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REALIZATION OF SIGNAL CONVERTERS OF THE THERMAL SENSORS AND HIGH-LNEAR ANALOG DEVICES OF BIOMEDICAL DESIGNATION

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Анотація. В статті розглянуто шляхи вирішення проблеми нестабільності ітераційних процесів при аналізі ВАХ вимірювальних перетворювачів з від'ємним диференційним опором, обумовленим самонагрівом цих перетворювачів. Розроблено експрес-метод визначення меж, в яких забезпечується коректний електротепловий DC аналіз. Запропоновано спосіб синтезу електротеплових моделей терморезистивних, діодних та транзисторних структур первинних перетворювачів теплових сенсорів потоку. На відміну від відомих пакетів схемного моделювання (PSpice чи MicroCAP) запропонований спосіб дозволяє за один цикл DC аналізу отримати ВАХ з врахуванням самонагріву вищевказаних перетворювачів. Розроблений диференційний термометр є універсальним пристроєм вимірювання різниці температур, зокрема для реалізації теплових сенсорів потоку, засобів біохімічного аналізу, теплопровідності тощо, і характеризується роздільною здатністю вимірювання різниці температур – не гірше 0,001°C.
Ключові слова: вимірювальні перетворювачі, електротеплове моделювання, самонагрів перетворювачів, біомедичні прилади та системи.
Abstract. Considered problems of instability of iterative processes in the analysis of I/V measuring converters with negative differential resistance caused by self-heating of these converters. An express method of determining the limits in which correct electrothermal DC analysis is provided has been developed. A method of synthesis of electrothermal models of thermoresistive, diode and transistor structures of primary converters of thermal flow sensors is proposed. In contrast to well-known circuit modeling packages (PSpice or MicroCAP), the proposed method allows you to obtain I-V characteristics in one cycle of DC analysis, taking into account the self-heating of the above-mentioned converters. The developed differential thermometer is a universal device for measuring the temperature difference, in particular for the implementation of thermal flow sensors, means of biochemical analysis, thermal conductivity, etc., and is characterized by a temperature difference measurement resolution of no worse than 0.001°C.
Keywords: measuring transducers, electrothermal modeling, biomedical devices and systems.

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INTRODUCTION

Proceeding from the results of modeling analysis and optimization of the circuits of primary converters of microelectronic thermal flow sensors, considered in the previous sections, we will examine main approaches to circuit realization of the signal converters of the above-mentioned sensor devices. The actuality of the problem of circuit engineering of sensor flow devices, including thermal flow sensors of biomedical designation, is stipulated by several factors.

First, circuit solutions, applied in the conventional signal converters, in particular, for measuring circuits of thermoresistive type, do not meet the requirements regarding the minimization of the energy expenses of microelectronic thermal flow sensors. Secondly, due to the transition to low voltage supply sources, minimization of the parasitic impact on the result of the measurement of the resistances of signal transmission lines becomes very important. Third, in the process of the development of sensor devices of flow speed measurement, all the requirements, regarding their correspondence to modern trends of microelectronic sensors development,in particular, interface compatibility, possibility of program control of the measuring process, expanded functional possibilities, correspondence to the intelligent sensors IEEE1451.2 standard, correspondence to the requirements to the equipment of biomedical designation.

Besides, it is necessary to take into account the trends of the development of modern microelectronics element base, renovation of which occurs every several years. Only the correspondence to the level of the last generation of element base makes electronic devices compatible. That is why, the realization of the approaches, obtained in the given research on modern element base, in particular, high linear analog devices is very important.

METHOD

Basically important parameter of the thermoanemometric sensors is the temperature of the heater. As a rule, the warming up of the heater is performed by the fixed power, connecting it to the stable supply voltage. The power is selected so that the heating temperature was several tens of degrees. Such approach provides simple circuit engineering realization and calibration of the flow sensors. Flow temperature has minor impact on the calibration characteristic – at stable thermal resistance of the sensors structure with the change of the flow temperature the temperature of the heater will also charge thus the temperature difference in the direction of the flow motion, in the first approximation will be only the function of the flow speed.

