Low Noise Programmable DC Amplifier with Remote Control

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Abstract

Introduction. The developmental direction of information-measuring systems used to record, pre-process and analyse excess low-frequency noise (flicker noise) in modern experimental technology is well known. Every measuring channel is presented in the form of a multistage circuit with specified parameters at each stage. This creates difficulties in adapting a measuring system to specific experimental conditions. While the solution may be to unify all the components of the channel, the problem lies in estimating the intrinsic noise of the electronic elements which provide a change in amplifier parameters.

Objective. To analyse the intrinsic noise of electronic potentiometers. To develop a low-noise unified DC amplifier with the possibility of external digital control parameters. To study the characteristics of a DC amplifier thus developed.

Materials and methods. The superposition method was used to perform theoretical calculation of noise gain for each component of a non-inverting amplifier. Experimental studies were based on a system consisting of a low-noise amplifying path and spectroanalyser using the data acquisition module E14-440. Software "Power-Graph" was used.

Results. The results of the theoretical analysis of noise amplification for metal-film resistors and experimental studies of the characteristics of electronic potentiometers indicated that their noise voltages specific values are almost identical. The use of a digital potentiometer as a feedback element and a low-noise bipolar-powered bias source (AD8400) permitted the implementation of a unified module with cascading capability. External digital control was based on a single-chip microcontroller PIC18F2550, using the "Master-Slave" channel level protocol and ASCII-command-line interface based on RS-485 network. This control enabled adaptation for measuring electronic component noise, low currents and voltages, flicker noise and the construction of systems for information collecting and processing.

Conclusion. The theoretical and practical results achieved herein enable the design of multichannel distributed DC measuring systems. The systems will offer adaptability for measuring channels to the tasks required, and the possibility of correction of real time characteristics.

Key words: low noise preamplifier, electronic digital potentiometer, switch capacitor filter, DC amplifier, low-frequency excess noise, flicker noise

Малошумящий программируемый усилитель постоянного тока с дистанционным управлением

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Аннотация

Введение. В современной технике эксперимента известно направление, связанное с разработкой информационно-измерительных систем регистрации и анализа избыточных низкочастотных шумов. Любой измерительный канал представлен в виде многокаскадной схемы с заданными параметрами каждого каскада, что затрудняет адаптацию измерительной системы к конкретным условиям эксперимента. Решением проблемы является унификация всех компонентов канала, однако при этом одной из основных проблем является оценка собственных шумов электронных элементов, обеспечивающих изменение параметров усилителя.

Цель работы. Анализ собственных шумов электронных потенциометров, разработка малошумящего унифицированного усилителя постоянного тока с возможностью внешнего цифрового управления параметрами и исследование его характеристик.

Материалы и методы. С помощью метода суперпозиции произведен теоретический расчет шумового усиления для каждого компонента неинвертирующего усилителя. Экспериментальные исследования проводились на базе установки, представляющей собой малошумящий усилительный тракт и спектроанализатор на основе модуля сбора данных E14-440 и программного обеспечения «PowerGraph».

Результаты. По результатам теоретических расчетов шумового усиления для металлопленочных резисторов и экспериментальных исследований характеристик электронных потенциометров показано, что их удельные значения напряжений шумов практически идентичны. Использование цифрового потенциометра в качестве элемента обратной связи и малошумящего источника смещения с двухполярным питанием (AD8400), позволяют реализовать на их основе унифицированный модуль с возможностью каскадирования. Внешнее цифровое управление на основе однокристального микроконтроллера PIC18F2550, разработанного протокола канального уровня «Master-Slave» и ASCII-интерфейса командной строки на базе сети RS-485 позволяет адаптировать его к задачам измерения шумов электронных компонентов, малых токов и напряжений, фликкер-шумов, построения распределенных систем сбора и обработки информации.

Заключение. Полученные теоретические и практические результаты делают возможным проектирование многоканальных распределенных измерительных систем постоянного тока с адаптацией измерительных каналов к поставленным задачам и возможностями программной коррекции характеристик в реальном времени.

