

A Method of Temperature Compensation in Semiconductor Pressure Transducers

Metoda kompensacji wpływu temperatury w półprzewodnikowych przetwornikach ciśnienia

Janusz Bryzek · Politechnika Warszawska · 1978

English translation

janusz.bryzek.com

Title page

WARSAW UNIVERSITY OF TECHNOLOGY

FACULTY OF PRECISION MECHANICS INSTITUTE OF METROLOGY AND MEASURING INSTRUMENT DESIGN

mgr inż. [M.Sc. Eng.] Janusz BRYZEK

METHOD OF COMPENSATION OF THE EFFECT OF TEMPERATURE IN SEMICONDUCTOR PRESSURE TRANSDUCERS

Doctoral dissertation

SUPERVISOR Doc. dr inż. [Dr Eng., Associate Professor] Wojciech WŁODARSKI

WARSAW

1978¹

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To my wife, Barbara, I dedicate this work

Translator's notes

1. original reads "mgr inż." (magister inżynier) and "doc. dr inż." (docent, doktor inżynier); "Praca doktorska" = doctoral dissertation, "PROMOTOR PRACY" = supervisor of the dissertation. The title page prints "CISNIENIA" without the diacritic; the intended word is "CIŚNIENIA".
2. the contents page is headed "SPIS TRESCI" and item 6.3.2 reads "Źródła", as printed, for "SPIS TREŚCI" and "Źródła". Page numbers are those of the typescript, as printed.

1. INTRODUCTION

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1.1. Introductory remarks

The principal application of measuring transducers for non-electrical quantities is in automatic control systems for industrial processes in industrial plants. Large plants may be equipped with several thousand transducers. Since a change in the temperature of the ambient and of the measured medium is the source of the most significant measurement error, each transducer has a built-in circuit compensating this error. The compensation circuit is the more difficult to realize, the wider the temperature range and the higher the transfer accuracy.

The problems of compensating temperature errors are the subject of an extensive patent literature. In the scientific and technical literature, on the other hand, they are presented sparingly and often as secondary matters. This situation arises for the following reasons:

- compensation circuits are used essentially only in transducers produced in series, and are consequently seldom developed by institutions detached from the manufacturing plant, that is, by universities and institutes,
- the cost of realizing temperature compensation may amount to as much as 50 % of the manufacturing cost of the transducer, depending on the choice of compensation method and the technology employed [1],
- the resultant temperature errors of the transducer (as an integral part of the transfer accuracy class) are a factor that significantly affects its selling price,
- the choice of compensation method is also a factor affecting the permissible operating temperature range, and hence the range of application of the transducer.

Thus the choice of temperature compensation method affects to a considerable degree the economic results of the manufacturer, who consequently keeps it as deep a secret as

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possible. Patent applications are filed as a necessary evil, owing to the need to protect the manufacturer's own proprietary rights on the market, and errors are often deliberately introduced into such applications to make the method harder to decipher.

The measure of the effect of changes in ambient temperature on the accuracy of measurement is the relative or absolute temperature error. The relative temperature error is most often expressed as a percentage of span, equal to the change of the parameter under consideration (e.g. the lower range value) referred to the span and to a specified change of temperature (e.g. 10 K). The absolute temperature error is most often defined as the difference between the values of the parameter under consideration at the temperature in question and at the reference temperature.

1.2. Aim and thesis of the work

The aim of the work is to develop a new, effective method of compensating the effect of temperature on the transfer accuracy of semiconductor pressure transducers, and to verify its applicability in practice.

By the name "compensation method" is understood in this work a method consisting in the use of a special electronic circuit, cooperating with a semiconductor pressure sensor, whose output signal is made temperature-dependent in such a way that it reduces the effect of temperature changes on the transfer characteristic of the measuring transducer containing this circuit and sensor.

The term "temperature" denotes the temperature at which the measuring sensor finds itself. Depending on the design, this may be the temperature of the measured medium, the ambient temperature, or a temperature resulting from the superposition of both of these temperatures.

"Semiconductor pressure transducer" denotes a transducer containing a sensor built from semiconductor elements, serving to convert the value of the measured gauge pressure (the difference

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between the measured pressure and atmospheric pressure) into a standard electronic signal.

As will be shown in Section 4, to compensate the effect of temperature on a linear transfer characteristic of the sensor it is sufficient to make the lower and upper range values independent of temperature. Accordingly, we may divide transducers into classes

according to the degree of the polynomial describing the temperature error of the lower and upper range values of the uncompensated transducer:

- linear, in which the error is a linear function of temperature
- quadratic, in which the error is a quadratic function of temperature
- cubic, etc.