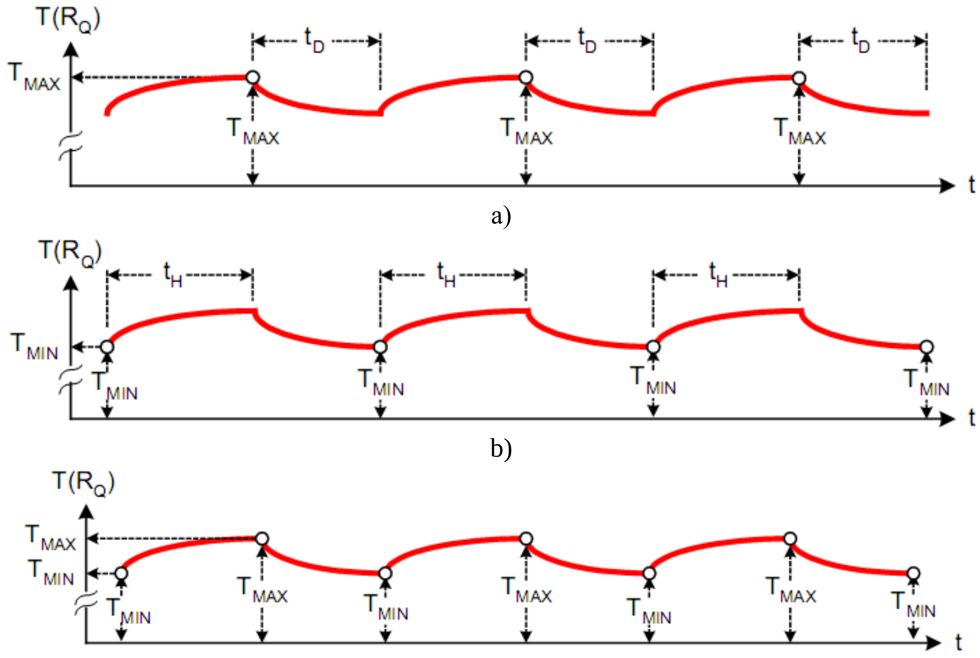
However when the flow speed increases above the certain value the loss of sensor sensitivity is observed, i.e., the decrease of temperatures TS2–TS1 difference, it is stipulated by the corresponding decrease of the heater temperature(HT) as a result of its intensive cooling by the flow. It is obvious, that such solution is not expedient from the point of view of the efficient energy consumption. Besides, in the flow sensors of medical designation, in particular, for measuring of the speed or voluminous losses of biological fluids in the devices for biochemical analysis, it is inadmissible the exceedance of the heater temperature above certain critical value at which thermal degradation of the substance occurs.

Proceeding from the above-mentioned, the problem of the development of the controllers of thermoanemometrs flow sensors temperature mode is put forward, these devices enable to expand the range of flow speed measurement, minimize the energy consumption of the device and limit the heating of the flow substance. This task provides the solution of two problems. The first problem is the necessity to measure the temperature of the heater without using the additional temperature sensor. The information value of the heater temperature must be the dependence of its resistance on the temperature. The second problem is the necessity of using band-pulse key circuits of warming up power control, unlike the circuits of linear control; it provides high energy efficiency of the controller.

The principle of temperature stabilization of the heater of thermoanemometric flow sensor, when thermoresistive structure of the heater is used both as the source of heat and a sensor of its temperature, provide the formation of the pulse mode of the periodic switching between heating and cooling of the structure [1]. The necessary condition of such mode realization is the available temperature different of the resistance (TCR) of the heater. As a rule, the realization of such condition is not problematic – greater part of the heaters materials are of thermoresistive type, for instance, cooper, silicon or polysilicon, the values of TCR is within the range of (0,1–0,5) % /◦ C. Thus, the task is reduced to periodic measurement of the resistance of the thermoresistive heater and fixation of this resistance at certain level by means of switching from heating to cooling.

The periodic switching mode can realized by the following criterion: fixation of cooling phase duration (Fig 1a), fixation of heating phase duration (Fig 1b), and the preset temperature hysteresis between the periods of heating and cooling (Fig 1c).

In the first of them, measurement of the heater temperature is performed in the process of its heating, which lasts till the moment of reaching the preset temperature value (T_{MAX}). After that the phase of cooling starts. In order to minimize the switching losses the cooling stage has certain fixed duration (t_D), in the process of which thermal relaxation occurs. For typical thermal anemometers the value of thermal relaxation can be approximately 1% of the difference of temperature between the heater and the flow. Taking into account the heat capacity of the structure of sensors, the duration of cooling can be 1-100ms. The second criterion – fixed duration of heating (t_H) provides measurement of heater temperature in the process of its cooling to the value T_{MIN} after that the heating phase of the fixed duration. The third criterion provides the preset hysteresis of the temperature $T_{MAX} - T_{MIN}$ and provides measurement of the latter in both phase, duration of these phases is not fixed.



