THE IMPACT OF IMPULSE ELECTROMAGNETIC FIELDS ON PERSONAL COMPUTER AND COMPONENTS

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The features of the test stand for studying an impact of ultra-short impulse electromagnetic fields are described. The tests results of a personal computer and its components are presented and the conditions for functional upset and failure of the studied objects are discussed.

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1. INTRODUCTION

Recent progress of pulse-power technologies relating the electromagnetic fields (EMF) of ultra-short pulse width (USP) is accompanied by increase of the level of radiation threat to electronic equipment and its components. The complexity of modern electromagnetic environment requires improving the methods and technologies of the tests on electromagnetic compatibility and resistance (EMSR) for standard radio-electronic and computer technique (RE&CT) [1], [2].

The provision and results of EMSR tests of a personal computer (PC) and components to intense EMF USP are presented. The tests were carried out using the test stand TS-6, created in the Laboratory of Relativistic Microwave Electronics of NSC KIPT NASU [3]. The TS-6 with the operating volume of $1\,\mathrm{m}^3$, ensures the EMSR tests of RE&C using the USP signals with a pulse width $\tau_P = 3...5\,\mathrm{ns}$ pulse rise-time $\tau_R = 0.25\,\mathrm{ns}$ (the frequency band of 80...1.5 GHz), and the strength of the electric component of the EMF $10...10^3\,\mathrm{V/cm}$.

The study included numerical simulation of the EMF USP dynamics in the operating area of the stand and their distribution in typical areas of the studied objects, as well as live tests of PC and its components.

2. TEST STAND AND TESTS

2.1. DESCRIPTION OF TEST STAND

The test stand TS-6 consists of a transmission strip line (length 3 m, impedance $\sim 80\,\mathrm{Ohm}$) which is asymmetric in the cross-section and non-uniform along its length, and the high-voltage generator (HVG) of USP, Fig.1. The test objects (TO) disposition is possible in the operating area consisting of two parts, Fig.2:

- *Area 1* (main), the so-called, TEM-cell – is the area of TEM wave spread ($L\times H\times W = 1.1\times 0.7\times 1.0\,\mathrm{m}^3$);
- *Area 2* (additional) located near the cell ($L\times H\times W = 1.8\times 0.7\times 0.7\,\mathrm{m}^3$).

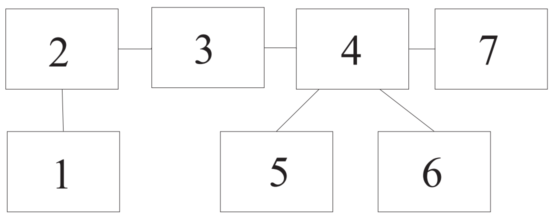

Fig.1. *Structural diagram of TS-6. 1 – control unit; 2 – HV impulse former; 3 – transmission line; 4 – test TEM cell; 5 – shielded room with measuring equipment; 6 – shielded hardware box; 7 – matched load (~ 80 Ohm)*

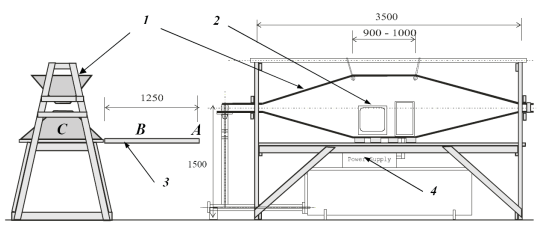

Fig.2. *SLayout of the TS-6 operating areas (axial and side views). 1 – stripline (main test area); 2 – test object; 3 – additional test area; 4 – shielded box. Points A, B, and C indicate the locations of test object: A – 2.15 m aside of the longitudinal axis of TEM cell; B – 1.15 m aside of the TEM-sell longitudinal axis; C – in the center and at the longitudinal axis of the TEM-sell*

The use of two operating areas allows testing the

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objects at extended range of the amount of coupling E-field. The test areas are equipped with the monitors for registration the signal envelopes and the E-field amplitudes. The Area 2 of the stand provides the OT disposition at a conducting or dielectric surface. For these two cases, the structure of the electromagnetic field away from the TEM cell (points A and B) differs. In the first case, the structure of the EMF is close to the structure of the wave in TEM cell. In the second case, an increased contribution of the radiative component is presented. The measurements indicate that in both cases the amplitudes of E-field component away from the strip line (points A and B) are approximately (within 15%) equal, Fig. 3.

