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Integral signal converters of the temperature sensor measuring-diagnostic devices for biomedical applications

The materials of the article present the results of research, which is a promising direction in the construction of high-linear analog devices for systems of measurement, registration and signal processing of biomedical components for the use of push-pull structures. There is a variety of existing models of high-linear devices in the production of leading world-famous companies, in particular Analog Devices, National Semiconductor, Texas Instruments, Linear Technology, ON Semiconductor, Philips, Inetrsil, have the opportunity. further improvement of their characteristics. The work analyzes the primary conversion circuits of highly sensitive differential temperature sensors on transistor structures and applies the optimal operating modes of differential transistor cascades of differential temperature sensors for biomedical devices. Developers of analog-digital systems often face the problem of choosing an amplifier that works with small errors in the current level transmission. The problem of signal matching also remains in the focus of developers' attention, after which in modern DACs the OA switching scheme is used as the I-V characteristic, and for DACs with VB and VVC voltage output, switching schemes are used. An effective approach to building such analog devices is the use of transimpedance amplifiers. They combine both high linear parameters of direct current and effective characteristics of alternating signal amplification. The order of development of new microelectronic technologies for creating thermal flow sensors, in particular based on the MEMs structure, further development of these sensors for medical diagnostics is promising and solves the problem of increasing the efficiency of the parameters of signal converters.

Keywords: *thermal flow sensors; signal converters; integrated electronics for biomedical electronics; biomedical diagnostics.*

Introduction. The surface temperature relief of the human body is determined by thermodynamic processes inside the body as a whole and in its individual parts.

The value of the surface temperature also depends on the individual characteristics of the autonomic and central nervous systems, as well as the properties and functions of the endocrine glands – that is, on the internal factors of thermal energy generation. Internal factors can lead to individual physiological and pathological changes that affect the temperature relief.

These are the following factors:

- congenital vascular anomalies;
- violations of the size (diameter) of the vessels due to disorders of the autonomic system;
- circulatory disorders (injuries, blood clots, embolism, sclerosis, etc.);
- violations of the venous duct (stoppage, opposite direction of flows, etc.);
- local changes in heat generation (congestion, injuries, tumors, etc.);
- changes in thermal conductivity of tissues (fat layers, congestion, etc.).

Therefore, in the general case, it is necessary to take into account the genetic factor, in which the occurrence of physiological variations in the temperature pattern is possible.

The temperature of a biological object is a parameter regulated by homeostasis systems. Therefore, the goal was set to see the spatial structure of the thermogram and its temporal dynamics of manifestations of these systems and to determine their characteristics. And indeed, it was possible to establish that in the thermogram of a person, along with areas where the temperature relaxes monotonously, there are also areas covered by active regulation.

In a healthy person, the temperature distribution is symmetrical relative to the midline of the body. Violation of this symmetry is the main criterion for thermal imaging diagnostics of diseases. The quantitative expression of thermal asymmetry is the size of the temperature difference.

The main causes of temperature asymmetry:

- congenital vascular pathology, including vascular tumors;
- vegetative disorders leading to impaired regulation of vascular tone;
- circulatory disorders due to trauma, thrombosis, embolism, vascular sclerosis;
- venous stasis, retrograde flow of blood with insufficiency of venous valves;
- inflammatory processes, tumors that cause a local increase in metabolic processes;
- changes in thermal conductivity of tissues due to swelling, increase or decrease in the layer of subcutaneous fatty tissue.

There is a so-called physiological thermal asymmetry, which differs from a pathological one by a smaller temperature difference for each individual part of the body. For the chest, abdomen, and back, the temperature difference does not exceed 1.0°C.

Thermoregulatory reactions in the human body are controlled by the hypothalamus.

The distribution and intensity of thermal radiation are normally determined by the peculiarity of physiological processes occurring in the body, in particular in both superficial and deep organs. Various pathological conditions are characterized by thermal asymmetry and the presence of a temperature gradient between the zone of increased or decreased radiation and a symmetrical part of the body, which is reflected in the thermographic picture. This fact has significant diagnostic and prognostic value, as evidenced by numerous clinical studies.