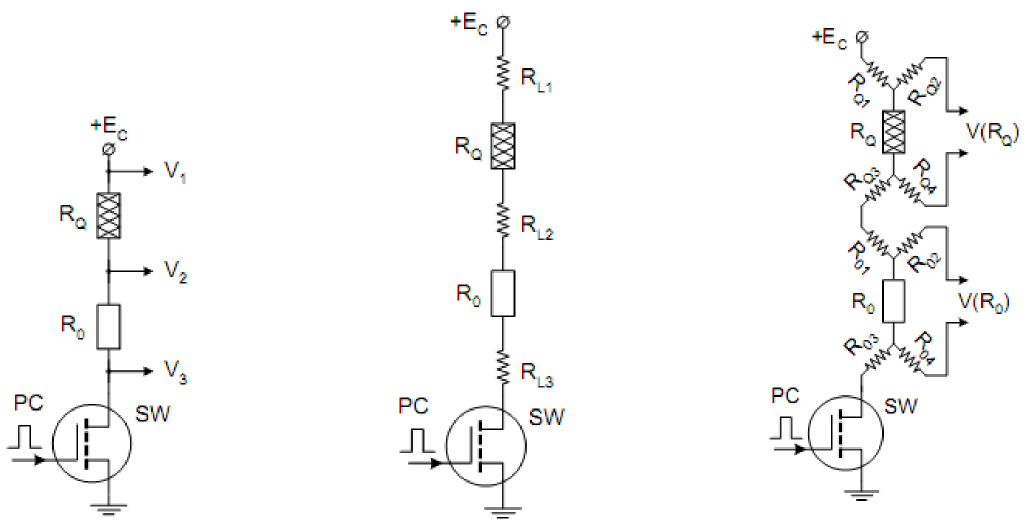
c)

Figure 1 – Time diagram of thermostability: a) with fixed duration of cooling phases;
b) heating; c) preset hysteresis of heating-cooling

The example of the realization of the controller of the heater temperature mode by the criterion of the fixation of the cooling phase duration , i.e., while temperature measurement in the process of heating, is presented below . As we established in the process of structural-algorithmic analysis, such mode is characterized by the optimal ratio between the accuracy of stabilization and structural expenditures for its realization.

It is important to note that unlike the conventional thermoresistive circuits of temperature measurement, the application of the measuring circuits of bridge type in the given task is impossible. This is stipulated by the impact of parasitic resistance of the signal line of thermoresistive heater.

We will analyze the given problem, for this purpose we will consider the half bridge circuit of the converter with the controlled heating power (Fig 2a).



a) b) c)

Figure 2 – Switching stage: a) of the temperature mode controller; b) its parasitic resistances; c) circuit of the minimization of the impact of these resistances.

In the first of them, measurement of the heater temperature is performed in the process of its heating, which lasts till the moment of reaching the preset temperature value (T_{MAX}). After that the phase of cooling starts. In order to minimize the switching losses the cooling stage has certain fixed duration (t_D), in the process of which thermal relaxation occurs. For typical thermal anemometers the value of thermal relaxation can be approximately 1% of the difference of temperature between the heater and the flow. Taking into account the heat capacity of the structure of sensors, the duration of cooling can be 1-100ms. The second criterion – fixed duration of heating (t_H) provides measurement of heater temperature in the process of its cooling to the value T_{MIN} after that the heating phase of the fixed duration. The third criterion provides the preset hysteresis of the temperature $T_{MAX} – T_{MIN}$ and provides measurement of the latter in both phase, duration of these phases is not fixed.

If E_C = 5V and heating power 1W the resistance of the thermoresistive heater is R_Q = 25 Ohm. To minimize the losses of the thermal power at the reference resistor it is expedient to take R_0 =1Ohm. Taking into account that the parasitic resistances of the circuit are also within the limits of Ohm units, measurement of the temperature by means of the direct measurement of the resistance of the thermoresistive heater or bridge circuit is impossible – parasitic resistance of the circuit introduce inadmissibly large error. To solve this problem as a rule the four-point connecting circuit is used (Fig. 2c).

When high-ohmic input circuits of voltage amplifiers $V(R_Q)$, $V(R_0)$ are used, the voltage drop tends to zero. However, measuring circuits of these voltages lose the common point, this makes circuit engineering of such signal converter rather complicated and requires high precision two-channel, in particular 24 bits analog-to-digital converters with the differential input. The problem is that such analog-to-digital converters are characterized, firstly , by considerable energy consumption, and, secondly, by rather high manufacturing cost. This limits, to a great extent, the usage of such types of converters in the portable measuring devices.

