Experimental Estimation of Shielding Effectiveness of Composite Materials by Use of Ultra Wideband Electromagnetic Pulses

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***Abstract*—A wide set of shielding materials is used for protection of electronic systems and their critical components against the impact of Ultra Wideband Electromagnetic Pulses (UWB EMP). Widely known protection solutions are materials with polymer metalized films, the needle-punched and felt fabrics with conductive fillers, materials with ferromagnetic fillers, fabrics impregnated by electrolyte solutions such as regular water, NaCl and $CaCl_2$ water solutions. In this paper, a technique for express in-situ measurement of UWB EMP shielding effectiveness of composite materials is developed. The shielding effectiveness of materials with complex structure is tested in framework of the developed technique by the use of Test System providing the generation of EMP with duration of 242±24 ps (at half of maximum) and rise time of 139±14 ps. The obtained value of shielding effectiveness for the EMP with the noted parameters is 15.5 dB for four layers of the needle-punched material with carbon additives impregnated by electrolyte solution, 13.9 dB for the two layers of felt fabric material with a layer of polymer metalized film, and about 12.5 dB for material with the metalized films.**

Keywords—electromagnetic compatibility; electromagnetic pulse; testing, shielding effectiveness, composite materials

I. Introduction

Pulsed electromagnetic fields (EMF) generated by broadband systems of various radio services (radar, radio navigation, radio communications, etc.) or of industrial, scientific, medical and other applications, have a duration of nanoseconds and effective frequency range of 5–6 octaves or more. It is one of the main causes of the difficulties related to ensuring electromagnetic compatibility (EMC) of these systems with other electronic equipment when they are located jointly at small distances in restricted space (premises, labs, platforms, etc.). This is due to the frequency dependence of the EM shielding effectiveness (SE) of technical means: elements of shielding structures, absorbers, filters, composite and frequency-selective materials, which are usually used to protect against narrow-band EM radiation in a limited frequency range. In addition, there is a significant progress in creation of compact and portable generators of powerful picosecond electromagnetic pulses (EMPs) for intentional EM impact on electronic equipment for various purposes (electromagnetic terrorism, hybrid non-peaceful actions, etc.), which are capable to damage a variety of electronic systems and components. This fact increases the interest in protection of electronic equipment from intentional and unintentional EMP exposure. [1–6].

One of the up-and-coming approaches to the protection of electronic equipment from the ultra-wideband (UWB) EMP is the use of non-woven fabrics, which provide the ability for wrapping of protected devices, production of protective coatings, curtains, tents, etc. The use of materials based on non-woven textiles and foam materials with metallized films for shielding of radioelectronic equipment is rational when they are additionally characterized by flexibility, air-penetrability, and cheapness. The shielding properties of these materials can ensure a sufficient suppression of electromagnetic radiation in the wide range of frequencies for protection from the UWB EMP [4, 5].

The objective of this work is to develop and verify a technique for fast in-situ measurement of UWB EMP shielding effectiveness of supple shielding materials as well as to test the shielding effectiveness of these materials. Materials under testing are based on specialized non-woven textiles and foam structures (such as needle-punched and felt fabrics with or without a layer of metalized polymer film, with and without an impregnating liquid).

II. Technique of Testing

A. EMP Shielding Effectiveness

It is known that the value of shielding effectiveness of shielding material or gasket does not fully define the results of in-situ measurements because the method and conditions of application and mounting of used protection solution play a significant role. In the framework of the developed

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technique for in-situ estimation of SE of protection solution, we define the shielding effectiveness S_{EP} [dB] with respect to broadband EMP as a ratio of the pulsed electric field amplitude E_{P1} measured in the absence of protection solution to the amplitude E_{P2} measured in its presence:

$$S_{EP} = 20 \log\left(E_{P1} / E_{P2}\right), \text{dB}. \tag{1}$$

Shielding effectiveness of materials changes with frequency. Physically, the processes of reflection and absorption of EM radiation determine the shielding properties of material. Shielding effectiveness of a solid metallic screen increases with the frequency increasing [7], but SE of perforated structures decreases with the frequency increasing [8]. As for UWB EMP analysis, frequency dependence of the shielding effectiveness causes a change in EMP amplitude and shape when EMP penetrates through the shield.