Analysis of the integral signal transducers of the microelectronic thermal flow sensors of general and biomedical designation. Modern state -of-art of sensor electronics is greatly determined by the microprocessor engineering. Wide introduction of modern microprocessors enables to improve substantially technical characteristics of microelectronic sensors, broaden their functional possibilities, provide mutual compatibility and the possibility of the formation of measuring-diagnostic system [1, 2]. Future oriented direction – smart sensors are formed [3, 4]. Criteria and parameters of the intellectualization of the process of physical environment parameters measurement and requirements to microelectronic facilities, providing this process are determined by the International Standard IEEE 1451 – networked smart transducer interface standard [5, 6]. High-efficient and convenient interfaces by means of which sensors are connected to the computer – based systems of data mining, are developed [7, 8]. Much attention is paid to the reduction of energy consumption of the devices and provision of the possibility of their operation, using low voltage power supply sources [9, 10].

For example, Figure 1 shows the generalized functional diagram of the smart MEMS device that contains; MEMS sensor, as it is shown in Figure 1 they may be light sensors, sound sensors, pressure sensors, chemicals sensors or temperature sensors; Input analog signal processing unit; Digital Signal Processing unit; Output analog signal processing unit; MEMS actuators, i.e., inverse relatively the sensor by the functional action transducer, that provides mechanics, display, electrical power or other devices; Optical or electrical communication.

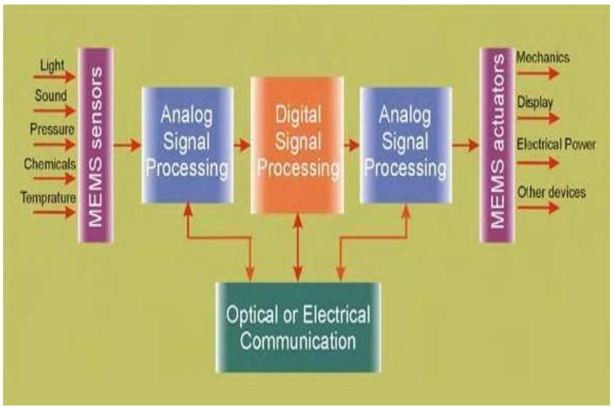

Fig. 1. Functional scheme of the Smart MEMS device

Unlike sensor devices of temperature, magnetic field, mechanical stress, humidity, etc, flow measuring sensors still are at the initial stage of the development of the methods and means of their intellectualization. Although the process of electric signal measurement, for instance, of thermoanemometric flow sensor of the bridge type is rather simple, the provision of all the requirements to modern smart electronics is far more complicated problem. We will consider this problem from the point of view of the methods, realized by the signal transducers of the thermal flow sensors.

The following principle methods and approaches, providing intellectualization of flow measurement sensor can be formulated:

- increase of measuring conversion accuracy on the base on special circuit engineering solutions;
- adaptation of the transducer operation modes according to the flow parameters and measuring conditions;

- minimization of the energy consumption and provision of the possibility of operation from low voltage small power supply sources;
- interface with modern operating systems (OS) of the computer equipment, collection and visualization of the measurements results.

Generalized structure of the flow sensor, the components of which are primary transducer, signal analog transducer (secondary transducer), analog-to-digital converter, microcontroller and interface, is shown in Figure 2.

