Measurement of Microcontroller Radiated Emissions at Different Operation Modes

Alexander V. Demakov
Department of Television and Control
Tomsk State University of Control Systems and Radioelectronics, TUSUR
Tomsk, Russia

Artem V. Osintsev
Department of Television and Control
Tomsk State University of Control Systems and Radioelectronics, TUSUR
Tomsk, Russia

Valerij A. Semenjuk
Department of Television and Control
Tomsk State University of Control Systems and Radioelectronics, TUSUR
Tomsk, Russia

Maxim E. Komnatnov
Department of Television and Control
Tomsk State University of Control Systems and Radioelectronics, TUSUR
Tomsk, Russia

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***Abstract*— The paper presents the results of the investigation of the radiated emissions from microcontroller (MC) 1986BE91T with its different software configurations in a TEM cell. Radiated emissions were measured multiplying the clock frequency of the microcontroller using the high speed internal and external oscillator clocks, as well as when the arithmetic-logic unit, analog-to-digital and digital-to-analog converters units are functioning. It was revealed that emissions from the considered MC units are concentrated at frequencies up to 20 MHz and do not exceed 25 dBμV, and an increase in the clock frequency from 8 to 80 MHz leads to an increase in the maximum emission value from 11 to 29 dBμV at the fundamental and higher harmonics of the clock frequency.**

***Keywords*— electromagnetic compatibility, electromagnetic radiative interference, digital integrated circuits, microwave propagation**

I. Introduction

The trends in the development of a modern electronic component base (ECB) used in the design of various radioelectronic equipment are aimed to reducing energy consumption, increasing integrated-circuit density and operation speed. This is facilitated by an increase in operating frequencies, a decrease in the levels of supply voltages, as well as the transition to submicron production technologies [1], which in turn leads to an increase in the ECB susceptibility to external electromagnetic effects [2]. Semiconductor integrated circuits (IC) are the most sensitive to electromagnetic interference. In this regard, tests of IC for compliance with the norms of radiated emissions are carried out using standardized methods [3, 4]. It is known [5] that the maximum current amplitude is induced in the conductors of resonant structures with dimensions that are close to half the wavelength and when the orientation of the structure coincides with the direction of the polarization vector of the radiation field. In this case, the signal frequencies of modern ICs can reach the values of 5–6 GHz, which leads to an increase in the consumption current and an increase in the radiated emission in the high and ultrahigh frequency ranges [6]. It is known [7] that the use of surface-mounted IC packages (for example, BGA) allows reducing the level of radiated emissions due to the short length of the package wire leads. It is shown [8] that the use of radio-absorbing materials in the composition of the IC package allows one to reduce the emission level by dissipating the energy of an electromagnetic wave into heat. Also, well-known are methods for reducing emissions, which are based on placing a decoupling capacitor on top of each power bus and using current sensors inside the IC package to measure internal electromagnetic interference [9].

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Evaluation of sources of radiated emissions from ICs is a difficult task because both the functioning of its blocks and current-carrying printed conductors of various lengths contribute to the resulting emission, as well as various peripheral equipment placed on printed circuit boards (PCBs) with ICs. The amplitudes and frequencies of the emissions can also vary depending on the geometric and electrophysical parameters of the IC package and its operating modes. The combination of the results of TEM cell measurements and the surface scanning method [10], as well as the use of mathematical models based on equivalent dipole moments [11], makes it possible to more accurately determine the sources of IC emission. At the same time, the dependence of the radiated emissions of the IC on the supply voltages and operating modes of the internal units has not been sufficiently studied. However, this is an urgent task for ensuring the electromagnetic compatibility of modern radioelectronic equipment.

The aim of this work is to study the radiated emissions of MC 1986BE91T with its various software configurations at different clock frequencies using a TEM cell.