The points **A**, **B**, and **C** in the operating areas (see Fig.3) are selected so to provide a wide range of the E-field intensities without multiple changes of the HVG parameters. As a result, the desired range of the E-field amplitudes E=1...160 kV/m is achieved by using only two HVGs with the maximum output voltage of 15 kV and 120 kV, Table 1. Registration of characteristics of the EMF USP and response signals of the TO to the EMF impact is produced in real-time mode with the use of several information channels. The electric field distribution in the test areas (see Fig.3) is determined using calibrated capacitive voltage dividers with the integrators. A simple whip antenna connected to the semiconductor detector is used as an arbitrary-value E-field monitor inside the TO.

The information signals from the probes in operation areas and response signals of the OT to the EMF USP impact are transmitted using the electrical and optical signal lines with a frequency bandwidth, respectively, of 0.3...2 GHz, and 10...500 MHz, and are recorded by means of multi-channel digital oscilloscopes Tektronix 2024 (bandwidth 200 MHz) and Agilent 54845A (bandwidth 2.25 GHz).

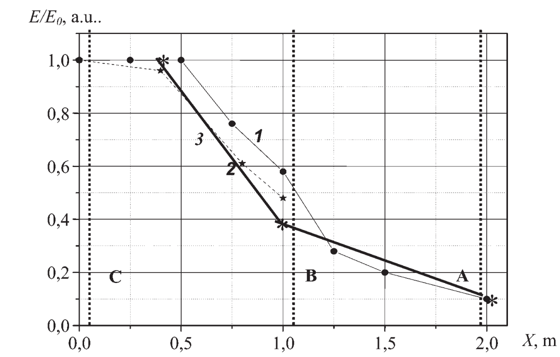


Fig.3. *Distribution of the E-component of TEM wave in transversal cross-section of the test area of TS-6: 1 – experiment; 2 and 3 – calculation for metal and dielectric platforms, relatively. Vertical dotted lines and points **A**, **B**, and **C** correspond to the TO positions in Fig. 2*

Electromagnetic protection of the TO is produced by placing the auxiliary equipment and the elements that should not be irradiated into a metal shielded box (SB). The SB is equipped by optical signal lines and standard autonomous power supply unit ARS-500. In the process of the tests the PC components can be removed from the SB and placed in the operating area of the TS-6. An independent shielding of the TO and connecting cables uses additional screens made of elastic carbon fabric.

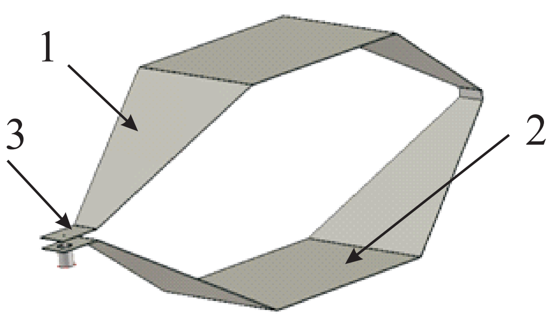


Fig.4. *Structure of the TS-6 test area. 1 and 2 – upper and lower electrodes of the transmission strip line; 3 – the coaxial feeder of the HVG output*

Table 1. *Characteristics of the stand TS-6 and test conditions*

Operating area		TEM strip line
Pulse width, τ_P, ns		3...4
Pulse rise time, τ_R, ns		0.25...0.4
Field strength $E(z)$, kV/m	$U_0 \leq 15$kV	Point A - 1
		Point B - 3
		Point C - 10
	$U_0 \leq 120$kV	Point A - 1
		Point B - 3
		Point C - 10
Operating mode		Single pulses Repeating pulses: 1, 10 and 50 Hz

2.2. TEST OBJECTS

The TOs to be exposed at the stand TS-6 to different levels of EMF USP are a personal computer (PC) and components. The studied PC has several test configurations:

Configuration 1. The PC full kit:

- system block of PC with the processors Intel Pentium or AMD K5 (2000-2005),
- 14” SVGA monitor,
- 101- keyboard,
- mouse.