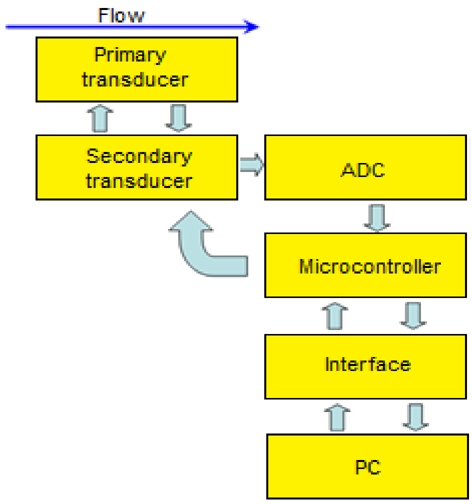

Fig. 2. Functional diagram of the Smart flow sensor

In recent years rapid development is observed in the sphere of the construction of signal transducers of microelectronic sensors, element base of new generation is created, projects, aimed at interfaces and supply parameters unification are realized, such a notion as the art of circuit engineering has appeared. These developments are highlighted in the monographs [11, 12] and papers [13, 14]. Latest achievements in the sphere of analog-to-digital converters (ADC) are presented in [15, 16].

The aim of the work is the basis of increasing the sensitivity and accuracy of heat flow measurement for the development of new algorithmic and structural approaches in the construction of signal converters of thermal microelectronic flow sensors that meet the requirements of biomedical equipment.

Presentation of the main material. It should be noted that sometimes there exists a misperception that microprocessors have completely ousted the means of analog processing of signals. In fact, this is true only for simple sensor devices, which do not possess high metrological characteristics. As the surrounding world is analog by its nature (obviously, that is not a question of the dual nature of the microworld) signal converters of the analog signal are and will remain the determinative components of highly precision and functionally complex sensor devices. Numerous studies on this subject, published in the editions of IEEE [13, 17] and the process of the constant renovation of analog integrated amplifiers prove this statement [15, 16]. New direction of the development of signal converters is their integration directly in the structure of solid-state integrated circuits of the smart sensor, in particular, in biomedical catheter CMOS blood flow sensor [17]. However, as we determined in the process of the analysis of the available literature sources, a greater part of signal converters of thermal flow sensors do not meet the requirements of modern electronics. This can be shown on the example of the circuit of the signal converter of thermal flow sensor, developed for biomedical application, presented in Figure 3 [18] (it should be noted, that the cited paper is published in the scientific community journal of microelectronic sensors Sensor and Actuator of the Elsevier Publishing House in 2008).

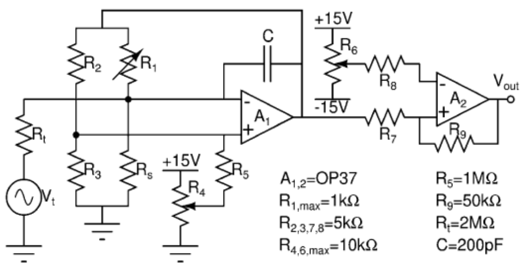

Fig. 3. Signal converter connection of the thermal flow senor [18]

As it is seen, the circuit of the signal converter requires bipolar + / – 15 V supply source, that does not meet the requirements of modern electronics (as it was already mentioned, modern microelectronic sensor devices must provide normal operation at 3V single pole supply), signal converter does not provide compensation of the parasitic impact of the signal lines, a number of nonoptimal circuit engineering solutions is also available.

It is important to note, that the problem of the transition on the small power low voltage supply source is one of the most complex as only in the recent years low voltage high precision analog integrated circuit became available (this class of circuits got the name of vLow Voltage Rail-to-Rail Circuits), the correct usage of low voltage analog circuits requires new circuit engineering solutions and regarding the thermal flow sensors, the determining problem is the decrease of the supply voltage of the circuit of the functionally integrated elements «heating – temperature measurement».

The impact of the signal line in the converter decreases due to the connection of one of the outputs (r_1) in series with the measuring resistor R_X, the second output (r_2) – in series with R_0 and the third (r_3) – in series with high input resistance of the operational amplifier (OA). Taking into account the resistances of the outputs and having met the conditions r1 << R_X, r2 << R0 determine:

$$U_{out} = -U_0 \cdot \frac{R_X + r_1}{R_0 + r_2} \approx -U_0 \cdot \frac{R_X}{R_0}\left(1 + \frac{r_1}{R_X} - \frac{r_2}{R_0}\right).$$

Further, having assumed $r_1 / R_X \approx r_2 / R_0$ we obtain:

$$1 + \frac{r_1}{R_X} - \frac{r_2}{R_0} \approx 1.$$

Thus, the impact of transmission lines resistances on the output voltage becomes minimal. We should also pay attention to the problems of the accurate provision of the necessary relations – the resistance of the signal line can change in time and the change of the measuring resistor RX. That is the base of the measuring process, in its turn, also changes the preset relation.