II. Description of the Test Set Up

The TEM cell [3] is a device in the form of a shielded transmission line consisting of a regular and two pyramidal parts, inside which there is a central conductor in the form of a plate connected to microwave connectors. Measurements of the radiated emissions are carried out by placing the MC under test on a measuring PCB with a size of 100×100 mm^2 located in the aperture of the TEM cell (Fig. 1). Microwave connectors are connected to the matched load (ML) and the test receiver (TR). After the external power supply of the measuring PCB is turned on and the correctness of MC operation is checked, the TR measures the voltage at the

TEM cell input, which is formed by induced currents from the MC to the central conductor of the cell. The results of the measurements carried out in the TEM cell and on the open area test sites can be compared by recalculating the frequency dependences of the voltage measured in the TEM cell into electric and magnetic dipole moments according to [3].

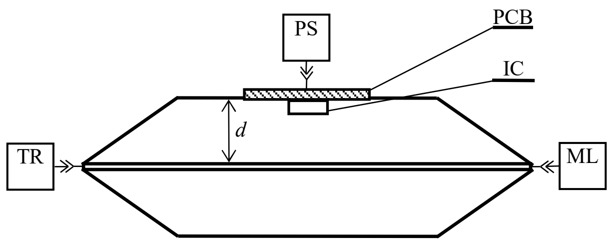

Fig. 1. Schematic diagram of a set up for testing ICs for radiated emissions in a TEM cell

The test set up for measuring the radiated emission is assembled using a small-sized TEM cell characterized by the upper cutoff frequency of 5.2 GHz, the value of the reflection coefficient magnitude $|S_{11}|$ of less than minus 17 dB and the distance between the central plate and the base of the cell enclosure d=15 mm [12, 13] (Fig. 2). A Rohde&Schwarz ESPR 7 test receiver was used to measure the voltage at the TEM cell output.

Fig. 2. Setup for testing radiated emissions of ICs in a TEM cell

III. RADIATED EMISSION MEASUREMENTS

The measurement of the voltage amplitudes at the TEM cell output was carried out in the frequency range from 150 kHz to 1 GHz with a step of 9 kHz using the detector in the mode of holding the maximum value. The analysis of the measurement results is given in the frequency ranges in which the emissions from the investigated MC blocks are clearly observed.

A. Multiplying the MC Clock Frequency Using High Speed Internal Oscillator Clock

The measurement of voltage U at the TR input was carried out with a sequential multiplication of high speed internal oscillator clock (HSI) frequency of 8 MHz through the phase-locked loop (PLL). Figs. 3*a*,*b* show the frequency dependences of U for the MC clock frequency f_c=8, 16, 40 and 80 MHz.

From the obtained results (Fig. 3), it can be seen that without frequency multiplication (PLL=1), emission is observed with a maximum level of 11.9 dBμV at f_c=8 MHz, as well as at higher order harmonics of 16 and 24 MHz with the amplitudes of 9 and 8 dBμV, respectively (Fig. 3*a*).

Doubling the clock frequency (PLL=2) produces emissions at higher harmonics of f_c at 15–20 dBμV up to 24th harmonic of 384 MHz (Fig. 3*b*). With a further increase in the frequency multiplier, an increase in the emission level at the frequencies of higher-order harmonics is observed. Thus, the maximum emission value at PLL=5 was 23.5 dBμV, and at PLL=10 it was 29 dBμV, at a frequency of 240 MHz. This corresponds to the 6th and 3rd harmonics of f_c, respectively (Fig. 3*b*).

B. Multiplying the MC Clock Frequency Using High Speed External Oscillator Clock

Similarly, emission measurements were performed by multiplying high speed external oscillator clock (HSE) frequency of 16 MHz for f_c=16, 48 and 80 MHz. Fig. 3*c* shows that the emissions at the frequencies f_c in the range up to 100 MHz coincide in thier level with the values measured using HSI. However, the maximum emission amplitude is clearly expressed at a frequency of 16 MHz for all considered clock frequencies of the MC caused by the HSE operation. Fig. 3*d* shows that the use of the HSE for MC clocking leads to an increase in the emission level at higher harmonic frequencies at frequencies above 100 MHz. For example, for PLL=5/2, the maximum emission level at 240 MHz was 33 dBμV, which is 4 dBμV higher than the value measured when using a generator with HSI. Also, for all values of the PLL multiplier, emissions are observed in the frequency range of 450-700 MHz with values of 10-17 dBμV, which are absent in similar measurements with the HSI. Thus, an increase in the PLL value leads to a sequential increase in the emission level at clock frequencies f_c and its multiple harmonics. In this regard, it is advisable to carry out further analysis of the emission during the operation of MC units at the minimum and maximum clock frequency.

