effectiveness.

CFRP enclosures shielding effectiveness can be improved by for example:

- Increasing the thickness and number of CFRP layers,
- Using higher conductive carbon fibers,
- Minimizing the presence of apertures and seams,
- Insuring even distribution of unidirectional, long fibers,
- Maintaining the continuity of electrically conductive connections of all sheathing elements,
- Adding a thin layer of metal sputtered on the surface.

After analyzing the results obtained, it is important to consider when the carbon fiber enclosure provides adequate protection against the effects of overvoltages resulting from the induction of interference from EMP.

5. Summary

The presented results of experiments related to the analysis of the effects of the inhomogeneous structure of carbon fibers on the propagation of electromagnetic waves causing the generation of surges in drone circuits can be summarized as follows:

- Without grounding medium range are the same in parallel and perpendicular directions inside and outside, but for long waves they are not.
- Inside signals look like they are reflected from inside walls and decrease more slowly than outside
- Most relevant frequencies are in the low range (expected) – the FFT shows that so the best measurement range is 30 kHz do 3 MHz
- The FFT shows that the peak is in 150-200 kHz.
- The levels of the signals inside are proportional to the density of the electric field outside in linear
- There is no difference between inside and outside signals for the same shape. For different shapes the values change, but they consist of detection range of the antenna
- As the signal frequency increases, the shielding effectiveness of CFRP hull also increases
- Long waves decrease slower than short waves

Tests carried out on real materials in conditions simulating a drone flight near a storm front allowed for obtaining results that have never been presented before in publicly available publications. Analysis of the results leads to new, previously unknown conclusions, and the data can be used to create a mathematical model of structures based on carbon fibers for UAV applications. For LEMP frequency ranges, using only a CFRP housing is insufficient and additional methods of protection against this type of electromagnetic pulse should be used.

Acknowledgments

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