Taking into account the above-mentioned, the task was put forward to develop the controller of the temperature mode of the thermoanemometric flow sensors that would combine high operation accuracy, small energy consumption and low manufacturing cost. The analysis, carried out, showed that the circuits, based on the analog integrators would be the optimal solution of the problem. Circuits of such integrators are usually applied in the analog-to-digital converters of the double integration and sensor devices of the capacity type [5, 6]. These signal converters are most precise and at least by order exceed the parameters of the circuits with the direct digital conversion. As we will show below, push pull circuits of the analog integration are able to carry out the function of signal transform from one potential level on the other, that is very important when using four-point measuring circuits.

Basic elements of the integrators (Fig. 3) are the operation amplifier (OA) and RC feedback circuit.

Input voltage V_{IN} is converted into the current $I_{IN} = V_{IN} – V_{REF}/ R$, where V_{REF} – is a reference voltage and the current I_{IN} , accumulating the charge of the capacitor C, forms the voltage on it V_C , which in the first approximation is directly proportional to the current I_{IN} and the time of the integration t and is inverse proportional to the electric capacity of the capacitor C. Output voltage of the integrator is $V_{OUT} = V_C + V_{REF}$.

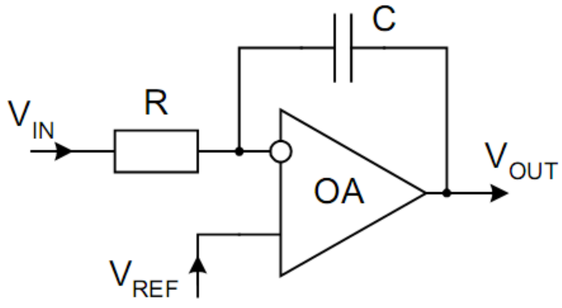
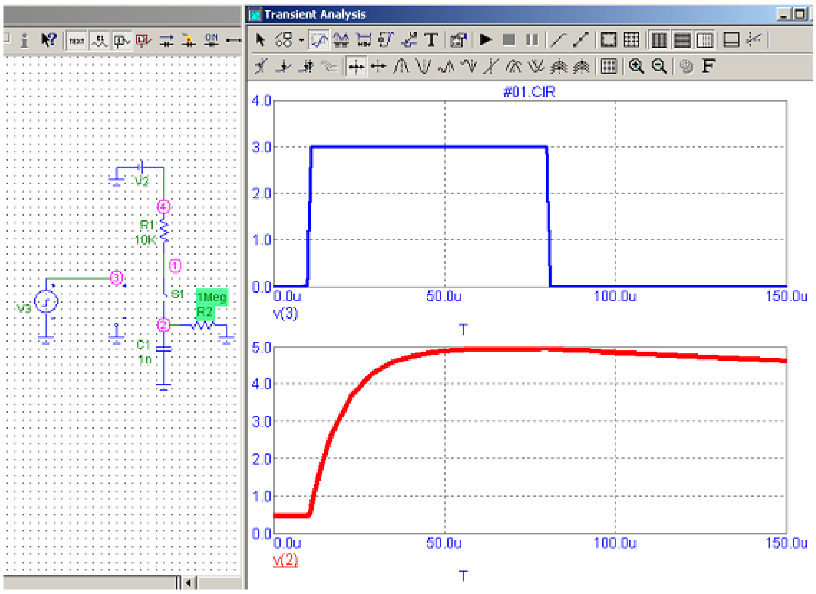


Figure 3 – Functional (simplified) diagram of the integrator

However, as it was mentioned above, measuring voltages $V(R_Q)$, $V(R_0)$ (see Fig 2c) do not have common reference point and this requires more detailed study of the processors of signal conversion. We will consider main approaches to circuit modeling of the integrators signals. Actually, the analog integrator is not completely analog circuit, it requires switching circuits, in particular, for the determination of time intervals of the integration or setting to zero the capacitor. That is why, it is referred to the approaches to mixed modeling, where both analog and digital (discrete) components are used.

RESULTS OF MODELLING

To realize the mixed modeling the monitoring keys are used, as it is show in Fig 4.