Taking into account the positive feedback, at the output of OA the doubled voltage − 2I0r2 is obtained. Half of this voltage across the resistive divider is sent to the non-inverting input of OA. It is obvious, that the same voltage will be formed at the inverting input. The stability of the circuit is provided by the advantage of the negative feedback over the positive *β*– > *β*+. Thus, the output voltage of he converter is:

$$U_{out} = I_0 \cdot (R_X + r_1 - r_2),$$

if $r_1 = r_2$ stipulates the absence of the impact on the output signal of the signal line resistance. Accuracy of balancing does not depend on the change of R_X. Four-wire communication lines provide considerable decrease of the errors, caused by the impact of line resistances.

The above-mentioned analysis of the circuits of the half-bridge and bridge measuring converters shows that the problems of the compensation of the parasitic impact of the transmission lines, as a rule, have rather efficient solutions. However, this conclusion cannot be applied to the full extent to measuring converters of thermal flow sensors.

At least, there are two reasons. First, in the most typical thermal flow sensors with functionally integrated elements «heating – temperature measurement» the release of heat takes place not only on these elements (a useful part of energy consumption) but also on the control elements of the output transistors of OA. This stipulates the excessive energy consumption and, in case of the monolithic integration of the primary converter circuit with the signal converter of the sensor device, parasitic heating of the sensor structure in the areas of the control transistors location. In their turn, such areas of the parasitic heating distort the temperature field of the primary converters, which leads to the increase of flow measurement error. Secondly, in the process of the transition to the small-size, low power, low voltage supply sources the voltage drop at the control transistors of the heating circuit could be comparable with the voltage at the primary functionally integrated converter, that considerably decreases the efficiency of energy consumption and the accuracy of sensor device operation.

Concerning the problems of the digital signal conversion, interfaces, software, etc., in the authors' opinion, the latter completely meet the requirements to the units of modern sensor devices and are rather universal.

Methods of the construction of the analog converting devices of measurement, registration and processing of signals in biomedical devices. Multi-digit analog-to-digital systems, as the variety of information systems comprise the systems of measurement, registration and processing of signals that is one of the spheres of engineering activity, where by means of electronic facilities registration, processing, accumulation, measurement and dissemination of information in the form of electric signals is realized [17].

At the same time, the above-mentioned systems include [17, 18]:

automated control-measuring technological units;

information-registration systems with digital recording and signals processing;

measuring complexes and devices for the analysis of the parameters and characteristics of the signals and paths.

Structural diagrams of these systems are shown in Figure 4, where – S1, S2, …, Sn – sensors; NA1, NA2, …, NAn – normalizing amplifiers; F1, F2, …, Fn – filters; B – buffer device; AS – analog switch; DA – difference amplifier; TE – threshold element; CC – comparison circuit; CCC – code-current converter; RSA– register of serial approximation; CU (MCU) – control unit (microprocessor).

Nowadays the above-mentioned systems of measurement, registration and processing of signals require analog-to-digital devices with rather high characteristics: dynamic range up to 100–140 dB; signal/noise ratio – 96/120 dB; coefficient of non-linear distortions – 0,001–0,002 %, spectrum of input signal frequencies – 16–20000 Hz, binary exit code length is 14–20 bits and sampling rate 44.1 kHz [19].

The most widely-spread devices in such systems are: ADC, DAC, buffer devices CVC, and VVC, sample-and-hold circuits (S/H circuits), etc. [20].