The new method that is the aim of this work should make it possible to compensate the temperature errors of a given class of transducers by carrying out the compensation procedure at a certain number of discrete temperatures. The number of these temperatures should depend on the degree of the polynomial describing the temperature error. The values of the coefficients of the polynomial, on the other hand, should be established in the course of compensation so as to ensure the nulling of the error of the particular sensor.

The new method should be characterized by ease of introduction into series production, that is, by inexpensive production tooling and the use of mass-produced components. The number of different versions of the elements serving to realize the compensation conditions should be minimized.

The thesis of the work is formulated as follows: It is possible to develop a method of complete compensation of temperature errors in semiconductor pressure transducers using one compensation-setting element for each selected compensation temperature and for each compensated parameter of the transfer characteristic of the transducer, the settings of these elements being characterized by unidirectional independence. The number of compensation temperatures is determined by the degree of the polynomial describing the temperature error of the given parameter.

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Compensation realized by this method may be incomplete in the case where the number of compensation temperatures is smaller than the degree of the polynomial describing the temperature error characteristic of the sensor.

A compensation procedure for temperature errors using this method is moreover possible such that compensating the error at one temperature has no effect on the compensation at the preceding compensation temperatures.

It is also possible to make the compensation conditions for the lower range value and for the sensitivity of the sensor independent of each other.

2. THE NATURE OF TEMPERATURE ERRORS

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The relation between the unknown value of the non-electrical quantity, which we shall denote by X , and the value of the electrical output signal of the sensor, which we shall denote by U , is called the transfer characteristic and is described by the function f .¹

Owing to the presence of signals interfering with the operation of the sensor, such as a change in ambient temperature, supply-voltage fluctuations, the presence of vibration, changes in atmospheric pressure, the presence of interfering electromagnetic fields, etc., f is a function of many variables. In the further considerations we shall confine ourselves to taking into account only the effect of changes in the ambient temperature T , and so we shall assume that f is a function of the two variables X, T .

$$u = f(X, T) \quad (1)$$

The output signal u of the sensor may take the form of a change of voltage, current, resistance, capacitance, mutual inductance, etc.

For the unification of the receiving instrumentation in an automatic control system, the signals being processed should be standardized. To this end a measuring transducer consists of a sensor and a supplementary electronic signal-conditioning circuit, which brings the output signal of the transducer to the accepted standard signals¹. Such circuits, besides standardizing the transfer characteristic of the sensor, often make possible a linearity correction of the transfer of the non-electrical quantity X and compensation of the effect of ambient temperature. Thus the output signal U of the transducer is defined

¹ The signals most commonly encountered at present in industrial automation are the current signals 0 to 6 mA, 4 to 20 mA and the voltage signals 1 to 5 V. For a given controlled plant, one signal range is usually used, e.g. 4 to 20 mA.²

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by the transfer characteristic described by the function g :

$$U = g(X, T) \quad (2)$$

Temperature compensation can be realized in two ways [2]:

- the compensation circuit makes possible the correction of the temperature error of the sensor only, while the temperature error of the signal-conditioning circuit should be negligibly small in comparison with the error of the sensor. In such a case the use of expensive components and circuit designs in the signal-conditioning circuit is required,
- the total temperature error of the transducer is compensated, this being the superposition of the error of the sensor and of the signal-conditioning circuit, both at the same temperature, which permits the use of cheaper electronic components and simpler circuit designs. This case can be reduced to the first case on the assumption that the error of the signal-conditioning circuit is referred to the sensor, and that in the error analysis an equivalent sensor error will be considered, consisting of two components: the error of the sensor itself and the equivalent error of the signal-conditioning circuit.

As already mentioned, the transfer characteristic is defined by a function of two variables: the value of the output signal of the transducer and the value of the measured non-electrical quantity, and so its graphical representation will be a surface described by relation (2) (Fig. 1a). For practical reasons, several parameters characterizing the values of the temperature error of the transducer have been adopted. The most commonly used are: (a) the temperature error (drift) of the lower range value (the so-called "zero"), defining the effect of changes in ambient temperature on the value of the output signal U at a constant value of the measurand X equal to the lower value X_p of the measuring range; the graphical interpretation of this error is the line of intersection of the plane defined by relation (2) with the plane $X = X_p$ (Fig. 1b)

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(b) the temperature error (drift) of the upper value X_k of the measuring range (the so-called "span"), defining the effect of changes in ambient temperature on the value of the measurand X equal to the upper value X_k of the measuring range; the graphical interpretation of this error will be the line of intersection of the plane defined by relation (2) with the plane $X = X_k$ (Fig. 1c).