C. Arithmetic-Logic Unit Operation

The radiated emissions generated during the operation of the arithmetic-logic unit (ALU) were measured using two developed test tasks. The first test task was implemented using basic arithmetic operations on an integer array with 1000 elements, filled with random values. The second test task calculates the Fibonacci numbers from 1 to 20 inclusive, followed by writing the result of the calculation to the MC memory.

It can be seen that when the MC is clocked from the HSI at f_c=8 MHz and the ALU unit is operating, an increase in emission is observed in the frequency range of 0.5–4 MHz with a maximum level of 18 dBμV when both test tasks are performed (Fig. 4*a*). A similar emission increase in the frequency range of 0.5-4 MHz is observed when using HSE; however, at higher harmonic frequencies, the emission levels are 2–3 dBμV higher than when measured without ALU unit (Fig. 4*b*). When f_c increases to 80 MHz and the MC is clocked from the HSI, there is an expansion of the emission spectrum up to 20 MHz caused by the operation of the ALU unit. In addition, there is an increase in voltage amplitudes up to 24 dBμV at a frequency of 10.1 MHz for the first test task, and up to 20 dBμV at a frequency of 9.3 MHz for the second one (Fig. 4*c*). The emissions from the ALU unit when using HSE at f_c=80 MHz have a similar type of dependences, but the maximum value of the measured voltage does not exceed 20 dBμV (Fig. 4*d*).