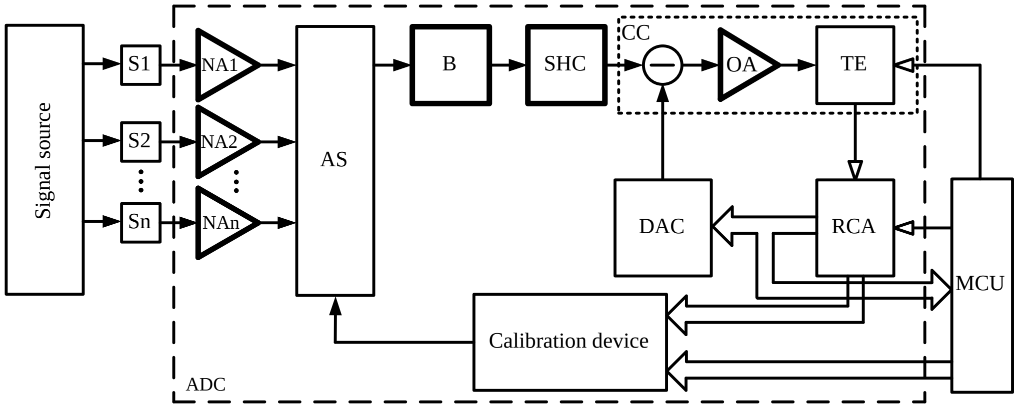

Fig. 4. Systems of measurement, registration and processing of signals with the calibration of the conversion characteristic: a) automated control-measuring technological unit; b) information – registration system of data collection and processing; c) analyzer of sound tracks parameters

Achievements in the sphere of digital technologies enabled the signals processing. One of the ways of the development of this priority direction both abroad and in our country is the construction and application of high-linear, multiple- digit ADC and DAC with weight redundancy [21]. However, in spite of the high performance of the existing ADC and DAC, their application in the systems of measurement, registration and signals processing remains current, as the element base in the form of analog devices with corresponding characteristics must be created. That is why, it is expedient to consider the system ADC and DAC not as functionally completed units but as a set of analog linear devices [19]. There exist such types of the above-mentioned devices: normalizing amplifiers; buffer voltage devices; current-voltage converters; voltage-voltage converters; analog signals sample-and-hold circuits; signals difference amplifiers for high sensitive comparators; filters of low and high-frequency signals; analog signals switches; alternative current signals amplifiers.

Almost in all modern high linear converters the elements of autocalibration and autocorrection are available, these elements provide efficient metrological characteristics due to the possibility to compensate for the primary errors of the element base. The correction is performed in a special mode, called self calibration and enables to determine real characteristics of the analog devices, as a result of applying the structural solutions with available feedback. The advantage of such approach is the possibility to provide high technical characteristics at the reduced requirements to the element base of the analog devices and technologies of their manufacture. The correction of static errors allows the application of circuit engineering solutions, providing high operation rate [19].

On the other hand, a high level of accuracy, achieved by means of self calibration can be provided only in case of low level of non correctable errors of the analog devices, ADC and DAC consist of. And this, in its turn, requires such an approach to the design, where along with structural solutions special circuit engineering methods, aimed at provision of high accuracy and operation rate, are used. As a result the analog devices of multiple digit ADC and DAC possess a number of features, enabling to distinguish their study in an independent branch.

Experimental results. Thus, having considered the specific features of the systems of measurement and processing of the signals, we make a conclusion that in the process of practical realization of ADC and DAC with self calibration, there exists a number of problems that require separate studies of the analog devices regarding their metrological characteristics, structural and circuit engineering solutions, methods of correction. Special attention should be paid to such analog devices as: AS, NA, OA VB, CVC, VVC and others, main requirements to these devices are given in Table 1. In its turn, the classification of the analog devices for the analog-to-digital systems is given in Figure 4.