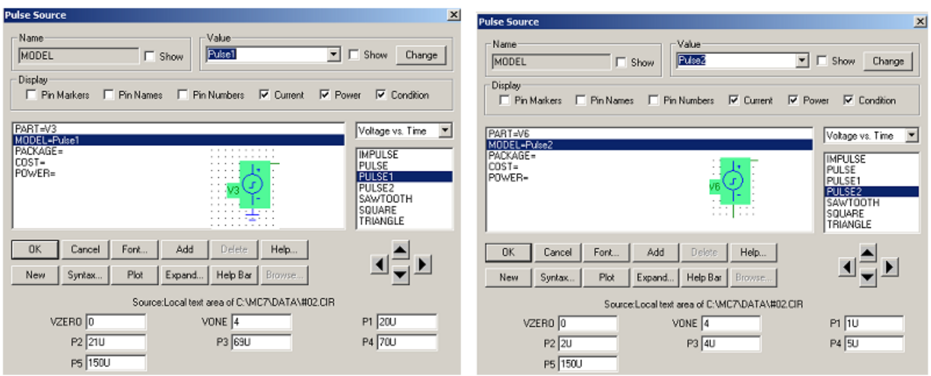
a)

b)

Figure 4 – Example of the mixed circuit modeling: a) control pulse; b) voltage at R2C1 element

Such circuit contains RC [1-16] section, presented by *C*1 and *R*2 elements, which is charged by the current across the switching key *S*1, the value of the current is determined by the resistor *R*1. Control pulse is formed by the source *V*3. As it can be seen from the time diagram the time constant of the circuit is determined by two parameters – resistor *R*1 resistance in the process of charging and resistor *R*2 resistance in the process of discharging the capacitor *C*1.

For modeling study of the integrator circuit it is necessary to use two sources of the pulsing voltage, the example of these sources specification is shown in Fig 5. The first source (*V*3, model PULSE1) forms time intervals of the integrated voltage pulse, and the second source (*V*6, model PULSE2) – period of the integrator reset (capacitor discharge).



a) b)

Figure 5 – Specification of the control sources of the pulsing voltage:
a) model PULSE1; b) PULSE2

The example of the model circuit of the integrator and the result of its study is shown in Fig 6.

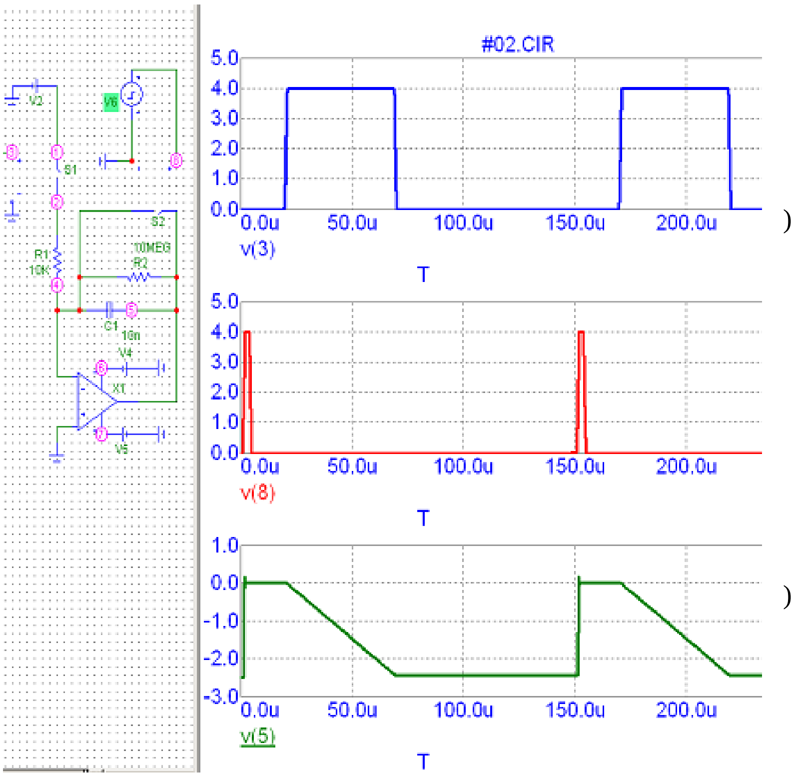


Figure 6 – Result of the modeling study of the integrator: a) input voltage pulses; b) reset pulses; c) output voltage pulses

The pulses of the input voltage, the amplitude of which is determined by the source of voltage V2, are formed by the monitoring key S1. The transformation of the input voltage in the current occurs at the resistor R1, one of the outputs in the time interval of integration is connected across the monitoring key to the source of the input voltage, and the second output – to the inverse input of the operational amplifier X1. The latter is supplied by two voltage sources V4 (–3 V) and V6 (+3 V). The reset of the integrator is performed by the key S2, controlled by the pulse voltage source V6.