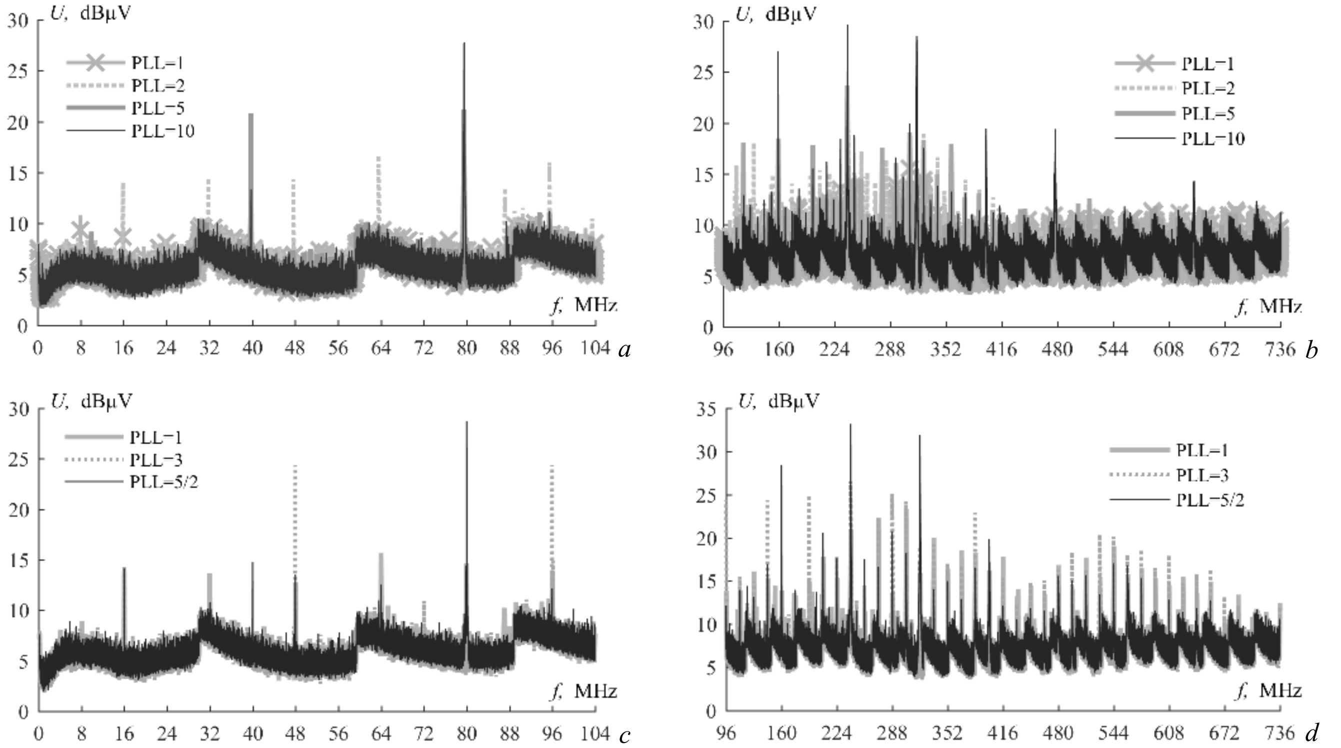

Fig. 3. Frequency dependences of voltages U measured with increasing f_c and clocking the MC from the HSI (*a*, *b*) and HSE (*c*, *d*) in the ranges of 150 kHz–104 MHz (*a*, *c*) and 96–736 MHz (*b*, *d*)