Taking into account that the damaging factors of EMP disturbance are the amplitude, rate of rise, and total pulse energy [9], the protection against EMP impact must take into account not only a decreasing of the pulse amplitude, but also a decreasing of rate of rise and total energy of the EMP. The decreasing of these three quantities leads to a decrease in the probability of equipment failure under EMP impact. That is why three types of shielding effectiveness are introduced in [10]: SE peak-value reduction (1), SE time-derivative reduction, and SE energy reduction.

It is reasonable to compare shielding effectiveness (1) with respect to UWB EMP amplitude and the traditional shielding effectiveness of the continuous wave (CW). For this purpose, the weighted average (2) of CW SE is used:

$$\langle S \rangle_f = \left(\int_{f_{min}}^{f_{max}} S(f) \cdot E_f(f) \cdot df \right) \Big/ \left(\int_{f_{min}}^{f_{max}} E_f(f) \cdot df \right), \tag{2}$$

where $E_f(f)$ is the spectral density of pulsed E-field obtained as direct Fourier transform of the digitized oscillogram of pulse (Fig. 3): $E_f(f) = FFT(E_0(t))$, $S(f)$ is the amplitude-frequency characteristic (AFC) of CW shielding effectiveness for sample under test (SUT).

The weighted average (2) is computed in the effective frequency range $[f_{min}; f_{max}]$ of the pulse (the range, which accounts for 90% of pulse energy from 5% to 95%).

B. Test Site and Equipment

To study the shielding effectiveness with respect to EMP, the Test System of UWB EMP [11] was used (Fig. 1). It has a radiating system (RS) in the form of a multi-element TEM-horn array that radiates ultra-short UWB EMP of linear polarization with amplitude of pulses at the beginning of the working zone $E_0 = 50$ kV/m. Working zone is characterized by the value of wave impedance $Z_0 = 120\pi$ and dependence of amplitude $E(r) = E_0/r$. It begins at the distance of 1.7 m from the marker point of RS. Measuring the amplitude of the electric field strength in the range from 2 to 20 kV/m with a relative error of ±20% is carried out by using Digital Field Indicator (DFI). The electric field sensor in form of a stripline is used in DFI.

The test site is the semi-anechoic chamber (Fig. 2). In accordance with the definition given in [12], design of the semi-anechoic chamber should ensure the absence of reflected waves in the area of the SUT mounting. The chamber walls are radio-transparent (made of bricks). All reflecting elements of infrastructure (grounding bus, radiators, etc.) are covered by radio absorbing material (RAM) panels TORA-39 (reflectivity -25…-50 dB in frequency range from 0.5 to 10 GHz) [13]. The DFI is mounted on the dielectric tripod at the radiation axis of RS.

The following settings of the test system are used: pulse repetition rate is 500 Hz, burst duration is 1 s, and the distance between the marker points of the RS and the DFI is chosen 4.5 m. It provides the value of the electric field amplitude of the pulse equal to 19±1 kV/m when a shielding material is absent.

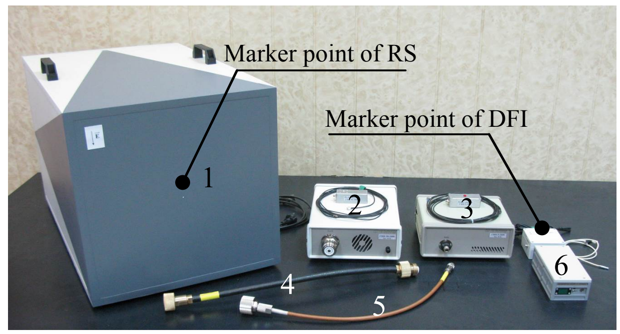
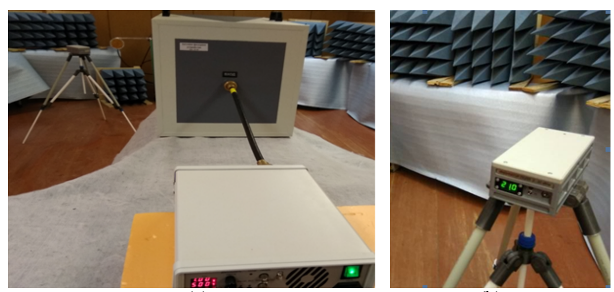


Fig. 1. Test System equipment: TEM-horn array radiating system (1), generators of high-voltage (HVG) pulses 50 kV (2) and 5 kV (3), high-voltage feeders 50 kV (4) and 5 kV (5), digital indicator of the electric field component (DFI) (6).