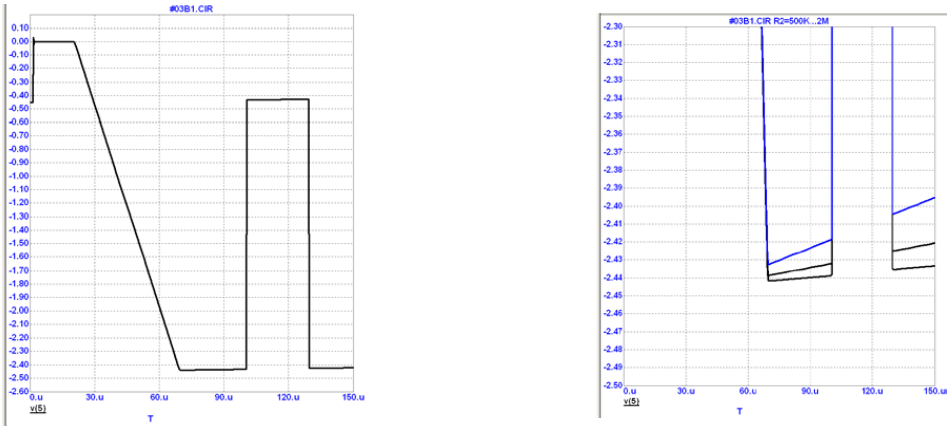
The capacitor of the integrator C1 is shunted by the resistor R2 (10mOhm), which simulates the parasitic leakage current of the capacitor and key S2. The presence of this parasitic current limits the accuracy and time characteristic, namely – time of signal storage after the integration period.As it is seen from the result of the research, three time intervals of the integrator output voltage formation are observed. In the first interval (up to 20 μsec) the output voltage is zero. Resetting is performed by the short (approximately 1 μsec) pulses. It is important to maintain zero level of the output voltage from the termination of the resetting pulse to the start of the integration of the input voltage.

In the next time interval (from 20 μsec to 70 μsec), where the source of the input voltage is connected to the integrator, the linear increase or decrease of the output voltage occurs. In case of the additive polarity of the input voltage the output voltage decreases (as it is shown in the above-mentioned example) and in case of negative polarity of the input voltage – the output voltage increases.

In the third interval (from 70 μsec to 150 μsec), where the input voltage is disconnected from the integrator, the latter maintains the output voltage at the constant level (approximately – 2,5V for this example). In this interval the output voltage of the integrator is converted into a digital code, is compared with a certain reference value of the voltage or is stored till the beginning of the next cycle of the push-pull integration. After the third interval (150 μsec) the reset pulse is sent and the cycle of the integration operation is repeated.

Further in the work the application of the considered integrator in the circuit of push-pull integration will be shown – in the first stage the measurement of the current across thermoresistive heater was carried out, and in the second, counter phase stage – the measurement of the voltage on the heater was carried out. The result of such integration is the voltage, that acts as the informative value of the temperature of the heater of thermoanemometric flow sensor and is used for temperature stabilization of its operation.

As it is seen, the non-stability of the output voltage of the integrator for the parameters of the element base of the circuit, integrated in the model (in particular, the input currents of the operation amplifier and the resistance of the resistor, shutting the capacitor of the integrator) do not meet the above-mentioned requirements, concerning the accuracy (typically, the error must not exceed 0,1%). We give this example of the model study only to draw the attention to the problem of the element base selection and the results of the correct selection and real parameters of the pilot specimen of the temperature mode controller, created on the base of the integrator with the transfer of the potential will be given further in the given research.



a) b)

Figure 7 – Analysis of the nonstability of the integrator output voltage : a) simplified analysis; b) analysis with the iteration of *R*2 resistance [500 kOhm, 1 Mohm, 2 Mohm]

Proceeding from the above-considered circuit solutions and operation modes of the integrator with the potential transfer, we developed the controller of the temperature mode of the thermoresistive heater of the flow sensor. The controller contains two-channel push-pull integrator (operation amplifier (OA) with the integration circuits R_1C, R_2C) , comparator (CM) and paired signal switches SW_{1A}, SW_{1B}, SW_{2A}, SW_{2B} (Fig 7). The first channel of the controller is connected to the reference resistor *R0* , the voltage drop at this resistor is the informative value of the current, flowing in the circuit of the heater. The second channel is connected to the thermoresistive heater R_Q ,the voltage drop at this heater is the informative value of its temperature.

Measurement and stabilization of the thermoresistive heater temperature takes place in two stages, controlled by the pulses of PC1, PC_2, PC_3 from the microcontroller (it is not shown in the Fig). As it was determined in the process of the problem setting, it is important to note that to realize the proposed circuit of the temperature mode controller high precision analog-digital converters are not needed.

PRACTICAL REALIZATION

Instead, any inexpensive microcontroller could be used, it makes the suggested circuit economically efficient.

