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Research paper

New Electromagnetic Threat Protection Systems

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Abstract. The issues discussed in the article refer to a new category of military operations - electronic warfare (EW). In the context of EW, the high-power microwave (HPM) technology currently enables remote disturbances of operations lasting until the circuit is reset or the electronic system is destroyed. The article examines the problem of protection and defence against using HPM pulses. The research used a compact HPM generator developed at the Polish National Centre for Nuclear Research. It has a power of 3MW, an operating frequency of 2.9 GHz and a 3 μs pulse duration, emitted with a repetition rate of 1, 50, 100 and 250 Hz. The developed HPM pulse protection systems were subjected to intense field exposure in the open space of the training ground, in its land and sea sections, and in the circuit with a reverberation chamber. The distribution of the generated field on each measurement station was tested using a high-power D-dot probe, from which the data was transferred to the recording system via an optical fibre link. In all cases, this distribution turned out to be repetitive. The field probe with a logger was used for measurements inside composite structures. Unprotected electronic systems in hobby drones, mobile phones, cameras and systems using sensors based on micro-mechanical units were exposed. An analysis was conducted to check the operation of electronic circuits, effects caused and phenomena occurring during exposures to intense microwave radiation. It was found that the developed system meets the design assumptions in conditions similar to actual exposure to HPM weapons. Screening efficiency has been determined for various spatial configurations of radiation beam incidence. The presented systems for the protection and defence against the effects of HPM weapons implemented in the technology of composite hybrid absorbers enable effective elimination of electromagnetic pulse effects.

Keywords: unmanned aerial vehicles, electronic warfare, microwave directed energy weapons, electromagnetic compatibility

1. OUTLINE OF THE THREAT

Electronic warfare (EW) is a type of military operation that falls within a new category of conflict, namely information warfare (IW). These are any military operations involving the use of electromagnetic energy or directed energy weapons to gain control over the electromagnetic spectrum or to attack a hostile [1]. Electronic warfare includes three main forms of action:

- electronic attack,
- electronic reconnaissance,
- electronic protection [1].

Directed energy weapons (DEW) are systems including:

- laser technologies,
- technologies using high-power electromagnetic pulse (high-power EMP),
- technologies using charged particles beams or neutral particles beams [1].

Currently, weapons systems such as HPM weapons, laser systems or microwave-based disabling weapons are in the area of interest of armies in most countries, including Poland ("New weapons and defence systems in the field of directed energy", National Centre for Research and Development, Competition no. 1/PS/2014).

The longstanding competition among the military forces of different nations to establish supremacy has been a driving force behind the continual improvement of design solutions in weapons technology. This emphasis on developing advanced weaponry is crucial, especially in the field of aviation, where it plays a vital role in defending against terrorism and military operations. This includes the deployment of unmanned aircraft (UAVs) for combat or reconnaissance missions and safeguarding manned aviation against countermeasures.

Aircraft are particularly vulnerable to the effects of exposure to HPM weapons. In their case, the threat caused by high-power microwave pulses is disproportionately high, because disturbance of the operation of the engine control systems, information display, aerometric and gyroscopic systems, and navigation equipment and systems may cause loss of steering and stability, and thus the pilot's control over the aircraft. The aircraft usually cannot stop flying in the air, so the impact of HPM weapons most often ends in its destruction. In the case of vehicles and vessels, there is a greater chance of resetting the electronic systems, which usually allows the system to be restored and continue to function properly, unless the pulse has caused permanent damage to the components. The conclusions of the project show that the current state of technology enables remote and deliberate exposure of electronic systems to microwave radiation and causes a so-called soft-kill, i.e., some disturbance to its operation that lasts until the system is reset.

Modern aircraft structures increasingly consist of composite structures, which are characterised by a negligible level of screening, unlike the aluminium and its alloys used so far. In the Boeing B787 aircraft, the composites are already 50% of the structure, compared to 12% in the older Boeing 777 [2]. The electrical conductivity of aluminium (3.54×10^7 S/m, which is 61% of copper conductivity) can achieve shielding of 100 dB, provided that the galvanic continuity of the aircraft is maintained. However, methods of connecting structural elements using rivets or spot welds do not ensure electromagnetic integrity. In the case of a pulse with a sufficiently short wave (less than a single cm) penetrating into the aluminium structure, a multiplication of the pulse impact can be observed, caused by the formation of a standing wave and the overlapping of reflections in the hull recesses. UAVs are also used in the modern battlefield. Their small size and relatively quiet operation allow them to be used for observation or intelligence purposes. Due to manoeuvrability and achieved speeds, interception of hostile UAVs and their neutralisation is a technically demanding task, both due to the inability to have an effective impact on UAVs using kinetic weapons and the difficulties in detecting them. Protection of critical infrastructure, including airports, against the intrusion of UAVs will most likely be carried out using microwave weapons for jamming and disabling intruder vehicles.

Current development work in this respect includes both projectiles containing centrifuge-based single-use explosive pulse generators as well as stationary high-power microwave (HPM) guns.

2. DIRECTED MICROWAVE ENERGY (HPM) WEAPON

HPM anti-aircraft systems are developed in the countries leading in the work on directed energy electromagnetic weapons, primarily the USA, Russia, China and India [3]. An example of the USA work on the HPM anti-aircraft system is the Phaser system from Raytheon, whose tests were conducted back in 2013 at the U.S. Army Fires Center of Excellence in Fort Sill, Oklahoma. An example of a Russian system is Ranets-E, which operates in the X-band, has an HPM source of 500 MW and generates pulses with a duration of 20 nanoseconds and a repetition rate of 500 Hz. The antenna has a gain of 50 dBi [3]. Figure 1 shows the results of estimated EM field intensity calculations based on the above-mentioned emission parameters and assumptions, with a source frequency of 10 GHz and a 4 metre antenna diameter.