Table 1

Requirements, regarding static and dynamic characteristics of the analog devices.
Specific features of the structure

Linear devices	Operation rate	Linearity	Symmetry of the transient characteristics	Availability of OA
Analog switches	+	+	–	–
Buffer devices	+	+	+	+
Sample-and-hold circuits	+	+	–	–
Current-voltage converters	+	+	+	+
Voltage-voltage converters	+	+	+	+
Difference amplifiers	+	+	+	+

However, the application of the single-stage DCA is not very advantageous because such circuits introduce considerable distortions in the form of the signal being processed. The drawback is also different duration of the leading edge and trailing edge of the pulse signal and narrow band of the complete non-distorted power [2], as it is shown in Figure 5. Recently for the construction of the analog devices with the wide bandwidth the so-called current conveyors, with the corresponding switching circuits such as DCA, VB, CVC, VVC are used.

The characteristics of such devices are described by the relations:

DCC: $I_{out} = I_{in} \cdot \frac{R_1}{R_2}$; VB: $U_{out} = U_{out} \cdot \frac{R_{load}}{R_1}$;

VCC: $U_{out} = -I_{in} \cdot R_1$; VVC: $U_{out} = U_{in} \cdot \frac{R_{load}}{R_1}$.

As it is known, frequency operation range of OA-based circuits is limited by FBC. The increase of the dynamic and frequency ranges of the analog devices can be realized in the process of transition to signal processing in the current basis 18, 19). Circuit, operating in the current basis, has smaller resistance values in the nodes. Thus, maximum voltage values in the internal nodes of the circuits are smaller than signal processing in the voltage basis.

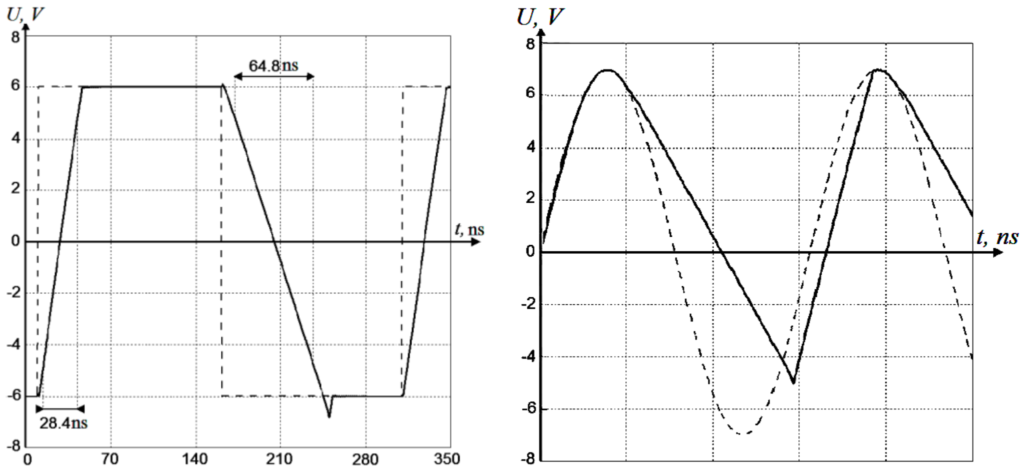

Fig. 5. Limitations of the dynamic characteristics of the single-stage DCA: a) symmetricity of the transient characteristics; b) distortion of the sinusoidal output signal

Another approach to the construction of DCA is the usage of the push-pull structures. Thus, it was impossible to make use of the advantages provided by PDCA with the symmetrical structure. The alternative approach is the construction of PDCA with loop-through amplification channels [19–21], its structural diagram is shown in Figure 6, that enables it to achieve the symmetry of the leading edge and trailing edge of the output signal.