As the control switches (two-channel analog multiplexors), which switch the analog signals of the input circuits of the integrator, CMOS integrated circuits ADG744 are used (Fig 8) [20]. These switches are characterized by the possibility of high precision switching of the bipolar signals and minimal resistance in the open state (not higher than 4 Ohm). Unique functional characteristic of such switches, having principal significance for the development of the low voltage electronic equipment is the possibility of the signals switching in the full range of the circuit supply voltage (Rail-to-Rail operation), normal switching mode takes place already at the supply voltage of 3V.

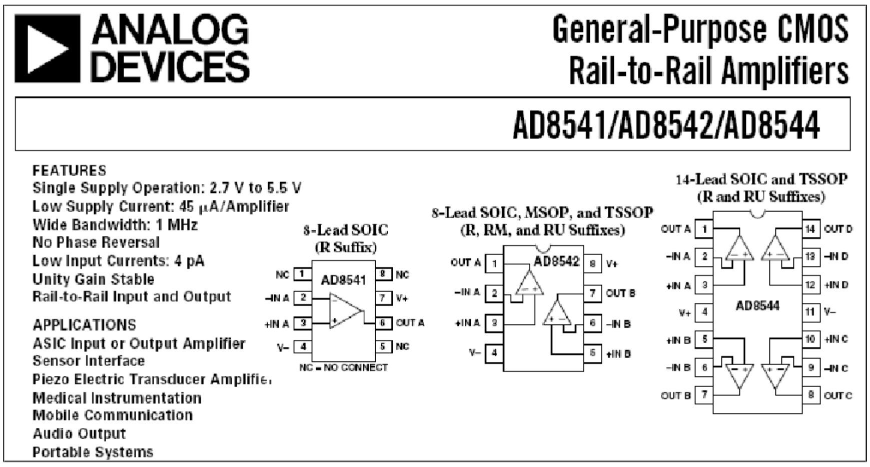


Figure 8 – Brief information about AD8541/2/4

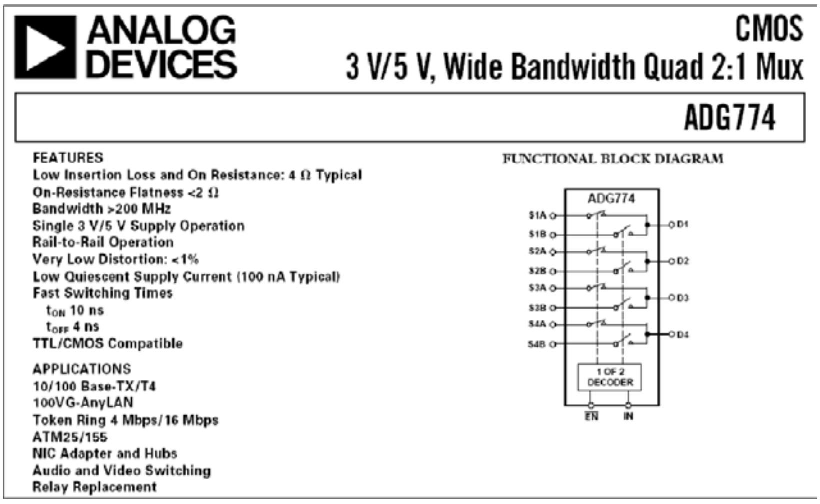


Figure 9 – Brief information about ADG774

Important is the selection of the power switch, which controls the supply circuit of the heater. Its determining parameter is the minimal resistance in the open state. We have selected MOSFET transistor IRLML2803 [20], manufactured by HEXFET® technology, it is characterized by the resistance in the open state of 0,25 Ohm (Fig 100). Such unique parameters are obtained due to the original construction of the transistor and high degree of the structure integration (actually this transistor integrates several tens of thousands of field-effect-transistors and many other elements, in particular, guard diodes and guard-rings).