(a) (b)

Fig. 2. Test site. RS is connected to HVG 50 kV (a); DFI on the dielectric tripod (b)

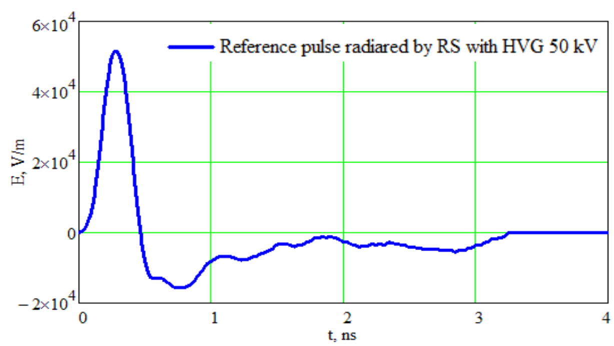


Fig. 3. Digitised oscillogram of the EMP reproduced by RS with HVG 50 kV at the beginning of working zone on the radiation axis (time window is 3.25 ns).

The digitized oscillogram of the pulse $E_0(t)$ created by RS with high voltage generator HVG 50kV at the beginning of working zone at absence the attenuation by the shield is presented in Fig. 3. The same sensor as used in DFI was connected to the oscilloscope for recording the pulse waveform. The spectral density of pulse $E_f(f)$ is presented in Fig.4. The cumulative function (energy fluence) is presented in Fig. 5. The effective frequency range of pulse 139/242 ps is from 0.17 to 2.31 GHz.

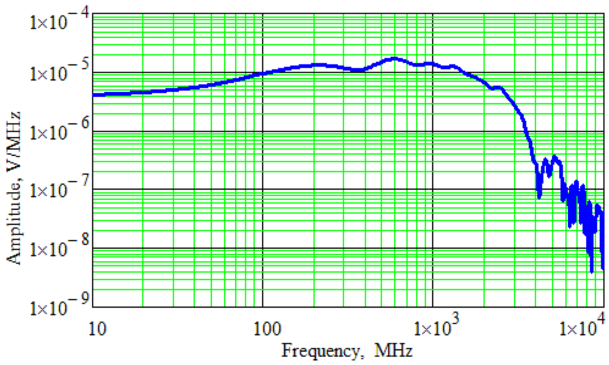


Fig. 4. Spectral density of the reference pulse

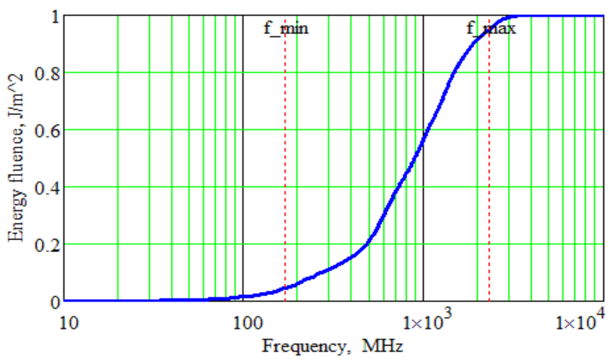


Fig. 5. Cumulative function of energy distribution and effective frequency range [0.17; 2.31] GHz of reference pulse.

Table 1 shows the parameters of the reproduced pulses and their values.