Ключевые слова: малошумящий предусилитель, электронный цифровой потенциометр, фильтр на переключаемых конденсаторах, усилитель постоянного тока, низкочастотный избыточный шум, фликкер-шум

ОРИГИНАЛЬНАЯ СТАТЬЯ

Известия вузов России. Радиоэлектроника. 2019. Т. 22, № 4
Journal of the Russian Universities. Radioelectronics. 2019, vol. 22, no. 4

ORIGINAL ARTICLE

Метрология и информационно-измерительные приборы и системы
Metrology, Information and Measuring Devices and Systems

Introduction. Measuring systems designed for the detection and analysis of excess low-frequency noises are at the present time seen as an individual solution. Primarily, this is due to the limited class of objectives they are designed to resolve. A measuring channel specifically designed for such tasks generally consists of a low-noise pre-amplifier (LPA), second-stage amplifier (intermediate amplifier – IA), high and low pass filters (HPF, LPF) [1].

In general, the provision of a high gain coefficient is less complex than in comparison with direct current component and voltage drift compensation. A high pass filter which limits channel passband from below is used to resolve the drift problem. For the reason of low LPA gain (optimising signal-to-noise ratio and preventing saturation caused by the presence of a DC component in a signal) filters are placed between the following amplification stages where bias voltage is much higher. However, the use of HPF limits the sensitivity of the diagnostic method based on low-noise measurement. HPF with an alternating cut-off frequency is required for the suppression of aliasing effects, especially for broadband signal (noises) detection.

It is important to match the output of the device which is being tested (OUT) with the input of the measuring amplifier. In most cases it is sufficient to choose a suitable operational amplifier (OA) to achieve a good ratio between noise current and noise voltage in combination with the signal source output impedance. In rare cases, other more specific solutions need to be used. This is the reason why LPA usually have a constant voltage gain coefficient and specified amplification band, in addition to typical solutions for signal source matching.

Experimental measurements of the systems using the measuring channel operating principals described above are presented in [2–8]. In these examples, the total voltage gain is low because the spectrum analyser used for analysis and processing has an internal LPA. In general, the methods and technical solutions used are designed to adapt the measuring channel to specific experiment conditions and are represented as particular solutions.

Amplifiers optimised for specific conditions of usage (for example, intrinsic flicker noise reduction) are presented in papers [9–13]. In most cases, the technology used is the parallel connection of several channels with the total output voltage or the applica-

tion of cross-correlation technology. This paper [10] deserves our special attention. The authors have attempted to extend LNA features using the modular approach combining the cross-correlation method previously proposed, the hardware features of the differential amplifiers and their cascading, in order to attain general noise level reduction.

Objective and formulation of the problem. In the aims of providing a high level of unification, the authors propose the concept of a general-purpose LPA capable of performing any kind of operation in the measuring path. There is no provision for a difference between the first and following cascades, nor is there a requirement for hardware solutions to enable parametrical drift compensation. The main requirements are low intrinsic noise level; the possibility of gain coefficient and bias voltage remote control; signal low-pass filtering with a programmable cut-off frequency; built-in digital drift correction; absence of frequency characteristic limits from below (DC-operation); presence of a digital drift compensation system in a single module, as well as in a measuring path system. Thus, the general-purpose amplifier could be used both separately and as part of the multi-stage system that greatly increases the amplifier's capabilities [14–15]. The main problem of the amplifier development process as described above is the need to choose and use electronic components to regulate amplification and bias which influences noise characteristics.

Electronic digital potentiometer as a control element. Electronic digital potentiometers (EDP) are widely used as control elements in general-purpose devices [15]. Three basic circuits of potentiometer connection are normally used for the control of the gain coefficient (see Fig. 1).

The use of EDP in low-noise amplifiers could be limited by excess noises (in contrast to metal-film resistors), the need for a unipolar voltage supply, and the low maximum value of through-current limited in the 3…5 mA range. The diagrams shown in Fig. 1, *a*, *b* demonstrate the advantage of providing a constant value of current in the potentiometer independently on the value of the specified voltage gain coefficient K_u. The dependence $K_u(R_L)$ is nonlinear, especially for the diagram in Fig. 1, *b*.