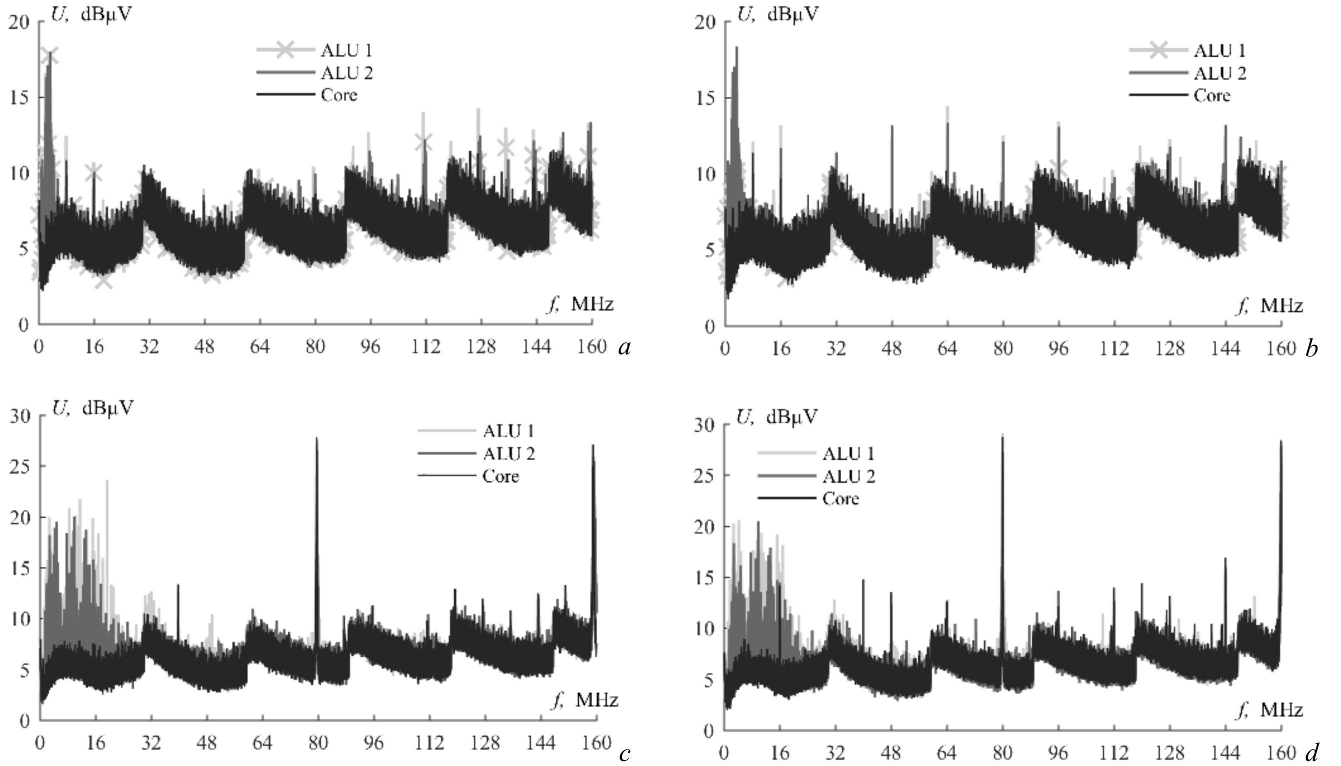

Fig. 4. Comparison of the voltages U measured during the execution of the ALU test tasks (1-2) and the operation of the MC core when clocked at f_c=8 MHz (*a*, *b*) and f_c=80 MHz (*c*, *d*) from the HSI (*a*, *c*) and HSE (*b*, *d*)

D. Analog-to-Digital Converter Unit Operation

The MC under investigation contains two analog-to-digital converters (ADC) with a capacity of 12 bits, supporting operation with 16 external channels. The test program was developed to configure the operation of one ADC for serial conversion of 2 internal channels (reference voltage and temperature sensor) and 1 external channel. The voltage with an amplitude of 3.3 V is applied to its input and the conversion result is subsequently saved in the MC memory.