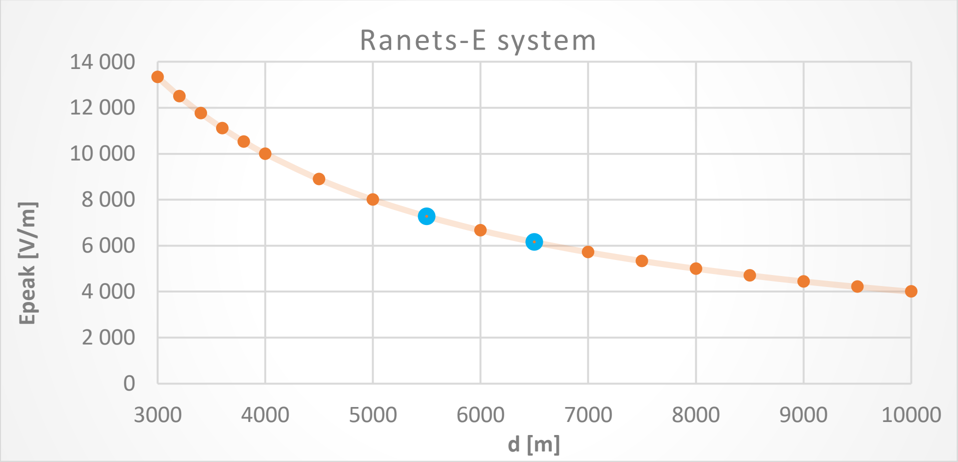


Fig. 1. Peak electric field intensity generated by the Ranets-E anti-aircraft HPM system at distances above 3,000 metres.

In analysing Fig. 1, it can be noticed that the Ranets-E system is able to generate significant field intensity at a very large distance from the source. If the provisions of the MIL-STD-464C standard specifying the requirements for the resistance of military systems to external interference are used as reference, it is possible to determine the ranges at which the Russian system can effectively affect targets. The results of field intensity calculations and standard values are presented in Tab. 1. They show that the system used against aircraft secured as per the requirements of the MIL-STD-464C standard can be effective when the target approaches at a distance of less than 6.5 km.

As the standard sets higher requirements to protect rotorcraft, the system will threaten helicopters approaching it at a distance of less than 5.5 km.

Table 1. The effective ranges of the Ranets-E system for various types of targets. Comparison of MIL-STD-464C provisions for the 8.5-11 GHz band with calculation results for the 10 GHz frequency.

No.	Type of systems	Maximum peak current of external electromagnetic field [V/m]	Estimated distance at which Ranets-E generates an equivalent field [m]
1	Ground	1943	20500
2	Rotorcraft (including UAVs) excluding operations from vessels	7430	5500
3	Fixed-wing aircraft (including UAVs) excluding operations from vessels	6299	6500

It should be noted that exceeding the field intensity specified by the standard does not automatically mean that the target will be disrupted, disabled or destroyed. This means that above the intensity limits listed in Table 1, the resistance to electromagnetic field effect was not tested and there is a potential possibility of disruptive or destructive impact of electromagnetic weapons on the target. The Ranets-E system was offered by Russia at LIMA 2001 Arms Fair in Malaysia in 2001 [4], as early as the first decade of the 21st century. Therefore, it can be expected that as a result of development works on similar systems, their current capabilities are that much greater.

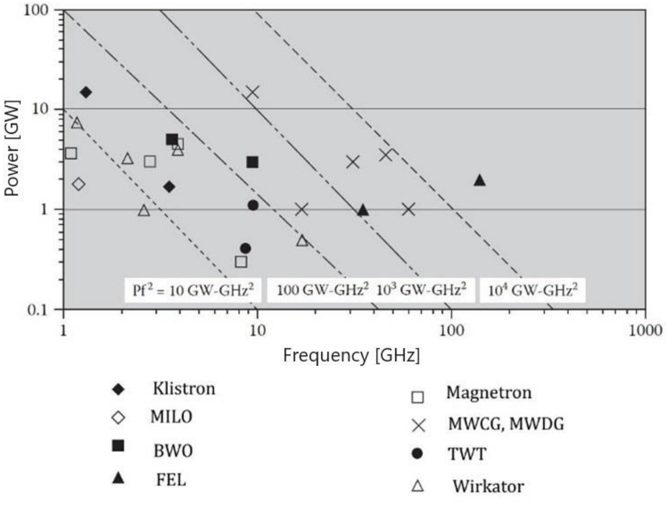


Fig. 2. Peak powers of pulsed HPM sources [3].

Analysis of data on HPM pulse source parameters (Fig. 2), carried out by Benford, Swelge and Schamilogl [3], leads to the assumption that the development of microwave technology currently allows achieving a power of a single GW and pulse times in single nanoseconds.

The use of a higher power generator or the use of pulse compression techniques in the modern HPM system results in a three- to four-fold increase in the distance between individual electromagnetic field values. Consequently, it becomes imperative to develop safeguards against electronic warfare specifically tailored for aviation applications.

2.1. METHODS

2.1.1. HPM generator used in research

As part of research on protection and defence against electromagnetic threats, tests were carried out using an HPM pulse generator constructed at the National Centre for Nuclear Research. This generator is compact and has a power of 3 MW and an operating frequency of 2.9 GHz. The principle of its operation is based on the pulse compression technique. They are generated in a microwave tube in the form of a klystron. Controlling the phase shift of subsequent pulses at the generator output allows for the accumulation of pulses in the compressor cavity as a resonating EM field. The mode caused by pumping the compressor system is changed by the phase shift of the pumping pulses, resulting in the emission of a pulse at the system output. The system can be used to select the number of pulses with a duration of 2-3μS and their repetition rate between 1, 50, 100 and 250 Hz. The HPM generator microwave system is filled with sulphur hexafluoride (SF6) of a high electrical breakdown value. Tests using this generator took into consideration its integrations in the measurement station in the reverberation chamber with a pyramidal antenna and at an open space station with a parabolic antenna.

2.1.2. Open space tests at sea

As part of the open space tests, measurements were carried out on the open sea in the maritime sections of the training ground in Ustka, with the participation of two vessels equipped with a generator and control and measurement equipment (Fig. 3), and a measurement point on which the test object was placed. The exposing vessel was equipped with an HPM pulse generator along with the power and cooling system. The EM pulse was triggered from a different vessel via optical fibre. A dedicated parabolic antenna, adjustable vertically and horizontally, was connected to the generator.

The operating parameters of the antenna and generator system were as follows:

- operating frequency 2.9 GHz;
- pulse power 3 MW;
- pulse duration 3 μs;
- repetition rate 250 Hz;
- antenna gain at least 32 dBi;
- beam width (-3 dB): max. 3.5 +/- 0.75 deg);
- connection to the generator via WR284 waveguide with SF6 gas at pressure of 800 hPa.