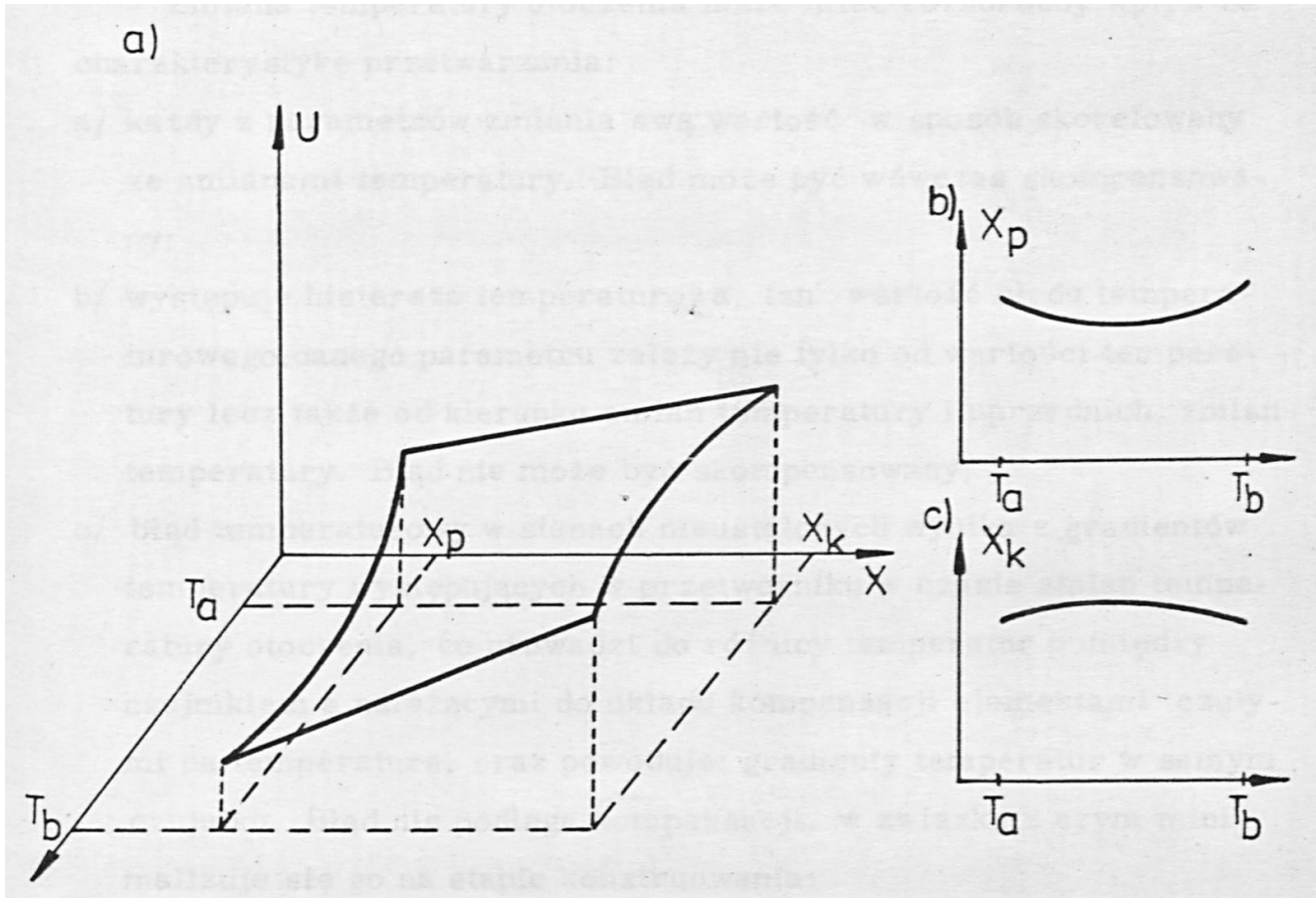


Fig. 1. a. Graphical representation of the transfer characteristic of the transducer, where: U output signal of the transducer, X measured non-electrical quantity, T temperature; b. Dependence of the lower range value X_p on temperature; c. Dependence of the upper range value X_k on temperature

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(c) the temperature error (drift) of the span, defining the effect of changes in ambient temperature on the output signal increment caused by a change of the value of the measurand from the lower value X_p to the upper value X_k ; this parameter is given in data sheets as an alternative to the temperature error of the upper range value.