TABLE I. PARAMETERS OF RADIATED UWB EMP

EMP parameter	Value
Amplitude at the beginning of the working zone	50 kV/m
EMP rise time	139±14 ps
EMP duration	242±24 ps
EMP repetition rate	500 Hz
Duration of EMP train (burst duration)	1 s ± 10%
Time interval between EMP trains	≥10 s
Effective frequency range of EMP exposure	0.17–2.31 GHz
EMP power at the beginning of the working zone averaged over its area	5.34 MW
The size of the irradiation zone with an EMP amplitude of 50 kV/m with an inhomogeneity of 3 dB at the beginning of the working zone	≥1,20×0,58 m
Distance from the center of the marker point of RS to the near border of the working area corresponding to an EMP amplitude of 50kV/m	1.7 m ± 20%

C. Test Procedure

Before measurement, the calibration procedure must be performed for the DFI to make sure that the values of EMP amplitude measured by DFI coincide in the limits of instrumental error obtained at Test System Certification, and features of test site do not influence on measurement results.

Block diagram of the test setup is presented in Fig. 6. During the measurements, the DFI was placed in the working zone where the level of reflected waves is minimized. The samples of shielding material were placed in the plane perpendicular to the radiation axis of RS in front of DFI in the immediate vicinity of its marker point (distance from marker point of DFI to the plane of the SUT is not more than 3.0±0.5 cm).

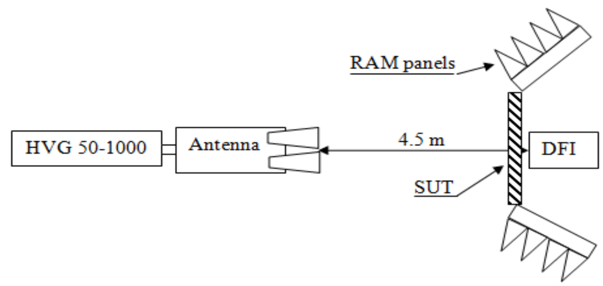


Fig. 6. Block diagram of test setup.

The dimensions of each SUT are not less than 0.7×0.7 m, and it is mounted symmetrically relative to the DFI at the radiation axis of the RS. The influence of waves diffracted by the SUT edges is eliminated by using of RAM panels, as well as by appropriate choice of SUT dimensions and its placement relative the DFI, see Fig. 6. Moreover, the stripline design of the DFI sensor improves measurement accuracy by recording only waves, which propagate along the axis of the stripline sensor (deviation from axis is no more ±10 deg). The DFI records the maximum value of E-field strength within a time window of 1 ns, so the waves reflected from objects located at a distance of more than 0.3 m from the DFI do not influence on measurement result.

During each test, five bursts of UWB EMP are emitted and the EMP amplitudes in the region of DFI placement are measured. The result is the average value of the amplitude over five measurements.

The measurements were carried out only for such SUTs, the SE of which could be measured. The minimum value, which can be measured by DFI (no less than threshold 2 kV/m) defines the dynamic range (DR) of test setup. It was established that for ten layers of dry SUT No 1, for five layers of SUT No 2, and for three layers of SUT No 3, some of five measurements had a value less than threshold and developed technique is not applicable.

III. DESCRIPTION OF SAMPLES UNDER TEST

A. Needle-punched material containing carbon fibers

SUT No. 1 was a needle-punched material containing carbon fibers [14], produced on industrial scale [15] and used for shielding the EM radiation of cellular communication systems. The decreasing of the field level in the shielded zone is provided mainly by the absorption of EM energy. Basic structure of this material is polyester fibers with linear mass density 3.3×10^{-7} and 4.4×10^{-7} kg/m, polypropylene fibers with linear mass density 3.3×10^{-7} kg/m, and wool with linear mass density 7.6×10^{-7} kg/m. Carbon additives in a form of 65 mm long carbon cellulose-hydrate filaments are used as conductive fillers (Fig. 7). Diameter of filaments is from 7 to 10 µm, linear electrical resistance is less than 20 Ohm/cm, volume electrical resistance is less than 24 mOhm·cm [14].

Fig. 7. Structure of a needle-punched material containing carbon fibers

The needle-punched non-woven fabric is made with the textile equipment, which consists of carding machine, cross lapping machine and needle-punched machine. Some samples of the needle-punched non-woven fabrics were produced with weight of fabrics from 160 g/m^2 up to 250 g/m^2, with width of fabrics from 40 cm up to 150 cm, and with thickness from 4.7 mm up to 6.0 mm. The number of strokes was from 450 up to 600. The frequency of the needle breakage was from 70 up to 120 per 1 cm^2 surface area and the needle punch depth was from 4 up to 7 mm [14].