Configuration 2. The PC in standard configuration with mock-up of a communication net – a 3 m length ”twisted pair” cable with a 10 kOhm load matched to COM1 interface (contacts 3...7).

Configuration 3. Separate units and components of the PC (system block, keyboard, mouse, monitor, and PC power supply unit) exposed individually to radiation during the PC operation.

During the tests, the susceptibility levels of the TO impacted by EMF USP are registered. The test technology assumes the following procedures:

- Preliminary estimating the general electrotechnical characteristics and productivity.
- EMCR tests of PC and components, and obtaining data on functional upset and failure.
- Final estimating the general electrotechnical characteristics and productivity.

3. SIMULATING THE EMF USP IMPACT ON THE PC MOCK-UP

3.1. TRANSMISSION OF THE EMF USP IN THE OPERATING AREA OF TS-6

The dynamics of the EMF USP distribution in the operating area of the TS-6, which contains the TO, is completed numerically by the FDTD and integral equation methods using CST Microwave Studio software [4]. The con-figuration of the modeled part of TS-6 includes: coaxial feeder of the HVG and units of the strip line, that direct TEM wave (Fig.4). The internal electrode of the coaxial feeder is short-circuited to the upper electrode of the strip line; and the outer electrode – to the bottom electrode of the strip line. The main characteristics of the stand mock-up are shown in Table 2.

Table 2. *The characteristics of the TS-6 mock-up*

TS-6 unit	Characteristics	Qualifier
Coaxial feeder	internal (outer) electrode diameters	0.018 m (0.064 m)
Widening (constricting) part of strip line	length	1.0 m
	angle in horizontal (vertical) surface	40° (33°)
	impedance	80 Ohm
Uniform area of strip line	length	1.0 m
	height	0.8 m
	width of upper (lower) electrode	0.8 m (1 m)
Electrical characteristics of TEM sell	line(load) impedance	80 Ohm
	TEM wave (test area) E_{MMAX}	1 V/m
	pulse width(HWHM)	4 ns
	pulse rise time	0.26 ns

Fig.5 shows the source voltage impulse, and Fig.6 demonstrates the distribution of E-field of TEM wave at characteristic points of the strip line at different moments in time. Since τ_P(HWHM)≈ 4 ns, and the traveling time of TEM wave along the stand is of 10 ns, it is obvious that the EMF impulse is almost completely located in the homogeneous part of the strip line. The amplitude of the wave E-field in every position of the stand is determined by the geometry of the transmission line and definite time of the USP that goes through this position. The stand discontinuities can significantly affect the impulse waveform increasing its risetime, as well as the signal width (compare the pulse dynamics in Fig.6). The simulation shows that the increase of the TEM wave rise time τ_R occurs most significantly in the area of the strip line where the line electrodes are most vertically separated.

At the amplitude of the initial impulse of 1 V, and the distance between the line electrodes of 0.7 m the maximum value of EY component of the TEM wave corresponds to the center of the line homogeneous area (point **C**, Fig.2) and reaches 1.5 V/m. At a distance of 1.0 m aside the strip line axis (point **B**, Fig.2) the field decreases twice. Gradual decrease of the E-field amplitude outside the strip line allows using these points as an additional operating area. This approach is the most effective in the case of tests of large-size TOs, and is widely used in our EMCR experiments with electronic equipment and components.

3.2. THE PC TESTS IN THE TEM CELL

The test object of the numerical experiment is a mock-up of the PC system unit disposed on the dielectric plate be-tween the strip line electrodes of the stand TS-6. The TEM wave with the vertical polarization of E-field ($E = E_Y = 1$ V/m) travels down the strip line and couples to the TO. Fig.7,a,b shows the scheme of the experiment on irradiation of the PC mock-up. The arrow and plane indicate, respectively, the direction and plane of the TEM wave. The E-field components are studied at the points outside and inside the PC system unit (see Fig.7,b and Table 3).