The diagram in Fig. 1, *c* is mostly preferable for LPA since the noise gain for resistor R_L is $G_{n, R_L} = 1$ [17]. However, in this diagram, only low-
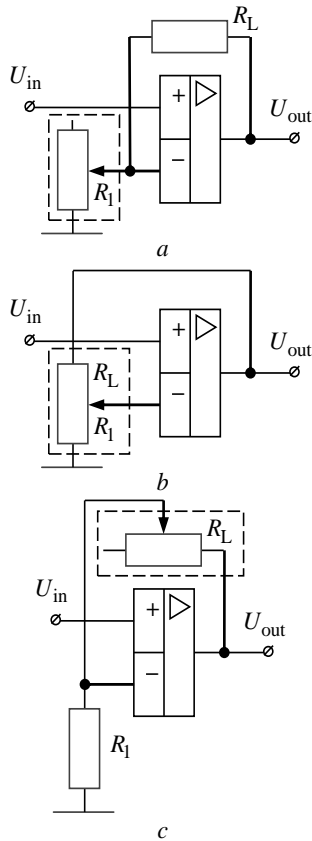
Известия вузов России. Радиоэлектроника. 2019. Т. 22, № 4
Journal of the Russian Universities. Radioelectronics. 2019, vol. 22, no. 4

ОРИГИНАЛЬНАЯ СТАТЬЯ

Метрология и информационно-измерительные приборы и системы
Metrology, Information and Measuring Devices and Systems

ORIGINAL ARTICLE

Fig. 1. Potentiometer wiring to adjust the gain

signal operation conditions are permitted for a low value of R_1, otherwise an overload of R_L is possible due to the saturation of amplification stages. This problem could be avoided by increasing all resistor ratings. This may lead to an increase of component contribution to the total noise level of the cascade. Limiting potentiometer current to prevent overloading can be achieved by means of the real-time digital adjustment of amplification using a built-in algorithm (digital current feedback servo system).

The contribution of the intrinsic electronic potentiometer noise to the total noise of amplification stage needs to be estimated, in order to use it as an adjustment element for LPA. The main problem is the lack of information in modern publications concerning the character and structure of potentiometer noises. A test setup needs to be developed to measure EDP noise and noise from a resistor with equivalent resistance. The diagram shown in Fig. 1, *a* can be used for this purpose, since the noise amplification for R_1 is $G_{n, R_1} = R_L / R_1$ which is the highest value for all the diagrams taken into consideration.

The percentage of the noise of R_1 and all other noise sources of a cascade need to be estimated. It is known [17] that for the diagram shown in Fig. 1, *a*, the total root-mean-square value of the voltage noise on the output of the cascade is defined by

$$U_n = \sqrt{E_{n\,R_L}^2 + E_{n\,R_1}^2 + E_{n\,op}^2 + \left(i_{n\,op}R_L\right)^2}, \quad (1)$$

where $E_{n,\,R_L}^2$, $E_{n,\,R_1}^2$ – the root-mean-square values of the noise of the resistors R_L and R_1, respectively; $E_{n,\,op}^2$ – (equivalent) voltage noise of OA the normalised to an input; $i_{n,\,op}R_L$ – the equivalent current noise of OA input.

Clearly, there is an optimal value of R_1 which gives the maximum contribution to the total noise value. Using (1) the contributions of R_L, R_1, OA [%] could be derived in the following way:

$$K_{R_L} = \left[\frac{E_{n\,R_L}^2 + \left(i_{n\,op}R_L\right)^2}{U_n^2}\right]100; \quad (2)$$

$$K_{R_1} = \left(\frac{E_{n\,R_1}^2}{U_n^2}\right)100; \quad (3)$$

$$K_{op} = \left(\frac{E_{n\,op}^2}{U_n^2}\right)100. \quad (4)$$

The study was carried out using a general-purpose electronic potentiometer with the following parameters: resistance is in the range between $R_{max} = 1$ kOhm to $R_{min} = 50$ Ohm;, resistance variation step $N_s = 255$.
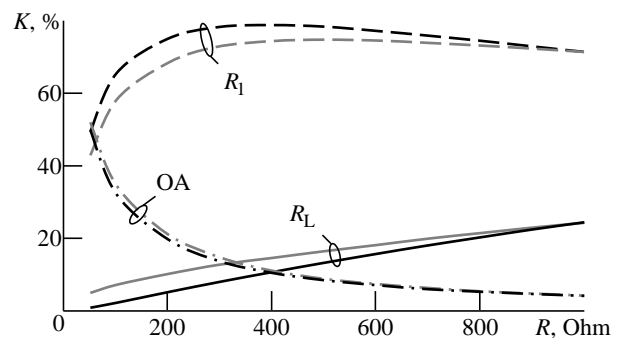