Fig. 3. “Zejna” exposing vessel with a microwave antenna

The measuring point was a platform for the test object subjected to exposure. The test object was located and fixed to the plane of a copper (grounded) measuring point with the dimensions of 5 × 3.75 m. In the same way as in the case of estimates in Fig. 1, an analysis of the field intensity on the raft was performed. Because the distance between them changed due to the drift of the vessels and ranged from 40 to 100 m at different times, the test objects were exposed to an electric field ranging from about 6kV/m to 15kV/m.

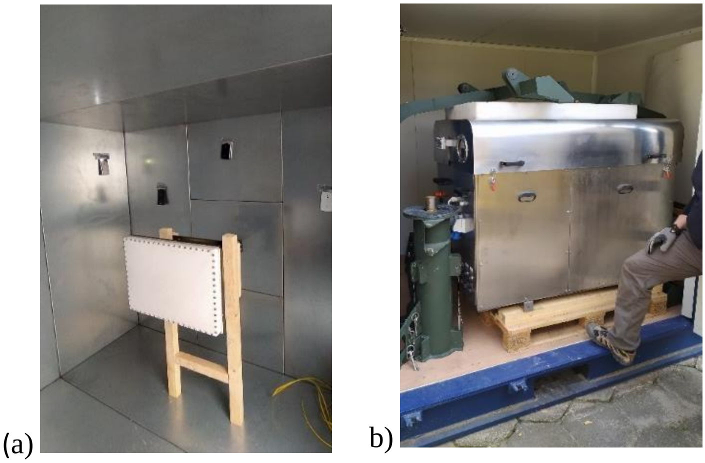
2.1.3. Open space tests at land

Tests in the open space were also carried out in the land section of the training ground in Ustka (Poland) and at the training ground in Nowa Dęba (Poland). In this configuration of the exposing system, the generator worked with the same parabolic antenna (Fig. 4).

Fig. 4. HPM antenna and generator

2.1.4. Laboratory tests

Another test system integrated as part of the work on HPM pulse protection was a reverberation chamber with walls not covered by absorbers (Fig. 5).



(a) b)

Fig. 5. a) LB-284-20 tube antenna used in tests; b) generator.

This means that, unlike anechoic chambers, it does not simulate exposures in the open space, and the distributions of electromagnetic fields inside it are similar to those in a microwave oven. EM radiation in its interior is reflected, creating complex modes and standing waves, resulting in local amplification of radiation intensity. Despite pulse reflections and superimpositions, intensity measurements confirmed the repeatability of the field distribution during HPM exposures. Radiation intensity was tested at the points visible in Fig. 6.

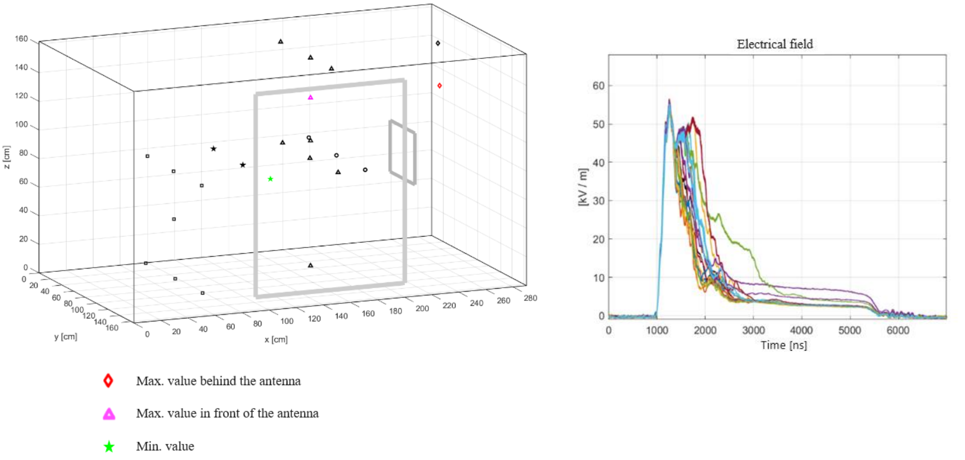


Fig. 6. General view of the chamber with marked points where measurements were made (visible outline of door and antennas) and electric field intensity curves for spatial coordinates [x = 261 cm, y = 82 cm, z = 125 cm]

3. PULSE EFFECTS

3.1. Pulse coupling

All electronic units are susceptible to failures and permanent damage when exposed to an electromagnetic wave of appropriate power and frequency. The electromagnetic pulse is determined by such parameters as: rise time (measured in V/s), electric field intensity (V/m) and frequency (Hz). The effectiveness of the impact on electronic systems is a result of these parameters. The shorter the rise time, the higher the frequency ranges of the bandwidth, and the pulse spectrum determines the energy transfer efficiency. Higher frequencies penetrate smaller apertures, and if the rise time is sufficiently short, the protection systems will not keep up with the response. On the other hand, the electric field intensity characterises the amount of available energy that can be released in the radiated system. The combination of the appropriate values of the described parameters makes the electromagnetic pulse destructive for electronic systems. When used as a weapon, the electromagnetic pulse induces high voltages and currents in electrical conductors. In the case of a sufficiently high field intensity, deformations of the material are observed, which causes these elements to vibrate in the acoustic range.

Circuits with a short signal or power path are more susceptible to high-frequency pulse coupling. It is the opposite in long transmission lines, such as high-speed catenary, Internet cables, etc. In this case, the coupling impedance is more susceptible to conduct low-frequency disturbances.

The efficiency of pulse penetration into the system depends on the pulse frequency and the match between the propagation medium and the coupling impedance. The degree of coupling determines the value of the interfering signal induced by the pulse. Coupling can be done through complex impedance networks, and the disturbance can propagate in the system through conducted signals induced on common inductance or capacity. The electromagnetic pulse can be coupled in the system in two primary ways:

- "Front door coupling" - direct coupling,
- "Back door coupling" - indirect coupling [1].

Front door coupling is observed when the pulse power is propagated directly to electronic systems used for receiving or transmitting electromagnetic waves, which include radar antennas as well as communication or electronic warfare items. The subsystem antenna is connected to the system output or input and acts as a path between the environment and the system circuits through which the disturbance power is propagated to the circuit, causing its destruction or disturbance [4]. The neutralisation of electronic systems by front door coupling is based on the assumption that the HPM generator operates in the frequency range of the systems at risk.