Inside the strip line at the test points externally to the PC unit a single USP signal, whose structure is almost un-changed (comparatively to the original signal) is observed. The changes in the E-field amplitude are most significant only in the areas close to a metal box of TO, particularly outside its back wall - in the "shadow" of TEM wave (see Fig.7,b). The above-described effect of increasing the rise time and pulse width depending on the distance from the input point (see Fig.6) is observed. Because of this, the spectral components of the UWB signal with a wavelength shorter than the distance between the electrodes may be partially emitted outside via the side surface of the line. In our case, the height of the stand (70 cm) corresponds to the critical waveguide mode of the strip line with a frequency of $f_C \approx 410$ MHz. Thus, as the USP signal propagates along the strip line its original frequency range (Fig.8) is depleted due to gradual withdrawal of high frequency components with $f > f_C$ (Fig.9).

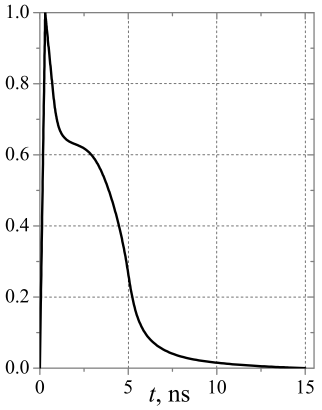


Fig.5. *Initial signal USP at the TEM sell input*

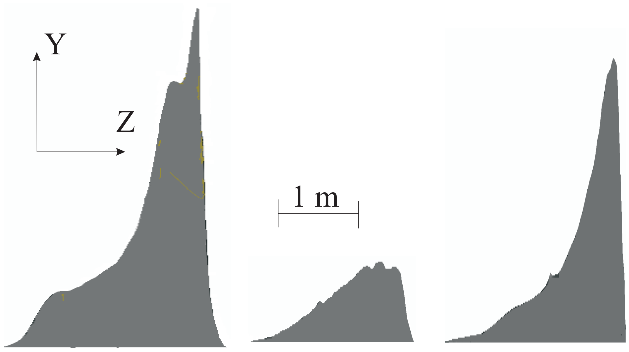


Fig.6. *E_Y component of TEM wave traveling along the Z axis of the strip line at several times*

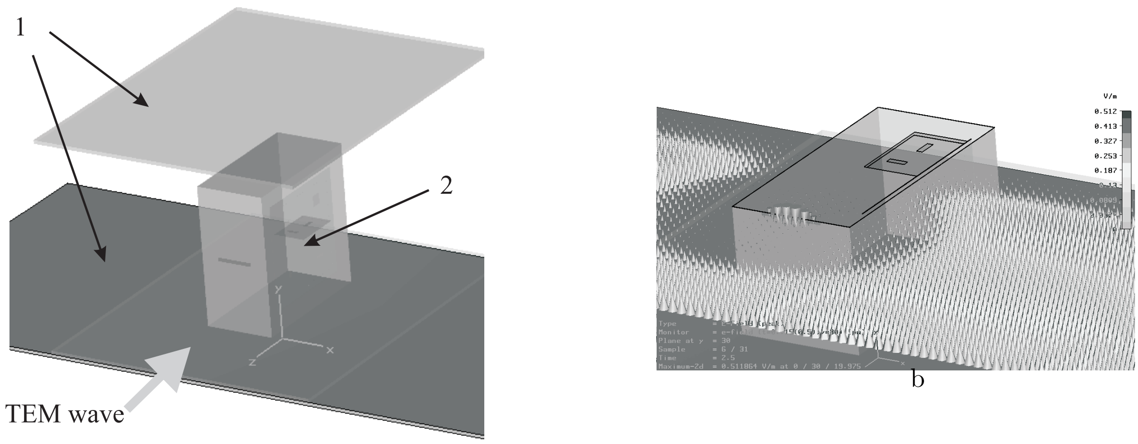


Fig.7. *TEM wave couples to the PS system unit. a) Configuration of the main elements of the model: 1 – strip line electrodes; 2 – testing PS unit; E-field vector of the TEM wave is directed vertically. b) E-field distribution at t=2.5 ns; cross section in horizontal plate at the level of the slot of the front wall of PC system unit*