Fig. 2. Contribution of circuit elements to amplifier noise: black curves for a fixed gain circuit; gray curves for a circuit with a fixed value of the R_L

ОРИГИНАЛЬНАЯ СТАТЬЯ

ORIGINAL ARTICLE

Известия вузов России. Радиоэлектроника. 2019. Т. 22, № 4
Journal of the Russian Universities. Radioelectronics. 2019, vol. 22, no. 4

Метрология и информационно-измерительные приборы и системы
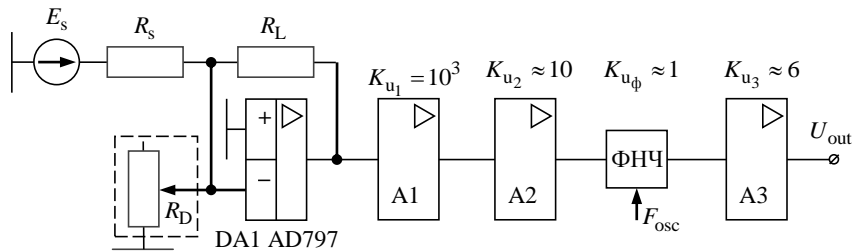Metrology, Information and Measuring Devices and Systems

Fig. 3. Functional diagram of the experimental setup for the study of the noise of electronic potentiometers

Two circuits were used: 1) with constant gain and 2) with constant value of R_L. The first circuit has the advantage that the total gain coefficient of the measuring path is constant and cannot be changed. However, this requires the synchronous measuring of R_l and R_L for the precise adjustment of voltage gain, which is not practically convenient. The second circuit could be used when the measuring setup has a broad dynamic range. Clearly the contribution of each element of the circuit will depend on the circuit type. Fig. 2 shows the dependencies of the above-mentioned components' contribution to the total noise level for the first and the second measuring circuits (black and grey curves respectively). Fig. 2 shows that the contribution of each component calculated on the basis of formulae (2)–(4) is in a state of weak dependence on the study method used herein. At the same time, the contribution of R_l is greatest with respect to other noise sources, especially in the 300...400 Ohm range of resistivity. These dependencies correspond to the most common case when the rating of the feedback resistor is in the range of 10…100 Ohm, as usually used in LPA. Increasing the R_L rating increases the resistor's contribution to the total noise and increases measurement accuracy. It is therefore practically reasonable to use the circuit with a constant value of R_L.

Fig. 3 shows the functional diagram for the experimental setup to study electronic potentiometer noises. Amplifiers A1 and A2 are based on OP37 and provide the main gain (approximately 10^4). Amplifier A3 forms the range of the output voltage ± 10 V required for the data gathering module E14-440. Thus, the total path gain is about $660 \cdot 10^3$.

MAX7400 filters with external control are used as the HPF with the cut-off frequency in the range of $f_{mid} = 0…20$ kHz defined by a frequency synthesis-er F_{osc} from the condition $f_{mid} = 100/F_{osc}$. The root-mean-square value of the voltage noise was measured using the special software "PowerGraph" by means of the digital band pass filtering of the signal in the range of 1...2 kHz and the normalisation of the average spectrum realisation relative to this value. The DAC AD5320 was used as the voltage source E_s and the resistor R_s for compensation of the bias voltage and prevention of the measuring channel saturation. The value R_s was chosen to provide the necessary adjustment range and the necessary accuracy of the bias voltage setup [1, 14, 15].