Additionally, material of SUT No 1 was impregnated by the liquid electrolytes for the analysis of its influence on shielding effectiveness. Impregnation was carried out using regular water and saturated NaCl water solution (temperature was 20^o C). It should be noted that the impregnation of the samples was carried out as long as the liquid could be retained by the material.

B. Foamed polyethylene with a metallized film

SUT No. 2 was a foamed polyethylene with a metallized film on one side (see Fig. 8). This material is usually used in building for a noise and thermal insulation because the thin metal film reflects the high-frequency EM radiation (infrared) and foamed polyethylene has a low thermal conductivity. The thickness of metalized film (aluminum) is about 1 µm.

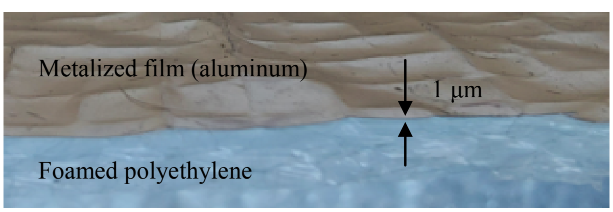


Fig. 8. Structure of foamed polyethylene with a metallized film

C. Two-layer material consisting of metallized polymer film and felt fabric impregnated with $CaCl_2$ water solution

SUT No. 3 was a two-layer material [14] developed for shielding of the UHF electromagnetic radiation generated by radio equipment of 2G, 3G, 4G and the future 5G mobile communications. The first layer of the material is a felt fabric impregnated with $CaCl_2$ water solution and the second layer is a metallized polymer film (Fig. 9).

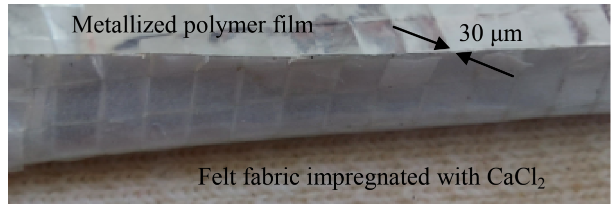


Fig. 9. External view of SUT No.3 (two-layer material)

D. RAM panel TORA-39

SUT No. 4 was a panel of radio absorbing material TORA-39 [13]. It is the pyramidal type panel made of foamed polyurethane with carbon filler.

The appearance of panels TORA-39 is given in Fig. 2, the structure of material is shown in Fig. 10.

Fig. 10. Structure of foamed polyurethane with carbon filler

IV. TEST RESULTS

A. Measurements of EMP and CW shieldig effectiveness

Two types of measurements were carried out. The first type was realized in the framework of developed technique presented in Section II and named as measurements of SE for UWB EMP. The second type of measurements is performed in accordance with requirements of standard [16] taking into account recommendations of [17] and it is named as CW measurements. In the framework of CW measurements, the transmitting antenna is connected to generator Agilent 5181 and spectrum analyzer Agilent 9020 measures the power at output of receiving antenna placed behind the SUT.

For comparison of SE obtained by these two types of measurements, AFC of SE defined by CW measurements $S(f)$ and spectral density of pulsed E-field $E_f(f)$ given in Fig. 4 are substituted in Formula (2).

B. SE of needle-punched material containing carbon fibers

The measured values of shielding effectiveness with respect to UWB EMP 139/242 ps performed according to the technique based on formula (1) for the dry needle-punched material are shown in the second column of Table II. Values of averaged CW SE calculated by formula (2) using data presented in Fig. 11 are shown in the third column.