Table 3. *Characteristics of the TEM wave source and tested object*

the size of the electrodes area of the strip line (upper/lower) ($W \times L$)	$0.7 \times 1.0\,\text{m}/2.0 \times 1.0\,\text{m}$
the size of the dielectric plate for the PC system unit ($W \times L$)	$0.7 \times 1.0\,\text{m}$
the size of the PC system unit ($W \times H \times L$)	$0.2 \times 0.4 \times 0.4\,\text{m}$
the size of the slot of the PC system unit	$0.1 \times 0.01\,\text{m}$
the size of the motherboard ($W \times L$)	$0.3 \times 0.3\,\text{m}$, $\Delta = 1\,\text{mm}$
the motherboard material (dielectric with losses)	$\varepsilon = 5.0$, $\text{tg}\delta = 0.03$
the pulse width (HWHM)	4 ns
the pulse rise time	0.25 ns

At the internal points of the PC system unit the oscillations at characteristic frequencies, which may be determined by the dimensions of the PC case, are observed. The effectiveness of the E-field excitation inside the PC system unit with a slot is defined by the slot orientation relative to the polarization of the incident wave. For a horizontal slot the vertically polarized E-field excites inside the PC case the most intense oscillations. This is well illustrated by the difference in the intensity of the excited E_Y and E_X component of the USP signal, Fig.10.

The E-field oscillations inside the PC case has the following features:

– there are considerably strong changes in the structure of the USP signal compared to the original; the lifetime of the oscillations are ten times excides the time of the impact impulse and hundreds - of its rise time;

– the spectrum of UWB fluctuations inside the case has specific lines - as opposed to a continuous initial (compare Figs.8 and 9) with a dominant frequency of 1.35 GHz and the strong satellites, spaced at 200...300 MHz; the interference of these oscillations can cause a complex envelope of the observed signal (the period of the interference is of 4...6 ns);

– the shielding effect of the metal case results in a substantial reduction of the E-field components in comparison with their initial amplitudes – for the E_X component up to 75 times, and for the E_Y component up to 500 times;

– due to the presence of absorbing elements in the PC case (motherboard and video card) there is the difference in the ratio between the E-field components in the center of the case $E_Y/E_X \approx 10$, and near the sides of the case, next to these elements $E_Y/E_X \approx 2$;

– there is noticeably large difference in the time of buildup of these oscillations: 10 times larger for E_X component than for E_Y-component.

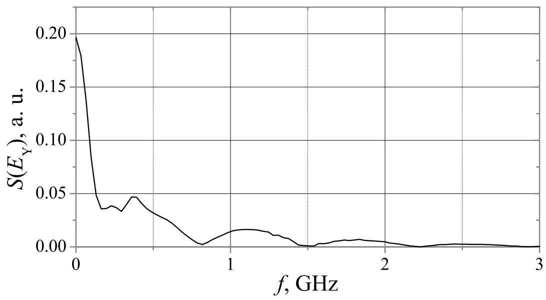


Fig.8. *The spectrum of the initial USP signal at 0.4 m in front of the slot of the PC system unit*