Fig. 4 represents a comparison of the experimentally obtained noise characteristics of the electronic potentiometer for the LPA gain coefficient $K_{u_p} = 11$ as well as the calculated characteristic of the resistor with equivalent resistance value. As shown in the Fig. 4, the electronic potentiometer is nearly equivalent to the metal-film resistor in the noise characteristics, allowing them to be used as the control elements in any LPA. The measurement data correspond to the frequencies 1...2 kHz and omit excess noise. However, by using the specified initial values for the Johnson noise and comparing of the noise spectral characteristic with the OA noises, it can be concluded that the
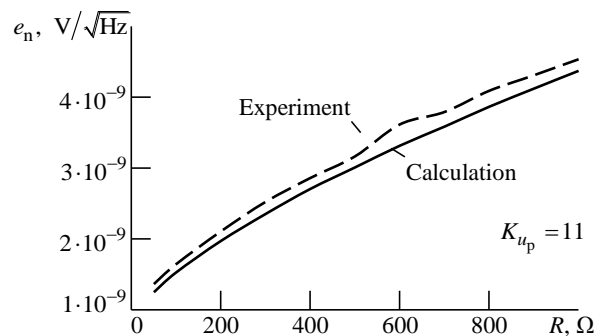

Fig. 4. Equivalent voltage noise values for an amplifier with an electronic potentiometer (experiment) and an equivalent resistor R_l (calculation)

Известия вузов России. Радиоэлектроника. 2019. Т. 22, № 4
Journal of the Russian Universities. Radioelectronics. 2019, vol. 22, no. 4

ОРИГИНАЛЬНАЯ СТАТЬЯ

Метрология и информационно-измерительные приборы и системы
Metrology, Information and Measuring Devices and Systems

ORIGINAL ARTICLE

contribution of the low-frequency noises is minimal and negligible compared to the OA flicker noise.

LPA hardware design. Fig. 5 shows the functional diagram of the developed LPA with the digital remote control. The main amplifier is OA DA1. The diagram provides for replacement of the signal source by OA of another type, since the signal sources might have various output impedance. For example, AD797 could be replaced by TL071, OP37, AD795 that allows for a choice of OA for the specified sensor resistance without changes to the control circuit. The gain is adjusted by EDS DA3 AD8400-1K in the range $K_{u_\mathrm{p}} = 5...100$ with the step $\Delta K_{u_\mathrm{p}} = 0.39$ for the specified resistance $R_1 = 10\,\mathrm{Ohm}$ (for decrease of R_1 contribution to the total amplifier noises).

The bias is adjusted by EDS DA4 AD8400-10k according to a potential divider circuit. The range and adjusting accuracy of the bias are defined by the additional resistor R2–R4. The bias voltage U_of on the amplifier output is derived from the equation:

$$U_\mathrm{of} = \frac{\left(\dfrac{2U_\mathrm{p}}{256}N_1 - U_\mathrm{sup}\right)\left(\dfrac{10^3}{256}N_2 + 50\right)}{R_2}, \quad (5)$$

where U_sup – the supply voltage; N_1, N_2 – the values of control codes which are fed to DA4 and DA3 relatively. Control codes are defined by the mi-

crocontroller (MC) DD2 PIC18F2520 using a hardware SPI protocol. The analogue switcher DA2 is proposed to achieve a drift periodical compensation regime by adjusting output bias value and compensation using DA4. This regime could be used locally in each amplifier, but in the case of cascading, a more complex compensation algorithm is possible.

Using (5), the amplification stage which balances between compensation accuracy and compensation range can be tuned. The implementation and study of these algorithms is the object of subsequent work.

Clearly in the case of the cascading of universal amplifiers, a high accuracy setting of zero bias can be achieved, if each amplifier in the measuring path is implemented. This leads to a broadening of the compensation range but requires reciprocal data exchange between the amplifier cascades. Wiring of all amplifiers to a single net based on RS-485 interface makes this possible.

Subsequent experiments show that the analogue key DA2 does not contribute the additional noises. Thus, the module shown here (Fig. 5) produces a compensation method with sufficiently extended functions and advantages in comparison with solutions based on a modulator and demodulator. Spurious commutation frequency harmonics DA2 could be suppressed by software, as well as by data gathering synchronous with commutation frequency.