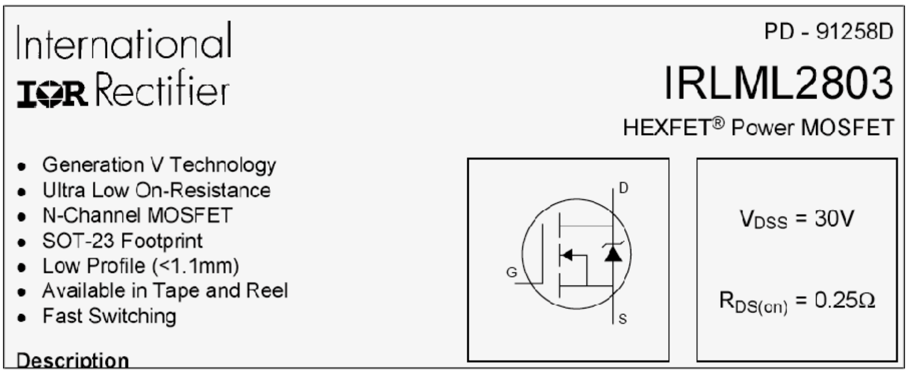


Figure 10 – Brief information about IRLML2803

The transistor is used only in switch mode – either completely closed or completely open. In the process of heater supply circuit switching (by the current of not higher than 1A) such operation mode and minimal resistance of the transistor in the open state provide minimal power losses and the transistor is not practically warmed up.

The external view of the studied prototypes of the controller of the temperature mode heater and the interface unit of the signal convertor of the flow sensor is shown in Fig 11.

In the process of the adjustment and study of the controller parameters first of all the accuracy of the integrator operation, in particular, the instability of the output voltage in the process of the potential transfer was determined . It was shown experimentally, that due to the application of the above-mentioned Rail-to-Rail CMOS operational amplifiers and controlled switches of the analog signal the voltage instability in the process of the push-pull integrator potential transfer does not exceed 0,03 %.

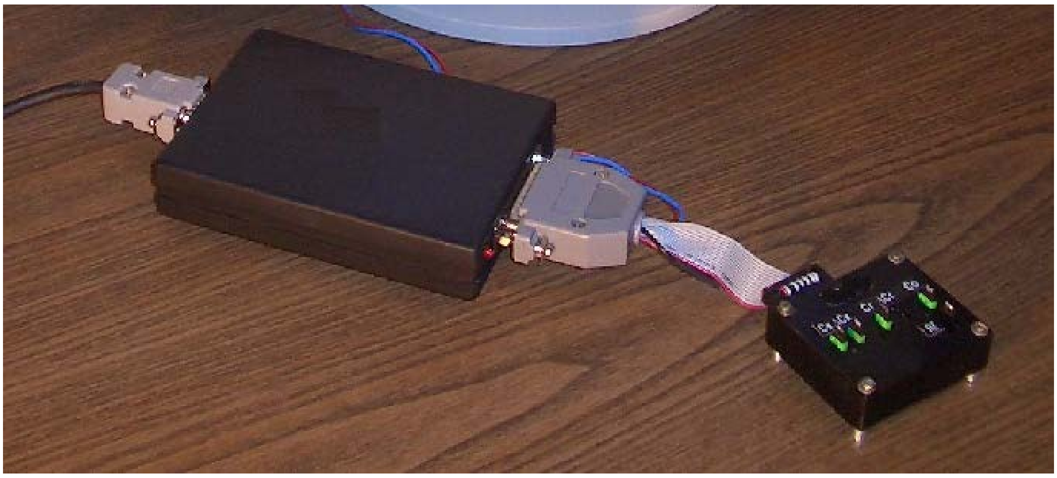


Figure 11 – External view of the controller prototypes (on the right) and the interface unit of the signal convertor of the flow sensor (on the left)

Main parameters of the controller of the heater temperature mode are:

- heating current – from 1mA to 1A;
- supply voltage (EV): +5V ± 10 %;
- type of measuring conversion: two stage integration;
- voltage measurement range: from 0.01 V to (EV–0,01) V;
- duration of one stage : from 0.01ms to 10ms;
- temperature stabilization error: not greater than 0,1ºC.

Conclusions

Considered problems of instability of iterative processes in the analysis of I/V measuring converters with negative differential resistance caused by self-heating of these converters. An express method of determining the limits in which correct electrothermal DC analysis is provided has been developed. A method of synthesis of electrothermal models of thermoresistive, diode and transistor structures of primary converters of thermal flow sensors is proposed. In contrast to well-known circuit modeling packages (PSpice or MicroCAP), the proposed method allows you to obtain I-V characteristics in one cycle of DC analysis, taking into account the self-heating of the above-mentioned converters. The developed differential thermometer is a universal device for measuring the temperature difference, in particular for the implementation of thermal flow sensors, means of biochemical analysis, thermal conductivity, etc., and is characterized by a temperature difference measurement resolution of no worse than 0.001°C.

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СХЕМОТЕХНІЧНА РЕАЛІЗАЦІЯ СИГНАЛЬНИХ ПЕРЕТВОРЮВАЧІВ ТЕПЛОВИХ СЕНСОРІВ БІОМЕДИЧНОГО ПРИЗНАЧЕННЯ

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