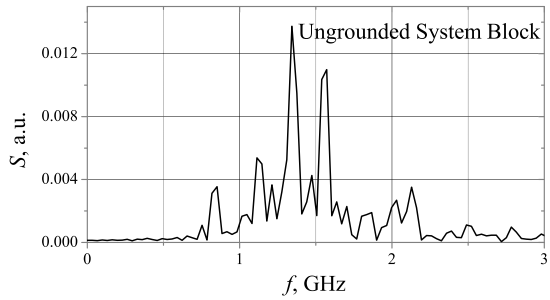


Fig.9. *The spectrum of the USP signal in the center of the PC system unit*

E_X E_Y

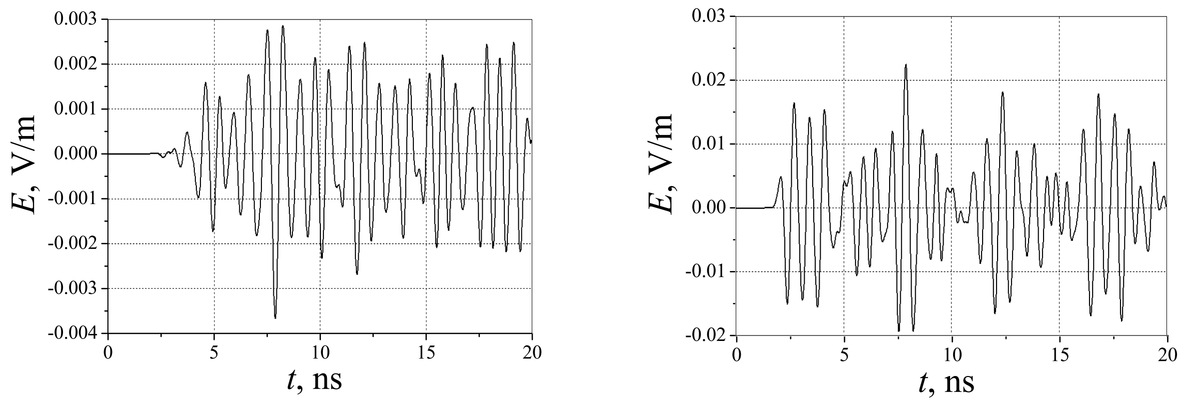


Fig.10. *E-field components in a separate characteristic point inside the PC case*

4. LIVE TEST RESULTS OF THE PC AND COMPONENTS

4.1. FEATURS OF THE TEST OBJECT REACTION

On the base of results of EMCR tests of the PC and components the following general outcomes can be made:

1. *The data of the live tests*, which were fulfilled in one-shot and repetition-shot modes with repetition frequency F up to 50 Hz and E-field amplitudes 1...100 kV/m, indicate very high sensitivity of the objects of digital technique to the USP factor. These effects can be seen in the form of functional upsets and partial or complete failures of the most vulnerable components. The critical levels of these effects are in good accordance with the known EM resistance of modern semiconductor high integration component base. Typical response signals of the PC and components to the EMF USP exposure are shown in Fig.11.

2. *Functional upsets of the PC system unit and components.* For all test conditions, beginning from the E-field amplitudes of 1...3 kV/m the reaction of the system unit was recorded. The pulsed EMF USP impact on any of the items or the whole set of the PC resulted in characteristic interferences in the ISA and COM1 buses as well as on the power bus +5 V. The result of every upset produced self-rebooting of the PC. In some cases there was a "hang-up" of the PC, requiring a reboot. The nature of the interferences was strongly depended on the element to be tested, on the PC configuration, on the position of the cables in the operating area and their shielding. The nature and the amplitude of response signals correlated with the intensity of the EMF USP.

3. *The duration of the PC functional upset* that was logged during the test of any of the component of the PC considerably exceeded the width of the USP. For example, this ratio for the PCI clock bus always exceeded 10.

4. *The amplitude of the PC response* to the impact of the EMF USP reached maximum value after 75...150 ns after the start of the signal-response.

5. *The most sensitive components* of the PC are the keyboard, mouse, and system unit.

6. *The runtime of the BIOS standard boot program* measured after tests (even in cases where functional upset of the PC or partial degradation of its components took place) remained the same (22 s).

7. *The threshold E-field* (Table 4), which correspond to a functional upset of the PC (E_{CRU}), and to a complete failure of the PC components (E_{CRF}) were determined.

At the same time, the tests showed that the degradation of the PC components was in direct correlation with the exceedance of the critical values of E-field. This was evident from random degradations of the TO after 10...25 tests even when the field amplitude was much below the observed critical level.