An eighth order elliptic filter DD1 MAX7403 is installed on the output DA1. The cut-off frequency is
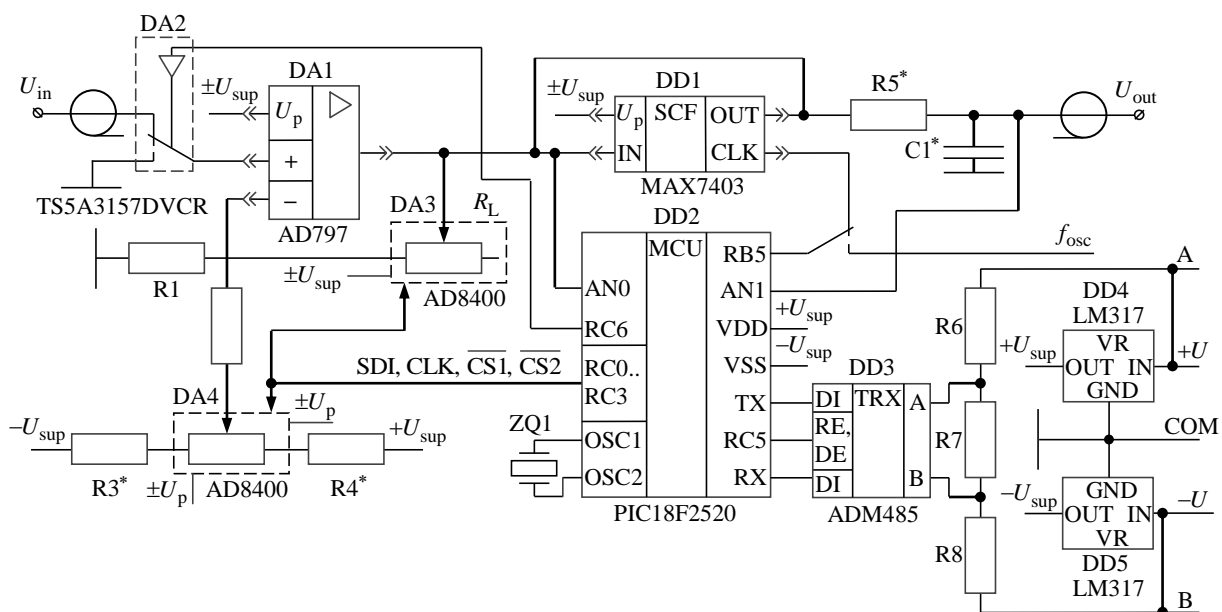

Fig. 5. Functional diagram of the low-noise pre-amplifier with digital remote control

ОРИГИНАЛЬНАЯ СТАТЬЯ

Известия вузов России. Радиоэлектроника. 2019. Т. 22, № 4
Journal of the Russian Universities. Radioelectronics. 2019, vol. 22, no. 4

ORIGINAL ARTICLE

Метрология и информационно-измерительные приборы и системы
Metrology, Information and Measuring Devices and Systems

controlled by MCU or the external frequency synthesiser. Using MCU as the clock generator has an advantage in the event of a requirement to provide a fixed cut-off frequency for each module in the measuring path for a relatively narrow range of the fixed values. Meanwhile, the application of the external synthesiser allows any cut-off frequency in the range 0...30 kHz to be set. The filter is an optional module since its presence is essential only in the lateral cascades of the measuring channel. The first order filter R5C1 limits the pass band at frequencies higher than 20 kHz which sufficiently suppress spurious harmonics DD1 MAX7403 in the low frequency range [1].

Remote control protocol. The specific data transfer protocol and the command line interface are used for the external control of the amplifier. The development of a proprietary protocol was necessitated by the specific feature of the task to be resolved and the unreasonable utilisation of MCU sources by most of the known protocols (for example, ModBus-RTU). The closest analogue of the developed protocol is ModBus-ASCII [18]. The transferred data is represented as an ASCII-code which allows the use of any terminal programme for control. Control protocol has the following requirements: simple software realisation in MC; possibility of data transfer between MCs in the same net, as well as between a central device (master) and a remote device (slave) (point-to-point connection); the possibility of extending and developing an instruction system without using of a menu; the possibility of operation in symbol-by-symbol, line-by-line, and packet regimes; operation in an asynchronous regime without timeouts; independence of external libraries and support of any MC with the built-in UART module; absence of collisions during role assignment to each device (master, slave); operation without an established connection; fixed positions of symbols in a frame header. As preliminary experiments have shown, a topology deviation from protocol RS-485 according to cascade or tree-type principle does not lead to an increase of errors number at a low transfer rate. The optimisation of the exchange protocol and possibility of the data transfer through the power source lines are the objects of special study.