TABLE II. COMPARISON OF SHIELDING EFFECTVENESS OF SUT NO. 1 (NEEDLE-PUNCHED DRY MATERIAL) FOR EMP AND FOR CW

Number of layers	Peak-value reduction SE for UWB EMP, dB	Frequency-averaged SE for CW, dB
1	1.8	2.3
2	4.4	4.5
3	6.6	8.5
4	10.8	10.9
8	12.2	15.6

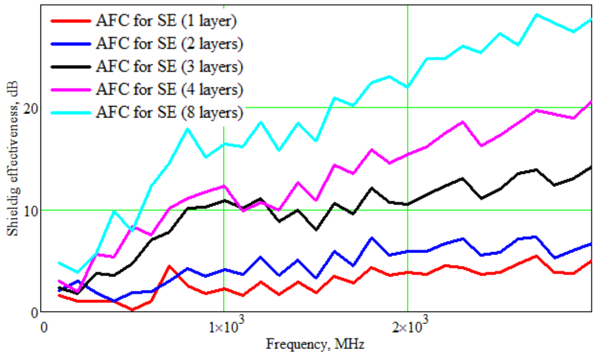


Fig. 11. AFC of electric field shielding effectiveness for dry needle-punched material with carbon filaments obtained by CW measurements.

The comparison of shielding effectiveness for UWB EMP 139/242 ps and shielding effectiveness for for the CW averaged over the effective frequency range of the pulse shows the coincidence of results with error of 0.5…3.4 dB. Note, that values (1) of SE obtained by the developed technique (ref. Section II) are less than SE values calculated by (2) for CW measurements.

C. SE of needle-punched material containing carbon fibers impregnated by conductive liquids

Table III contains the results of measurements of shielding effectiveness for UWB EMP 139/242 ps by the needle-punched material impregnated by regular water (second column) and by saturated NaCl water solution (third column).

TABLE III. UWB EMP SHIELDING EFFECTVENESS OF SUT NO. 1 (NEEDLE-PUNCHED MATERIAL) IMPREGNATED BY REGULAR WATER AND IMPREGNATED BY NACL WATER SOLUTION

Number of layers	**Peak-value reduction SE for UWB EMP, dB (regular water)**	**Peak-value reduction SE for UWB EMP, dB (NaCl water solution)**
1	10.1	12.0
2	12.7	13.5
3	15.3	15.4
4	15.5	15.5

As it seen from results presented in Table III, the shielding effectiveness of material impregnated by electrolytes is sufficiently more than SE of dry material (see Table II) especially for small number of layers. When the material is impregnated by electrolyte, the role of reflection in shielding process increases, it explains the observed result.

D. SE of foamed polyethylene with a metallized film

The AFC of shielding effectiveness obtained in framework of CW measurements in accordance with [16] for the SUT No 2 (foamed polyethylene with metallized film) is presented in Fig. 12. The SE of the SUT No 2 for UWB EMP 139/242 ps and averaged CW SE defined in accordance with (2) are presented in columns 2 and 3 of Table IV respectively.

The comparison of results (ref. Table IV) shows that values CW SE defined by formula (2) are noticeably more than the values of UWB EMP SE measured by the developed technique and calculated by (1).

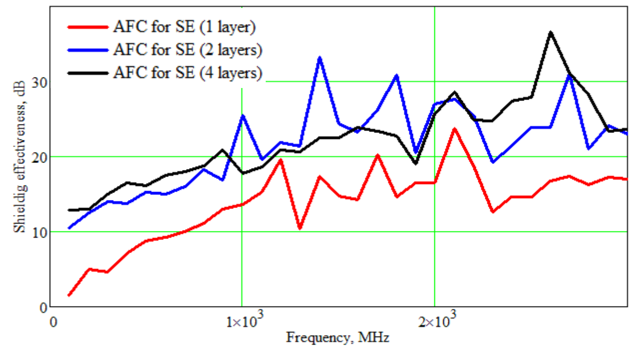


Fig. 12. AFC of electric field shielding effectiveness for foamed polyethylene with metallized film

TABLE IV. UWB EMP AND CW SHIELDING EFFECTIVENESS OF SUT NO. 2

Number of layers	**Peak-value reduction SE for UWB EMP, dB**	**Frequency-averaged SE for CW, dB**
1	9.4	13
2	10.7	20
4	12.1	21

E. Two-layer material consisting of metallized polymer film and felt fabric impregnated with $CaCl_2$ water solution

The measured SE for UWB EMP in accordance with the developed technique and averaged SE of CW measurements for SUT No3 are presented in Table V. As in the previous cases, the value of CW SE is more than SE for UWB EMP.