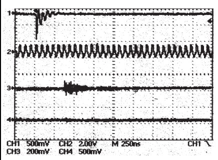
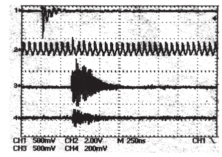
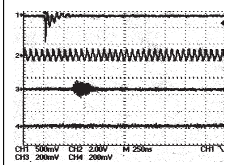
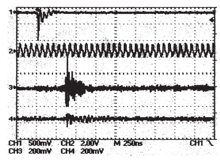
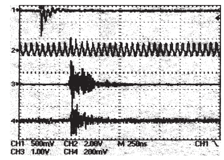
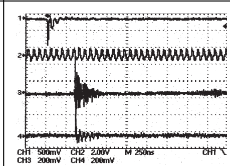
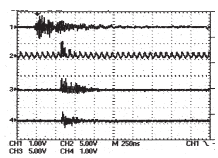
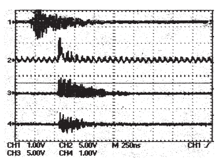
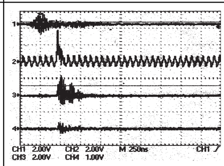
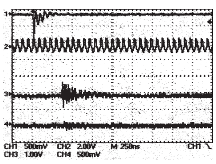
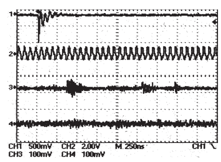
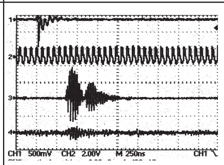
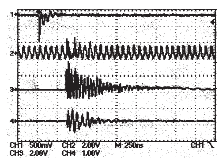
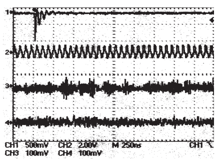
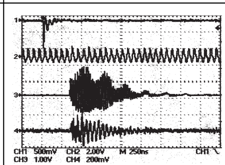
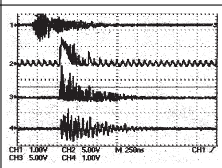
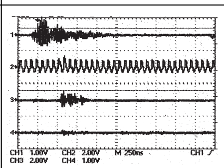
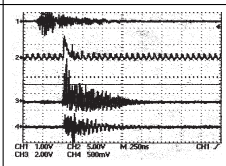
TO	E, kV/m	Response signals	TO	E, kV/m	Response signals	TO	E kV/m	Response signals
	1.4			1.4			1.4	
Key bo- ard	14		Net mock-up	14		PC sys- tem unit	14	
	142			142			142	
	1.4			1.4			1.4	
Mouse	14		Moni- tor	14		PC kit	14	
	142			142			142	

Fig.11. *Plots of the PC components response to the single-shot EMF USP, registered at various PC buses: osc. 1 – the mark of impact impulse; osc. 2 – ISA bus, clock signal; osc. 3 – COM1-port, contacts 2 – 5; osc. 4 – power supply unit, bus +5 V*

Table 4. *The E-field threshold levels corresponding the TO upset and failure for various impact regimes. The duration of the repetition impact regime is 1 s*

TO	TO component	Functional upset, E_{CRU}, kV/m		Failure, E_{CRF}, kV/m	
		single-shot mode	repetition mode, 10 Hz	single-shot mode	repetition mode, 10 Hz
1. PC components (PC full kit)	Key-board	1...3	1...3	30	1...3
	Mouse	3...10	1...10	30...40	1
	System unit	3...5	3	90...100	30
	Monitor	10	10	≈ 100	10
2. PC with net mock-up	Net mock-up	3...10*	1...10*	30*	10*
3. PC (full kit)	PC full kit	1...3**, 10***	1...3	3	1...3
4. PC power supply	Power supply	30	30	≥ 100	≥ 100

*– relating the proximity to the screen; **– cables are at the metal table; ***– cables are 10 cm above the metal table.

4.2. CHARACTERISTICS OF RESPONSE SIGNALS OF THE PC AND COMPONENTS

The disturbance at the PC buses at low levels of EMFs.

(a) The response of various PC buses to the USP impact was different, especially at low-level of the USP signal. It began to occur already at $E > 1$ kV/m. The duration of the response $T_R \geq 0.05$ μs ($> 10\tau_P$).

(b) The PC response feature at low levels of the USP signal were always regular or chaotic damped oscillations. The functional upsets features.

The functional upsets features.

(a) The PC functional upsets were accompanied, as a rule, by response at the PC buses with increased duration compared with τ_P. Usually, if $E \geq 10$ kV/m $T_R \approx 0.6$ μs ($> 100\tau_P$).

(b) The feature of the response were always chaotic (or regular passing into chaotic) oscillations at relatively low frequencies (approx. 5...15 MHz).

(c) The increase of the USP amplitude ($E > 10$ kV/m) resulted in the appearance of low frequency relaxations (with $F < 3...5$ MHz). As they covered several cycles of the clock signal, the PC synchronization was usually lost, and a result of the exposure was the upset with the hung-up PC. This dynamics of the response is typical for a complex digital unit, when the excessive level of the external signal excites nonlinear effects.

(d) The most sensitive components of the PC leading to upsets were: keyboard, mouse, and system unit, Table. 4.

The failure features.

(a) The highest probability of the failure showed the same PC components (keyboard, mouse, system unit), which were most sensitive to the upset, Table. 4.