In order for the HPM damaging system to be the most effective, it should be narrow-band, even dedicated to specific potentially disabled systems, or have a wide bandwidth and enormous power.

Back door coupling occurs when the electromagnetic field from the HPM source causes further propagating disturbance or an electrical state in the attacked system on an element not originally used as an antenna. In such a case, the pulse can enter the system through:

- power cables,
- signal cables,
- small holes in the screen and gaps between aluminium or carbon fibre sheets,
- elements of the system connected with each other by parasitic impedances or having a common mass.

The pulse can penetrate the system by means of cables, power cables or conductive elements that unintentionally act as an antenna. Holes (apertures), such as doors, hatches, ventilation ducts or windows, cause the HPM pulse energy to penetrate into the hull. Microwave radiation can enter the inside of the hull and enclosures through covers, ducts and vents, as the physical sizes of these apertures can be comparable to the radiation wavelength. However, intense microwave radiation can induce significant values of eddy currents that tend to radiate the disturbances to discontinuities inside them. Covers intended to ensure electromagnetic integrity, the edges of which have not been properly galvanically sealed, may fall into resonance under the influence of microwave radiation and directly introduce energy into the housing.

The standing wave generated in the housing can be characterised by a very high value of the electric field. The hull and the elements located in it (tunnels, housings, partitions) and items create many potential resonance cavities, in which resonant modes may appear. In addition, the pulse penetrating through small apertures, a high-order mode in a random cavity, eddy currents or conduction can propagate in different parts of the structure. The variety of cable lengths, shapes of their arrangement and parasitic impedances make it impossible to predict back door coupling. During the field tests, this type of situation was observed, such as when the electromagnetic seal began to show signs of wear, despite redundancy.

Predicting the distribution of these fields in a deterministic manner for complex or large elements is very difficult due to the complexity of the boundary conditions. Housings are often much larger than the wavelength of HPM radiation, so numerous modes with similar frequencies will appear in cavities. In addition, there are oscillations, vibrations and temperature changes on board an aircraft, for example, as a result of which the boundary conditions change.

Due to its complex nature, back door coupling is much more difficult to simulate than front door coupling, but when trying to simulate the technical solution of the HPM-resistant optical channel in the ANSYS numerical simulation program environment, it was possible to obtain a model example of a back door coupling event as described above.

The model used for simulation takes into account a shielding defect in the form of an unnoticeable gap, the presence of which could result from the exposure to vibrations. The gap between metallic layers intended to act as an electromagnetic shielding in composite structures, the optical channel and the tank hull allowed the pulse to penetrate into its interior (Fig. 7).

Analysing the simulation results, it can be concluded that analogous field intensity while using a composite without absorption additives and shielding structures would be lower in the protected area than in the absence of damaged electromagnetic protection. In many cases, an electromagnetic pulse can have a very wide spectrum, making it much more difficult to predict potential paths of its penetration, at the same time increasing the probability of radiation entering the system.

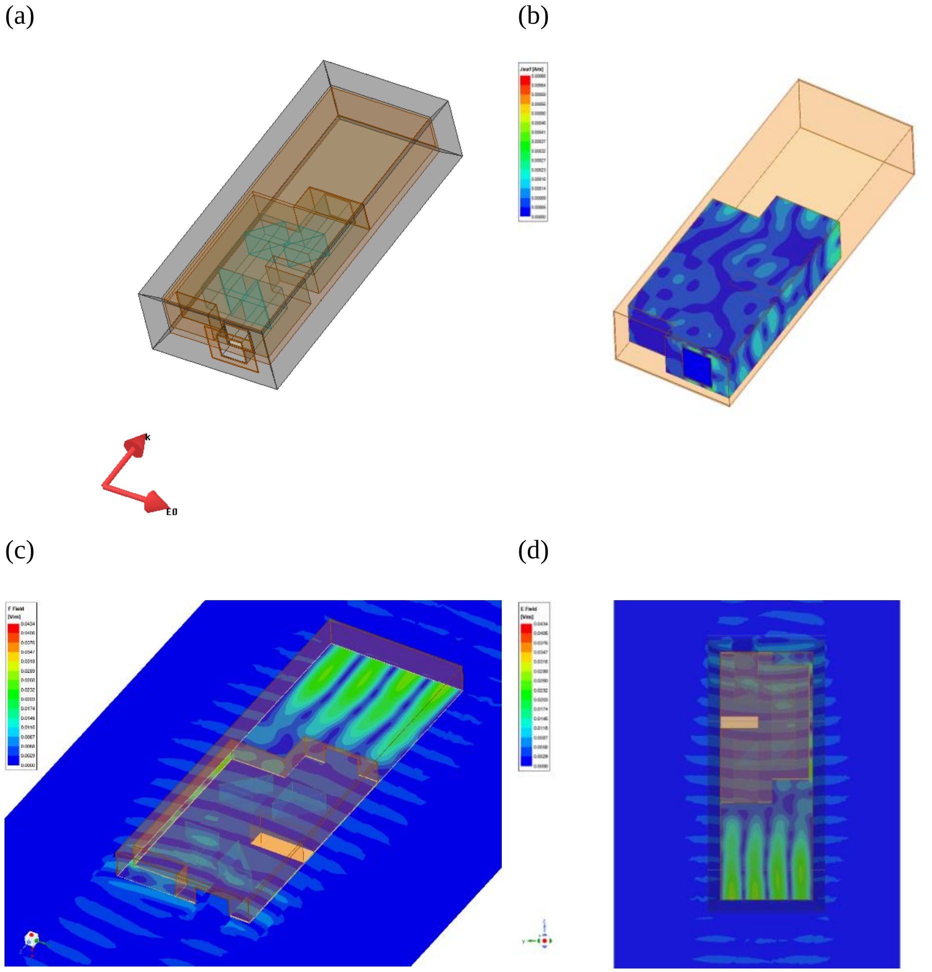


Fig. 7. Simulation results for a tank with an optical channel in the absence of galvanic integrity of protection, a) model with visible layers of absorbers, EM screens, channel prisms, b) surface currents of the channel EM screen, c) and d) electric field distribution inside the tank

3.2. Pulse impact on electronic units

The impact of the electromagnetic pulse on electronic systems can be divided into four primary levels:

- system upset,
- system lock-up,
- system latch-up,
- system damage/burnout.