TABLE V. UWB EMP SHIELDING EFFECTIVENESS OF THE SUT NO. 3

Number of layers	**Peak-value reduction SE for UWB EMP, dB**	**Frequency-averaged SE for CW, dB**
1	11.9	19
2	13.9	20

F. RAM panel TORA-39

AFC of the shielding effectiveness obtained in the framework of CW measurements for TORA-39 in effective frequency range of pulse 139/242 ps is presented in Fig. 13.

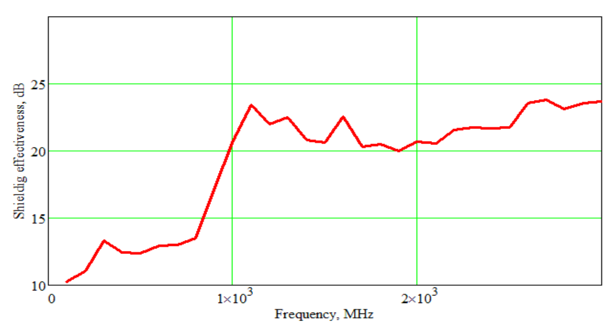


Fig. 13. AFC of electric field shielding effectiveness for TORA-39

The value of TORA-39 shielding effectiveness for UWB EMP 139/242 ps measured by the developed technique and calculated by formula (1) is 7.9 dB. The value of CW SE averaged by (2) over the effective frequency range of this EMP is 17.6 dB.

The value of averaged CW SE for TORA-39 is noticeable more than the UWB EMP SE measured by the developed technique. The shielding effectiveness of RAM panel is less than the reflectivity specified by the manufacturer in about 2 times for frequencies 0.5…3 GHz.

V. Conclusion

The developed technique of in-situ measurement of SE with respect to UWB EMP can be recommended for the express-analysis of suitability of applied protection solution. The use of high-amplitude EMPs for measuring the shielding effectiveness of protection solution is reasonable when the limit of its linearity is unknown [18]. In addition, when installing a protective solution, dielectric gaps can occur, in which a discharge can realized under the impact of high-amplitude EMP.

The SE values with respect to UWB EMP (1) obtained by the developed technique (ref. Section II) are less than frequency-averaged CW SE values calculated by (2). This correlates with the results obtained in [19] for the test object in the form of an enclosure (equipment shelf made of metal).

The values of UWB EMP shielding effectiveness (1) measured in accordance with the developed technique for all SUTs (ref. Tables II–V) are noticeably less than declared by the manufacturers for radio frequency electromagnetic fields of SHF and upper UHF bands. This is caused by the presence of relatively low-frequency components (0.10…0.50 GHz) in the UWB EMP spectrum, the shielding of which by these materials is much weaker, especially for absorbing materials.

The measured shielding effectiveness of needle-punched materials containing carbon additives (the dry material) for UWB EMP 139/242 ps is 2…12.2 dB (depending on the number of layers), SE for this material impregnated with regular water is 10.1…15.5 dB, and SE for the material impregnated with a saturated NaCl water solution is 12.0…15.5 dB. The shielding effectiveness for the considered UWB EMP is 11.9…13.9 dB for a felt fabric with a layer of metalized polymer film impregnated with $CaCl_2$ water solution, and 9.4…12.1 dB for the foamed polyethylene with metalized film. Nevertheless in spite of the relatively small values of shielding effectiveness for UWB EMP, the design advantages of the investigated needle-punched and felt materials, low specific weight and prices allow us to consider these materials as promising ones for the purpose of protecting electronic equipment from the effects of EM radiation (including UWB EMP).

By varying the thickness of the materials (the number of layers), the conductive content, and the type of the impregnating liquid, it is often possible to provide the required UWB EMP shielding effectiveness of the materials jointly with a low cost of the protection solution. The simplicity of the manufacturing process and the availability of materials allows to create not only shielding structures around the equipment cases and wire transmission lines, but also to create protected rooms and protective zones, since these materials can be used for interior wall decoration for providing a noise and thermal insulation.

The implementation of constructive and technological solutions that retain the impregnating liquids in the needle-punched and felt materials and stabilize their properties provides the UWB EMP shielding effectiveness of at least 12…15 dB which is, in many cases, sufficient to ensure the required protection (especially if the minimum possible distances to the sources of UWB EMP are rather large).

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