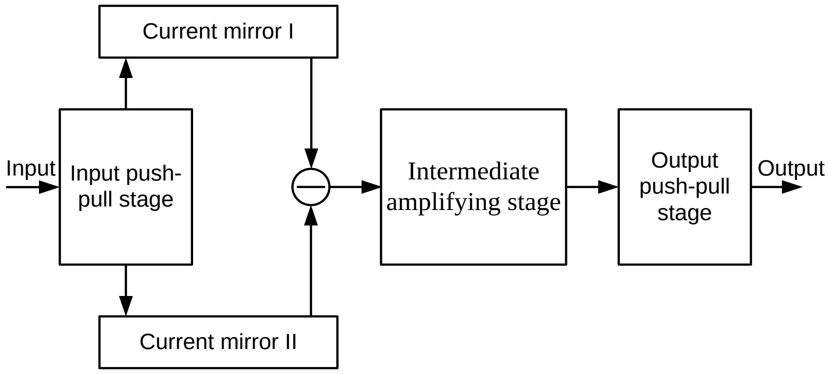

Fig. 6. Structural diagram of modern PDCA with the loop-through amplification channel

Characteristic feature of the given approach is the usage of CR, which determines the increment of the current flowing across the input stage.

It is known, that Analog Devices company manufactures PDCA AD810–AD815, Intersil – EL5160–5165, ON Semiconductor – NCS2501, NCS2510, NCS2511, NCS2530 and NCS2535 [22, 23]. Their basic characteristics are shown in Table 2.

Table 2

Characteristics of the modern PDCA with the loop-through amplification channels

Model	Bandwidth, MHz	Slew rate, V/ms	Input offset voltage, mV	Input offset current, mA	Distortion/ Frequency, dB/ MHz
AD810	80	1000	1,5	2	–61/5
AD811	140	2500	0,5	2	–74/5
AD812	145	425	2	0,3	–90/1
AD813	100	250	2	0,5	–90/1
AD815	120	900	10	2	–66/1
EL5160	200	1700	5	–	–50/5
EL5161	200	1700	5	–	–50/5
EL5162	500	4000	5	–	–50/5
EL5163	500	4000	5	–	–50/5
EL5164	600	4700	5	–	–73/5
EL5165	600	4700	5	–	–73/5
NCS2501	200	450	4	4	–55/5
NCS2502	110	230	4	20	–49/5
NCS2510	1400	2500	4	35	–69/5
NCS2511	1000	2500	10	35	–67/5
NCS2530	200	450	4	5	–55/5
NCS2535	1400	2500	10	35	–69/5

Analyzing the Table we make a conclusion that PDCA, constructed according to the considered structure, possesses good dynamic characteristics. At the same time, it is worth mentioning that the general gain factor determines IAS and PPOS, as CR has the transfer coefficients close to unit and OPPS – ½ [21]. The enhancement of the gain factor is possible by means of increasing the amount of the amplifying stages, but the usage of the great quantity of IAS leads to great phase shifts, the correction of these shifts P will result in the reduction of PDCA operation rate [19–20]. The drawback of such circuits is the possibility of operation only with low ohmic loading and great dependence of the gain factor on the loading resistance [22, 23]. The corresponding AFC is shown in Figure 7.

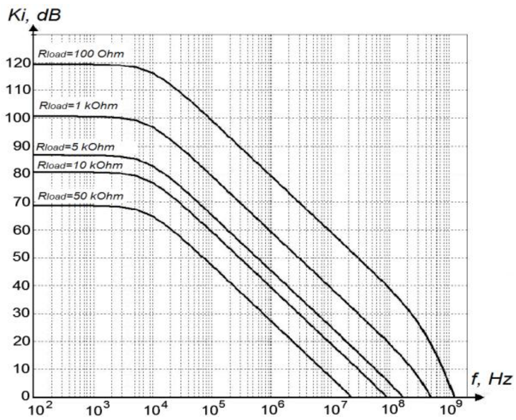

Fig. 7. AFC of PDCA with the loop-through amplification channel at the change of the load resistance

The solution of the problem of direct current mode setting was by means of introduction in the circuit current compensators (CC), which provide identical operation modes of DCA stages [14, 22]. This enabled the construction of PODCA with the separated amplification channels, characteristic feature of these channels is the available auto balancing of the operating points of the intermediate transistor stages.

Conclusions and prospects for further research. At the same time, it is worth mentioning the advantages that could be achieved constructing DCA, using push-pull structures: high operation speed; symmetrical transient characteristic at the reaction on the input bipolar pulse; high Slew rate; large bandwidth; maximum usage of the frequency properties of the transistors up to boundary frequency ft.