The first two are often referred to as “soft–kill”, the other two as “hard–kill”. There is also a distinction with a different division of ways of intentional impact on the hostile. If this distinction were applied to the levels of impact presented above, they would be included in the first level, and the disturbance would probably affect the most susceptible of the systems, i.e., a wireless communication system. The interference can be broken down into categories taking into account the way in which dominance is achieved in the spectral range:

- Deception – otherwise spoofing, which is an ‘intelligent interference’ comprising falsifying the signals or jamming them in such a way that from the perspective of the target they are treated as natural difficulties or even accepted as a real signal. Individual divisions in the battlefield have smooth transitions in terms of energy levels, depending on what target is being disabled. Another important impact is the use of a spectrum for jamming purposes, while ensuring that our own equipment is secured.
- Jamming – the interfering signal generated by HPM systems is difficult to form when it comes to the signal structure (modulation, etc.), so jamming is aimed at blinding the initial receiving paths (LNAs, mixers). This category also contains a disturbance of the hostile radar systems.

3.2.1. "Soft-kill"

The effect of an electromagnetic weapon is to cause the system to malfunction or reset. A good example is a computer system that gets reset, goes into a data recovery mode or does not function properly. The result is temporary loss of functions that can severely affect the operation of any system that is critically dependent on the electronic system [5]. If one or more electrical states of the unit caused by an electromagnetic pulse are changed, the system is "upset" [6]. When the state of change does not disappear with the interfering signal, the term used is system "lock-up". During the tests on the naval training ground in Ustka, reference electronic systems in the form of two autopilots were used. Both were tested beforehand, worked properly, and the recording was uninterrupted. Electronic systems were exposed and re-verified after the tests. After the exposure, it was found that one of the autopilots was destroyed because the testing team was unable to activate the "locked-up” autopilot at the test site. Stored data could be read from the second autopilot. During recording, the electronic system was locked-up when the test objects were exposed. There were visible deviations from the initial parameters and the lack of response of the autopilot system. During the subsequent analysis of the autopilot systems and the data they recorded, it was found that both systems were not permanently damaged and were able to function properly.

This would mean that a "soft-kill" was achieved in the form of an "upset" (Fig. 8. PCB1) and "lock-up" (Fig. 8. PCB2); however, in the case of systems responsible for maintaining a flying object in the air, this would mean its destruction. This record shows strong peaks caused by the impact of the HPM pulse.

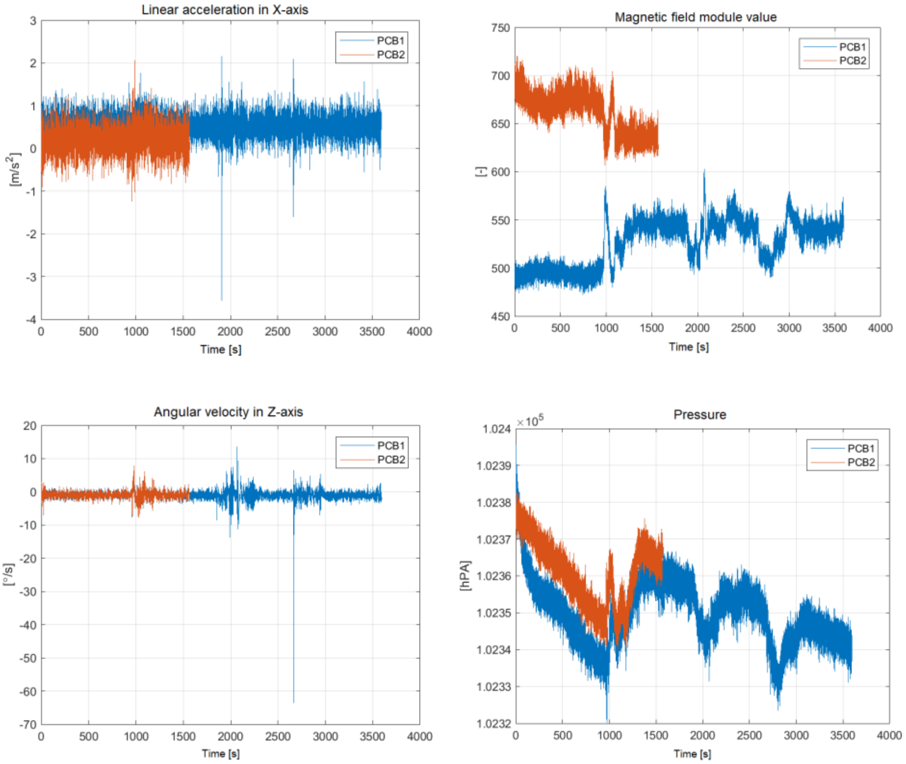


Fig. 8. Some of the collected autopilot data showing readings from magnetic field and pressure sensors, and linear and angular accelerometers using MEMS technology

As part of the project in the field of defence against electromagnetic threats, the susceptibility of UAVs was tested depending on radiation intensity, polarisation, frequency or modulation. The tests were carried out in the Electromagnetic Compatibility Testing and Electromagnetic Fields Measurements Laboratory (LBEMC), which is part of the Military Institute of Armament Technology (MIAT) in Zielonka (Poland). The tests were conducted in the frequency radiation range 200 MHz – 18 GHz and for radiation intensity of 10, 20 and 50 V/m, and its effects were published [7].

The conclusions from the analysis of the results allow us to assume an intensity of 50 V/m as an approximate value at which UAV disturbance is achieved, unrelated to communication disruptions, but with repeatable and immediate non-destructive damage to the unprotected UAV system.

3.2.2. “Hard kill'

A hard-kill causes permanent damage to the electrical components of some equipment or system. An example is a computer system that experiences damage to the power supply, interfaces and/or memory [8]. During the research with the use of a test station based on a reverberation chamber, a field intensity was achieved that allowed this type of effect to be triggered.