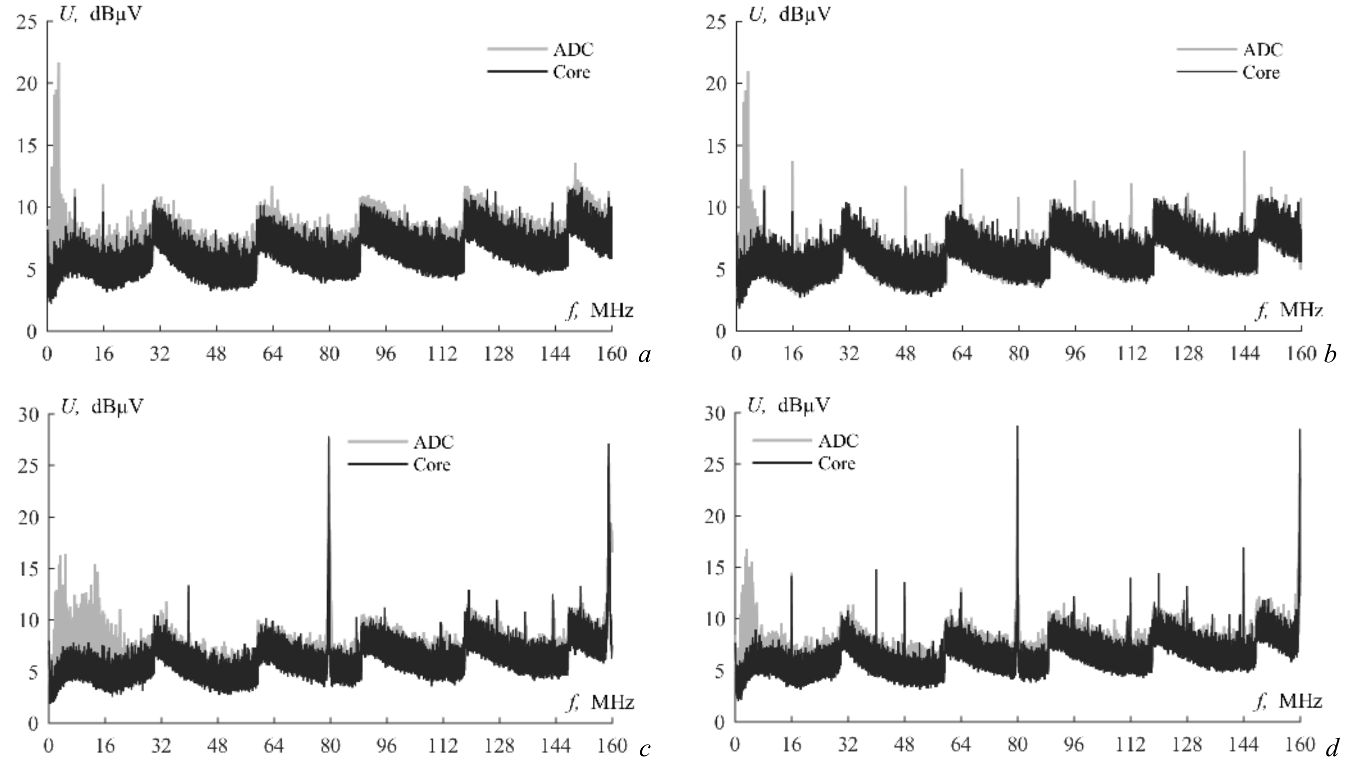

Fig. 5. Comparison of the voltages U measured during the operation of ADC unit and the MC core when clocked at f_c=8 MHz (*a*, *b*) and f_c=80 MHz (*c*, *d*) from the HSI (*a*, *c*) and HSE (*b*, *d*)

Fig. 5*a* and Fig.5*b* show that when using both an internal and an external oscillator and at f_c=8 MHz, the emissions from the ADC unit are equal in the range of 0.5–4 MHz with a maximum level of 22 dBμV near the frequency of 3.6 MHz. However, the use of HSE leads to an increase in the emission at higher harmonic frequencies by 3–4 dBμV in comparison with the levels measured when only the MC core is operating (Fig. 5*b*). When the clock frequency is increased to 80 MHz (Figs. 5*c*,*d*), emissions exceed the level of 10 dBμV in the frequency range of 0.5–6 MHz with a maximum value of 17 dBμV at a frequency of 2.7 MHz. Moreover, emission values in the frequency range of 6–20 MHz amount to 9–17 dBμV when using the HSI (Fig. 5c) and do not exceed 8.7 dBμV when using the HSE (Fig. 5*d*).

E. Digital-to-Analog Converter Unit Operation

The test program was developed to measure emissions from the MC with a working digital-to-analog converter (DAC) unit. To carry out this task, the MC uses one of the two DACs to form a sawtooth waveform with amplitude of 2.85 V and a frequency of 336 Hz.

Figs. 6*a*, *b* show that the emissions from the DAC unit are concentrated in the range of 0.5–6 MHz with a maximum value of 14 dBμV at 4 MHz using both internal and external clocking at f_c=8 MHz. There is also an increase in the emission amplitudes by 2–3 dBμV at the frequencies of the fundamental and higher harmonics of f_c in comparison with the levels measured without the DAC. As the f_c increases to 80 MHz, the upper frequency of the emission spectrum shifts from 6 MHz to 20 MHz, and the maximum level of the emission amplitude is 23.7 dBμV near 10 MHz (Figs. 6*c*, *d*).

IV. Conclusion

The results of measuring the radiated emissions from MC 1986BE91T in the TEM cell are presented considering its various software configurations. It was revealed that the multiplication of the clock frequency of the studied MC in the range from 8 to 80 MHz leads to the appearance of peak emission values at the 3rd harmonics from the fundamental MC clock frequency and an increase in its maximum value from 11 to 29 dBμV. When using the HSE for MC clocking and a sequential increase in the frequency multiplier, an increase in emissions in the frequency range of 450–700 MHz with values of 10–17 dBμV was revealed. These emissions were absent in similar measurements with the HSI. It is shown that the emissions caused by the functioning of the ALU, ADC and DAC units are concentrated in the frequency range of 0.5–6 MHz with an amplitude of 12–20 dBμV when the MC is clocked at a frequency of 8 MHz. An increase in the clock frequency to 80 MHz leads to an expansion of the upper frequency of the emission spectrum from the studied MC units to 20 MHz. During the operation of the ALU and DAC units, an increase in the maximum emission amplitude to 20–25 dBμV was revealed, and for the ADC unit, a decrease amounted to 17 dBμV. It is also shown that the operation of the considered MC units, when clocked at 8 MHz, leads to an increase in emissions at the frequencies of the fundamental and higher harmonics by 3–4 dBμV.