The developers of the analog-to-digital systems often face the problem, dealing with the choice of the amplifier, which operates with low errors of constant level transmission. The problem of signal matching also remains in the focus of the developers' attention, as the current DAC the circuit of OA switching is used as CVC, whereas for DAC with voltage output VB and VVC switching circuits are used. Efficient approach to the construction of such kinds of analog devices is the usage of the transimpedance amplifiers. They combine both high linear direct current parameters and excellent characteristics of alternating signal amplification. In the conventional OA with the closed feedback at the increase of amplification the bandwidth proportionally decreases. Transimpedance amplifiers, on the contrary, provide relative independence of the values of the bandwidth and amplification when the feedback circuit is closed at low values of amplification, nearly 20–30. When the gain factor starts to grow, then the frequency characteristic of the transimpedance amplifier behaves as the characteristic of OA.

Characteristics of these circuits on the changing signal have differences in the circuit configurations. High resistance input stage worsens certain parameters of OA at the amplification of the changing signals. Incompliance between the resistance of the signal source and the input resistance of the first stage of the amplifier creates a parasitic pole, which causes the distortion of the output signal. This influences the bandwidth and worsens the linearity and distorts the form of the output signal.

Besides, negative feedback in the ordinary OA creates quasizero potential at the inverting input, which enables us to consider this point to be virtual earth. For the stability of the amplifier with the negative feedback phase-correcting circuits are to be introduced, for instance, the circuit with feed forward high frequency components. The feed forward correction breaks the linearity of the phase characteristic of the amplifier.

Thus, as compared with the existing OA, transimpedance amplifiers have smaller levels of distortions, large bandwidth and symmetry of the reaction on the bipolar rectangular input pulse. The advantages of the transimpedance amplifiers are determined namely by the push-pull structure of such devices. CVC and VVC, constructed on the basis of devices exceeding by their characteristics CVC and VVC, constructed on the basis of OA.

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Перетворювачі інтегральних сигналів пристроїв вимірювально-діагностичних температурних сенсорів для біомедичних застосувань

У матеріалах статті наведено результати дослідження, що є перспективним напрямом у побудові високолінійних аналогових пристроїв для систем вимірювання, реєстрації та обробки сигналів біомедичних застосувань для використання двотактних структур. Незважаючи на різноманітність існуючих моделей високолінійних пристроїв виробництва провідних всесвітньо відомих компаній, зокрема, Analog Devices, National Semiconductor, Texas Instruments, Linear Technology, ON Semiconductor, Philips, Inetrsil, існують можливості подальшого вдосконалення їх характеристик. У роботі аналізуються кола первинного перетворення високочутливих диференційних сенсорів температури на транзисторних структурах та визначаються оптимальні режими роботи диференційних транзисторних каскадів сенсорів різницевої температури для пристроїв біомедичного призначення. Розробники аналого-цифрових систем часто стикаються з проблемою вибору підсилювача, що працює з малими похибками передачі постійного рівня. Проблема узгодження сигналів також залишається в центрі уваги розробників, оскільки в сучасних ЦАП як ВАХ використовується схема комутації ОА, а для ЦАП з виходом напруги VB і VVC використовуються схеми комутації. Ефективним підходом до побудови подібних аналогових пристроїв є використання трансімпедансних підсилювачів. Вони поєднують в собі як високі лінійні параметри постійного струму, так і ефективні характеристики змінного посилення сигналу. Поряд з освоєнням нових мікроелектронних технологій виготовлення теплових сенсорів потоку, зокрема на основі MEMs-структур, подальший розвиток цих сенсорів для задач медичної діагностики є перспективним і розв’язує задачу підвищення ефективності параметрів сигнальних перетворювачів.

Ключові слова: теплові сенсори потоку; сигнальні перетворювачі; інтегральна електроніка для біомедичної електроніки; біомедична діагностика.

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