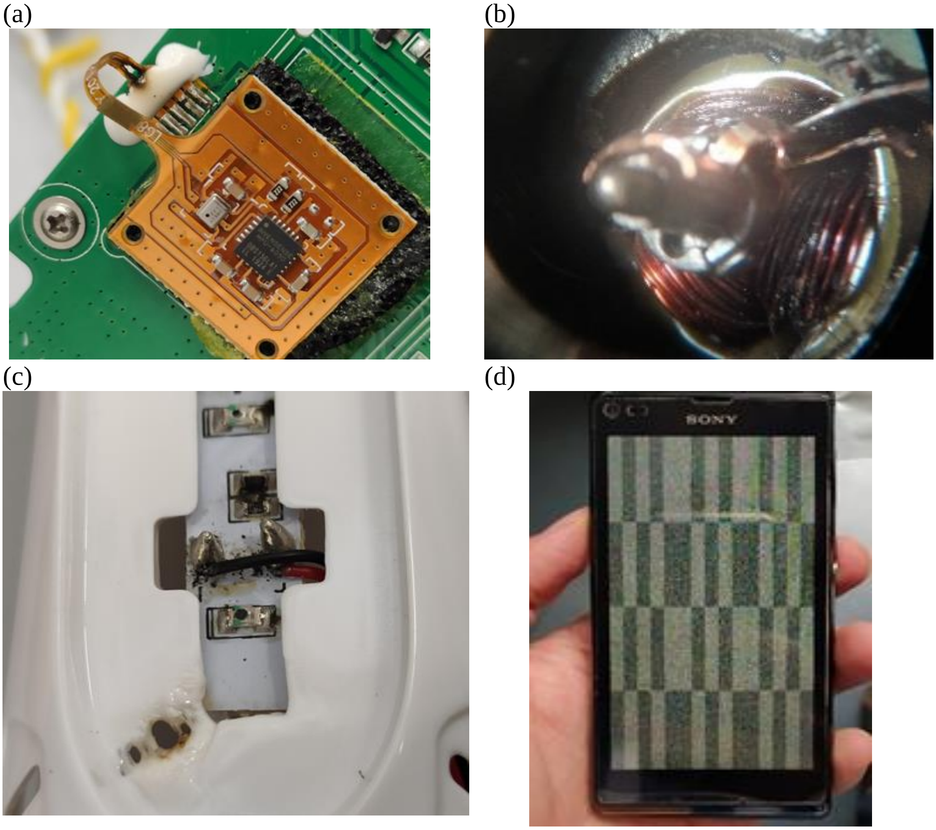


Fig. 9. “Hard-kill” units subjected to exposure in the chamber, a) “Burnout” of the UAV central unit cables, b) “Burnout” of the BSP rotor motor windings, c) “Burnout” of discrete elements (diodes, resistors) of the board in the immediate vicinity of the UAV rotor along with the burning of the plastic housing, most likely caused by an electric arc, and d) “Latch-up” – phone screen.

When a destructive change in one or more electrical states of the equipment is induced as a result of the action of a directed energy weapon, the effect is called "latch-up" (Fig. 9d). This effect is achieved when induced parasitic signals cause high current flow and automatic damage to a discrete element of the electronic equipment. This means that semiconductor elements, like transistors or diodes, are destroyed. The system or unit does not work properly or does not work at all.

When a destructive change causing electric burning of electrical components, capacitors, laminate, resistors and conductors, it is referred to as a “burnout" (Fig. 9 a, b, c).

Burnout usually occurs in the connector area, where many leads converge, e.g., base, collector and emitter wires, or in the immediate vicinity of long wires or printed circuit board paths. The process is often accompanied by sparking. During the visual inspection of the exposed systems, it was found that the most probable cause of the housing burnout (Fig. 9c) was an electric arc at the ends of the metal rod, which is the axis for the plastic gears of the electric motor spacer.

4. METHODS OF PROTECTION AGAINST A HPM PULSE

Protection against the HPM pulse impact on electronic and mechanical systems can be broken down into two main categories - mechanical and electronic. Mechanical protection involves separation from the external environment by using a Faraday cage, i.e., shielding, filtering wires or using electromagnetic radiation absorbers.

Filtering is used to remove interference signals induced in the signal cables or power supply. High-power electromagnetic disturbances are most often filtered using chokes, in which the disturbing energy is converted into heat energy. However, protection of the items to which the cables are connected is not simple, as they are easily penetrable by disturbances. If the shielding of signal cables is made properly, so as to eliminate interference between adjacent items or within the same one, it will probably facilitate the penetration of the HPM pulse into the system circuits. Moreover, each defect (lack of integrity) of the housing, the presence of connectors and the finite value of cable shield attenuation also has a large impact on the susceptibility of equipment damaged by directed energy weapons. It is important to reduce interference signals with as little impact on the operating signal as possible. The requirements for HPM pulse defence systems mean that sufficient filtration in the data link layer prevents the operation of high-speed digital circuits. For this reason, it is good practice to use optical fibres to make signal connections between individual shielded systems. Glass fibre from which the optical fibre is made is characterised by values of electrical and magnetic permeability for microwave frequencies close to unity with an imaginary value close to zero, which is why its interaction with the pulse is negligible. It does not induce an electric current under the influence of an electromagnetic field, which makes it much easier to shield the system.

Electromagnetic radiation absorbers are widely used in various fields of technology. Absorbing materials are used to reduce the unwanted effects of electromagnetic waves in various items, such as digital circuits, computers or in various types of research equipment. The absorption band of such material in some applications is narrow and strictly limited. In other cases its task is to absorb electromagnetic radiation over a wide frequency band. Their task is also to reduce radiation so that as little of it as possible is reflected. Materials with various electromagnetic energy absorption mechanisms are usually used for making absorbers. Composite absorbers, which consist of several materials, are used in addition to structurally homogeneous absorbers. In the case of structural absorbers, it is possible to use this fact to modulate the properties of the composite material by spatial structuring of its elements.

There are many absorption materials, but not all have appropriate properties ensuring proper protection of equipment against high-power electromagnetic pulses.

The two main groups are dielectric materials and magnetic materials. Magnetic materials are described by the permeability value with the actual component that determines the magnetisation value and the imaginary part that describes the losses. Similarly, the value of the actual part of electrical permeability describes the susceptibility of the material to polarisation, and its imaginary part is responsible for dielectric losses. Two conditions must be met for absorbers to be effective: matching the impedance of the absorption element to the free space impedance (equal to 377 Ω) and the appropriate thickness of the absorption element [9].