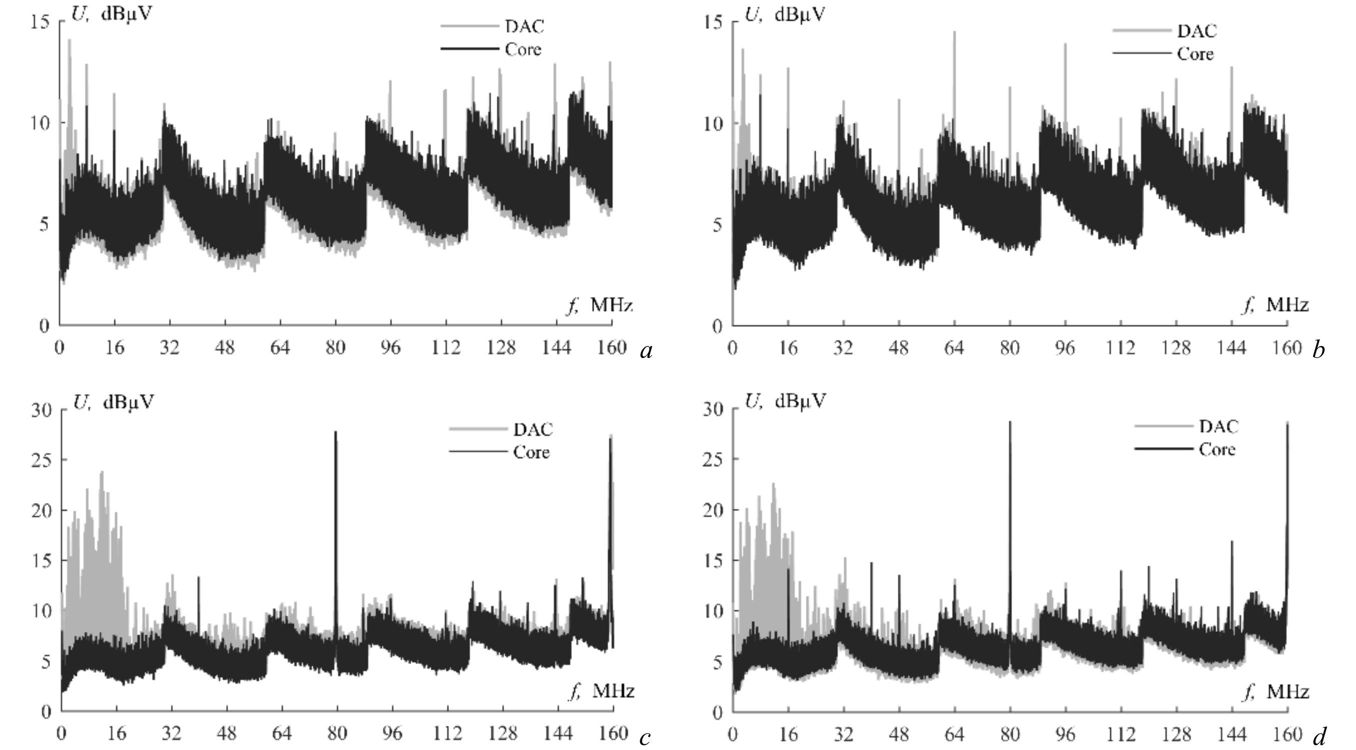

Fig. 6. Comparison of the voltages *U* measured during the operation of DAC unit and the MC core when clocked at f_c=8 MHz (*a*, *b*) and f_c=80 MHz (*c*, *d*) from the HSI (*a*, *c*) and HSE (*b*, *d*)

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