(b) The failure in the single-shot mode occurred with the highest probability when the E-field amplitude exceeded almost in order the level of E_{CRU}. For example, for the PC system unit $E_{CRF} \approx 90...100$ kV/m.

(c) The PC failure taken place in the mode of repeated shots occurred when the amplitude of the E-field was 3...4 times less than for single shots. For example, for the PC system unit $E_{CRF} \sim 30$ kV/m.

4.3. THE EMF USP TEST RESULTS

The PC and components tests to the EMF USP impact were featured by high probability of functional upsets and failures. It can be highlighted several reasons for such high efficiency of this factor. Firstly, this is due to *the feature of the impulse EMF USP – its ultra-wide frequency range* (from MHz to a few GHz). This feature creates the possibility for exciting a large number of dimensional resonances in an electric circuit of the TO characterized by a set of the spatial scales proportional to $1/4\lambda$. Considering the real size of tested objects and cables, it can be argued that the maximum spectral density of the EMFs is located within an wide spatial resonance region – from several centimeters to several meters. Obviously, in our case, the most vulnerable objects are the units with cables: key-board, mouse, network, circuit, and system box.

The second important factor that influence to processes in the tested electronic devices is associated with the *conditions of electromagnetic shielding*. Therefore, effective shielding for the EMF USP is hard enough to provide for the objects with complicated structure, which have no covering screen or have long slots in the screen housing (for example, the PC system unit). The objects with developed infrastructure with connecting cables are also a potential "victims" of the EMF USP. An experimental verification of this effect, when the connecting cables were shielded, showed that the response amplitudes of the PC circuits was reduced tenfold.

Another significant factor for the EMF USP interaction with the objects having complex structure is the *polarization of the radiation.* At a certain polarization, the favorable conditions for EMF penetration inside shielded enclosures with gaps can be created.

The result is high sensitivity of the object to spatial orientation in the area of its irradiation.

It is important to note the features one of the most important coupling EMF USP – *the full-energy of the impulse.* Obviously, the short duration of the pulse limits both the pulse energy and the energy that can be transferred to the object as a result of interaction. However, the same small time scale prevents the heat from absorption the EMF energy in the surrounding region, realizing the adiabatic regime of interaction. The inducing micro-scale local thermal effects are able to produce temporary functional upset or irreversible failure in a microstructure of the most sensitive elements of the objects [5]. In the case of nanosecond exposures, the efficiency of degradation phenomena increases significantly compared with long-pulse irradiation, when the heat exchange with the environment is realized.

At the same time, the PC tests demonstrate that the degradation of its components does not define only by exceeding the critical value of the absorbed energy sufficient to defeat the TO with a single pulse. Apparently, the accumulation of irreversible changes in the microstructures of the object in condition of a large number of the USP exposures is significant [6]. In our case, the manifestation of an additive effect is demonstrated by the TO failure as the result of 10...25 exposures when the EMF USP amplitudes were substantially lower the degradation threshold, $E << E_{CRF}$. This reduction of the degradation threshold indicates an extreme danger for to the objects of modern electronics and digital technique exposed to the EMF USP with large repetition rate.

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ВОЗДЕЙСТВИЕ ИМПУЛЬСНЫХ ЭЛЕКТРОМАГНИТНЫХ ПОЛЕЙ НА ПЕРСОНАЛЬНЫЙ КОМПЬЮТЕР И ЕГО КОМПОНЕНТЫ

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Описываются особенности испытательного стенда для исследования действия импульсных электромагнитных полей сверхкороткой длительности. Приводятся результаты тестов персонального компьютера и его компонентов, и обсуждаются условия функциональных сбоев и выхода из строя исследуемых объектов.

ДІЯ ІМПУЛЬСНИХ ЕЛЕКТРОМАГНІТНИХ ПОЛІВ НА ПЕРСОНАЛЬНИЙ КОМП'ЮТЕР ТА ЙОГО КОМПОНЕНТИ

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Описуються особливості випробного стенда для дослідження дії імпульсних електромагнітних полів замалої тривалості. Приводяться результати тестів персонального комп'ютера і його компонентів, та обговорюються умови функціональних збоїв і виходу зі строю об'єктів, що досліджуються.