Since matching the impedance of the absorber front to the free space impedance plays a key role in limiting reflection and the effectiveness of their operation, a solution of anechoic chambers and spatial structuring was used in the HPM-resistant aircraft tank created for the purpose of presenting the technology. Layers with higher combined magnetic and electrical permeability were shaped into a regular quadrangular pyramid. In such a solution, for a frequency of about 3 GHz ($\lambda = 10$ cm) there will be a smooth change in the impedance of the medium, while for radiation of tens of GHz (12 GHz; $\lambda = 2.4$ cm) the pyramid pattern will result in a large dispersion.

Matching is also achieved by selecting appropriate magnetic materials. The models proposed by the authors used iron compounds, which have the largest dielectric constant among common elements, and its molecular structure is a material meeting the electrical and magnetic requirements. The absorber developed in Air Force Institute of Technology (AFIT, Warsaw, Poland) was used in the preparation of HPM radiation shielding matrices. Their shape and absorption coating were selected in such a way as to provide the most effective protection against exposure to strong electromagnetic pulses.

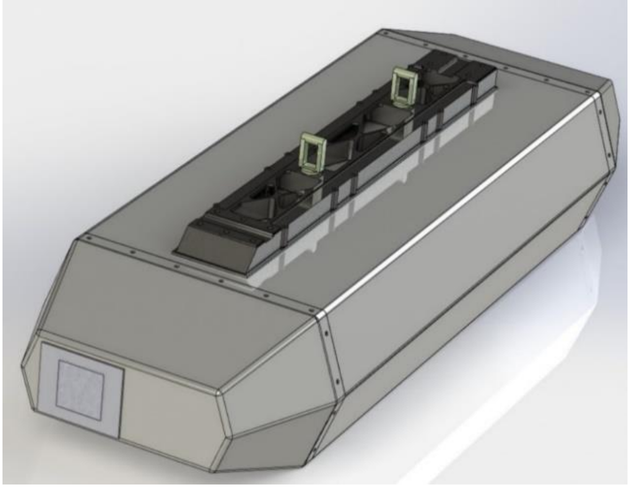


Fig. 10. 3D model of the test aircraft pod

The following elements were used to build the aircraft pod's (Fig.10) internal protection chamber (Fig.7):

- L285 epoxy resin with H286 hardener;
- Aeroglass glass fabric 110 g/m2;
- carbon fabric 160 g/m2;
- carbonyl iron;
- RGO graphene oxide;
- JB and CFE absorbers;
- 30 mm herex as the shield core;
- Resoltech 1250M epoxy foam as the shield filler;
- T-217 shielding cover from Astat.

Works related to the construction of this element consisted in combining absorbent properties with load-bearing elements, which together form a protective element against the HPM pulse and against environmental exposures.

Work on the tank insert began with the production of trial composite shields (Fig.11). The shields were made using a milling plotter, which created geometry in the shield core through machining. Three layers of a mixture of epoxy resin with a CFE absorber and carbonyl iron were sprayed onto the core. The composition of the shielding and absorbing layer on the shielding core involved:

- L285 epoxy resin (30%);
- carbonyl iron (30%);
- CFE absorber (20%);
- JB absorber (10%);
- reduced graphene oxide (10%).

Fig. 11. A ready-made demonstrator of a structured, composite electromagnetic shield designed to verify whether the PGT4 readiness level has been achieved

After applying the layers to the core, further works were carried out to make the shielding, which consisted in supplementing the screen with 1250M structural foam with the addition of JB and CFE absorbers. After complete hardening, further machining was done to prepare the shielding for final reinforcement with glass fabrics and carbon fabrics, which also serve as microwave radiation shielding. The last layer of the shielding is made of T-217 shielding applied to the wall and reinforced with carbon fibre.

The analysis of broadband characteristics made at MIAT allows us to conclude that the main mechanism of operation of the shielding in a wide band is reflection. The shielding begins to absorb radiation 6.5 GHz more effectively, after which subsequent peaks of its absorption appear at frequencies of 10.5 GHz Exposures were performed as part of the tests using the HPM generator described in Section 2. The tests in the reflection chamber located on the premises of the Naval Academy (Gdynia, Poland) were performed by placing the protective chamber of the tank at point $x = 63.5$ cm, $y = 85$ cm, $z = 50$ cm, where the radiation intensity was mapped at 27.9 kV/m with a standard deviation of 0.5 kV/m. These measurements were carried out using an electric or magnetic field probe (D-dot SFE3-5G or B-dot SFM2G from montena), the montena BL3-5G balun and an optical fibre link (montena MOL3000). All of the above-mentioned elements have a continuous galvanic metal housing designed to provide sufficient shielding against EM interference under measurement conditions.

A calibrated PI-01 field probe with a Smart Fieldmeter RFP-05M logger was placed inside the protective chamber of the container, which allowed for determining the attenuation of the demonstrator. In this way, the field intensity values inside the tank were measured with different spatial configurations.

The value of the shielding effectiveness was determined using the following formula:

$$a_s = 20\log(\frac{E_1}{E_0})$$

where:
a_s – shielding effectiveness [dB];
E_0 – electric field intensity for reference measurement [V/m] (at the tested point E_0=27.9 kV/m);
E_1 – electric field intensity inside the housing made of absorption material.

Table 2. Shielding effectiveness test results

Measurement	When exposed “from the side”	When exposed "from the front"	When exposed "from the other side"	When exposed “from the back”
Shielding effectiveness a_s	**96.41 dB**	**75.16 dB**	**78.49 dB**	**81.91 dB**

A similar test methodology was used during tests on the land section of the traverse in Ustka. The antenna connected to the HPM pulse generator did not have the directional gain characteristics. Before measuring the effectiveness of shielding, the emission conditions were tested to integrate the measurement station. The position of the main lobe in the azimuth is obvious and results from the spatial geometry of the system. The measurement system consisting of: SFE3-5G electric field probe, BL3-5G balun, optical fibre link and acquisition system. Similar measurements were carried out to confirm the repeatability of the obtained intensities and collect their values in different places of the station. At the test object location point, the measured electric field intensity was 17.0 kV/m.