Fig. 6 shows the frame formats of the developed protocol. The sign of the frame beginning is the "M" symbol after which the module is allocated a "CCC" address in the range 0...255. In the case of address
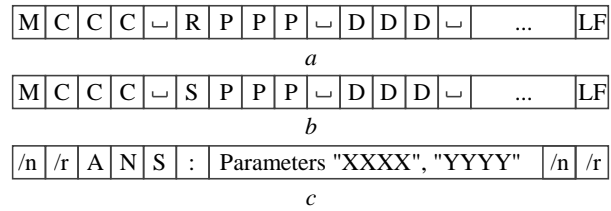

Fig. 6. Data transfer frames for amplifier control:
a – reading a given parameter, *b* – writing
a parameter, *c* – module response

coincidence, the symbol of operation type is analysed ("R" – reading (Fig. 6, *a*), "S" – writing (Fig. 6, *b*). Then, depending on the operation type, a parameter address and parameter value (for writing operation) are defined in the range 0...255 and 0...9999 correspondingly. The end-of-frame character is the symbol "LF". If the operation is successfully accomplished then the answer as a parameter value is formed independently on the type of operation (Fig. 6, *c*).

If the protocol operates within the single measuring channel then another address system with the structure "MXXXX.YYYY" should be used, where "XXXX" – is the address of the measuring channel, "YYYY" – is the address of the module in the measuring channel defined by the number of amplification stages. In total, nearly 30 base commands were achieved and any kind of amplifier in multichannel system could be configured. Specified configurations can be stored in PRAM of MC and restored during the module power up.

Results of noise characteristics study. The results of the noise measurements of the described amplifier prototype are shown in Fig. 7 for following parameters: the cut-off frequency $f_{\text{mid}} = 10\,\text{kHz}$, $f_{\text{osc}} = 1\,\text{MHz}$, $K_{u_{\text{p}}} = 11$, data gathering sampling rate $F_{\text{d}} = 50\,\text{kHz}$. As seen in the figure, the equivalent spectral density of the voltage noise at the fre-
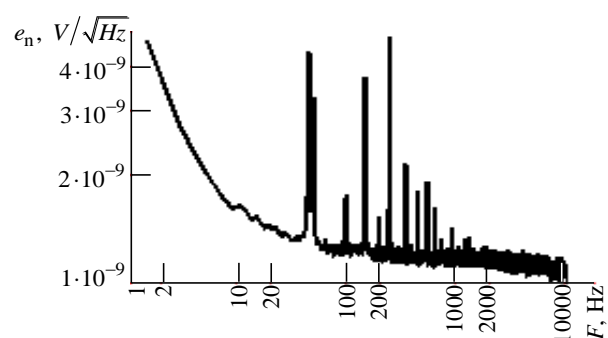

Fig. 7. Equivalent voltage noise spectral density of the low noise amplifier.

Метрология и информационно-измерительные приборы и системы
Metrology, Information and Measuring Devices and Systems

quency 1 kHz does not exceed $1.2 \text{ nV}/\sqrt{\text{Hz}}$, slightly differs from the value e_n used by OA. Further measurements show that this value is maintained for any $5 \le K_{u_\text{p}} \le 100$.

In addition to commercial frequencies the 45 Hz component, which is the combination frequency of the MC clock frequency, is also present.

Conclusion. The developed prototype of a universal measurement amplifier could be used in the construction of complex multichannel distributed measuring systems. The main advantages of such an amplifier are low intrinsic noise, DC operation, possibility of parameter remote control without too much change to the noise characteristics, modularity, flexibility and simplicity of the adjustment, insensitivity of supplied voltage, wide options for realisation of built-in algorithms of sensitivity improvement and suppression of intrinsic flicker noise.

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