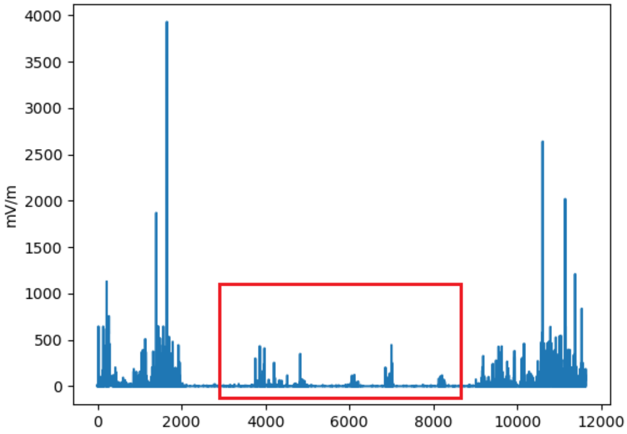


Fig. 12. Log 85 from the Smart Fieldmeter RFP-05M logger, with the marked exposure time showing pod’s correct operation

The value of the shielding effectiveness coefficient was determined as in the case of measurements in the reverberation chamber. The highest recorded value in the marked area is **445 mV/m**.

Attenuation: $a_s = 20\log\left(\frac{E_0}{E_p}\right) = 20\log(\frac{17{,}000{,}000}{445}) = \mathbf{91.64\ dB}$

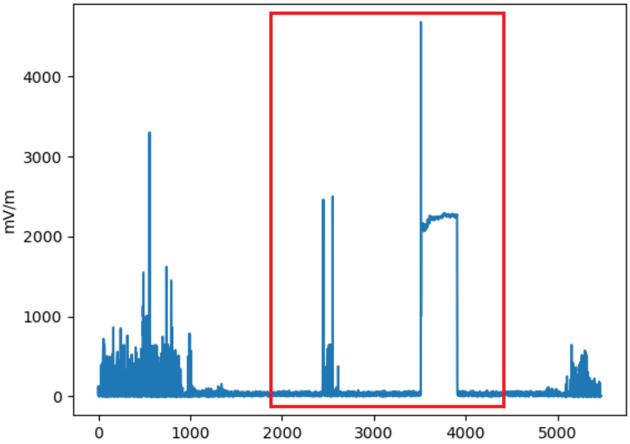


Fig. 13. Log 86 from the Smart Fieldmeter RFP-05M logger, with the marked exposure time showing fault in pod's shielding

Attenuation: $a_s = 20\log\left(\frac{E_0}{E_p}\right) = 20\log(\frac{17.000}{4.68}) = \mathbf{71.20\ dB}$

The obtained results are very similar to the values obtained at higher intensity in the reverberation chamber. It should also be noted that in analogous antenna-tank-probe arrangements, both measurements differ by no more than 5 dB.

5. CONCLUSIONS

A critical examination of traditional methods for shielding and attenuating microwave radiation reveals their incompatibility with objects necessitating protection. These conventional approaches prove insufficient in achieving the boundary conditions concerning weigh and shielding effectiveness.

Furthermore, the article sheds light on the innovative concept of incorporating shielding materials into composites, thus creating hybrid absorbers. This approach demonstrates promise in addressing the evolving landscape of electronic warfare. However, a pertinent challenge emerges in the specific context of aircraft construction. Aircraft, by their nature, are subjected to oscillations, vibrations, and temperature fluctuations during operation.

These dynamic conditions pose a significant obstacle as they can lead to the formation of small holes and gaps in the materials used for shielding. In the article we convincing that vibrations and temperature changes on board an aircraft can compromise the integrity of the shielding, rendering it less effective or, in some cases, causing a deterioration in the situation. We show test results from particularly problematic scenarios where reverberation occurs, potentially amplifying the impact of intense microwave radiation.

The delicate balance between effective shielding and the structural demands of aircraft construction underscores the need for a comprehensive and adaptive approach to developing protection systems. As technology continues to evolve, finding solutions that can withstand the rigors of aircraft environments becomes paramount in ensuring the efficacy of electronic warfare defense mechanisms.

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Nowe systemy zabezpieczeń przed zagrożeniami elektromagnetycznymi

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Streszczenie. Zagadnienia poruszane w artykule odnoszą się do nowej kategorii działań zbrojnych - walki radioelektronicznej (WRE). W ramach WRE technologia mikrofalowych generatorów impulsu elektromagnetycznego HPM (ang. *High Power Microwave*) pozwala obecnie na zdalne zakłócenia stanu pracy trwające do czasu zresetowania układu lub zniszczenie systemu elektronicznego. W pracy rozpatrywany jest problem ochrony i obrony, zarówno przed jak i z wykorzystaniem impulsów HPM.
W badaniach wykorzystano kompaktowy generator HPM skonstruowany w Narodowym Centrum Badań Jądrowych o mocy 3MW, częstotliwości roboczej 2,9 GHz i czasie trwania impulsu 3 μs emitowanego z repetycją 1, 50, 100, 250 Hz. Opracowane systemy ochrony przed impulsem HPM poddawano narażeniom intensywnego pola w warunkach otwartej przestrzeni poligonu, w jego części lądowej oraz morskiej, oraz w układzie z komorą rewerberacyjną. Rozkład generowanego pola na każdym stanowisku pomiarowym zbadano przy użyciu wysokomocowej sondy D-dot, z której dane były przekazywane do układu rejestrującego przez łącze światłowodowe.. We wszystkich przypadkach rozkład ten okazał się być powtarzalny. Do pomiarów wewnątrz struktur kompozytowych wykorzystano sondę pola z logerem. Narażeniom poddano również niechronione systemy elektroniczne w hobbystycznych dronach, telefonach komórkowych, kamerach i układach wykorzystujących czujniki oparte o mikrourządzenia mechaniczne. Przeprowadzono analizę pracy układów elektronicznych, wywoływanych efektów oraz zachodzących zjawisk podczas narażeń intensywnym promieniowaniem mikrofalowym. Stwierdzono że opracowany system spełnia założenia projektowe w warunkach zbliżonych do rzeczywistego narażenia bronią HPM. Wyznaczono skuteczność ekranowania dla różnych konfiguracji przestrzennych padania wiązki promieniowania. Przedstawione systemy ochrony i obrony przed skutkami broni HPM zrealizowane w technologii kompozytowych absorberów hybrydowych pozwalają na skuteczną niwelacje efektów impulsu elektromagnetycznego.

Słowa kluczowe: bezzałogowe statki powietrzne, walka radioelektroniczna, mikrofalowa broń skierowanej energii, zgodność elektromagnetyczna