A change in ambient temperature may have various effects on the transfer characteristic: (a) each of the parameters changes its value in a manner correlated with the changes of temperature. The error can then be compensated; (b) temperature hysteresis occurs, i.e. the value of the temperature error of a given parameter depends not only on the value of the temperature but also on the direction of temperature changes and on previous temperature changes. The error cannot be compensated; (c) the temperature error in transient states results from temperature gradients occurring in the transducer during changes in ambient temperature, which leads to a temperature difference between the sensor and the temperature-sensitive elements belonging to the compensation circuit, and causes temperature gradients in the sensor itself. The error is not subject to compensation, and is therefore minimized at the design stage; (d) the temperature-decay error (Engl. "temperature decay"), that is, an error occurring immediately after a change of temperature and decaying gradually to zero. It is not connected with transient states, but with changes, for example, in the crystal lattice of the sensor material, and it is the greater, the greater the change of temperature and the longer the time spent at the temperature preceding the change. The decay time of this error may be very long, of the order of several tens of hours. The error is not subject to compensation; (e) temperature non-repeatability, in which the value of a given parameter may undergo a permanent change as a result of temperature changes,

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especially in the case of prolonged operation near the temperature extremes. In such a case the transducer must be calibrated to recover the original value of the parameter. The error is not subject to compensation.⁴

Thus only the temperature error named in item (a) can be subject to compensation. The remaining components of the error can only be reduced by selecting a suitable technology and design of the sensor and transducer.

The purpose of compensation is to reduce the equivalent sensor error. The permissible value of the temperature error (the error limit) can be defined in two ways.

In the first way, the maximum value of the temperature error is specified, reckoned relative to the value of the given parameter at the reference temperature T_o , independently of temperature (Fig. 2a). Such requirements may be imposed where the mean-square error is to be limited for random values of the ambient temperature, as occurs, for example, when transducers are used in material-balance systems for the final product of an industrial plant.

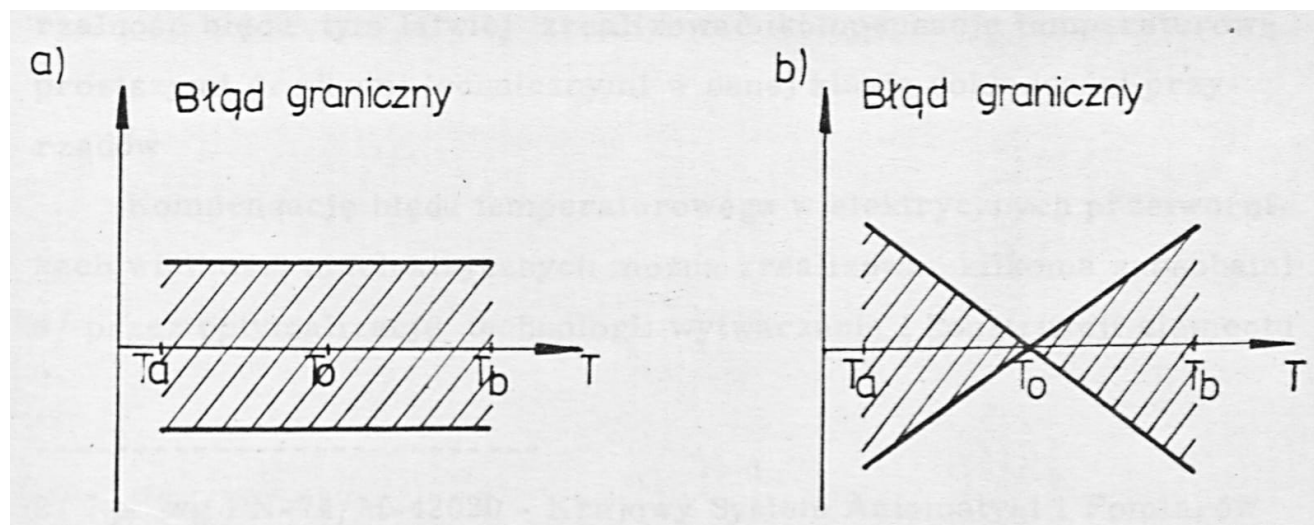


Fig. 2. Error limit as a function of temperature: a. of constant value; b. of constant slope

Labels: Błąd graniczny = error limit

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In the second method², the value of the slope of the error limit as a function of temperature is limited. Taking a certain temperature T_o as the temperature relative to which we measure the temperature error, the region of permissible values of temperature errors lies between two straight lines intersecting at the temperature T_o , with a slope equal to the imposed error limit (Fig. 2b).

The value of the temperature error limit is related to the accuracy class of the transducer. According to the Polish Standard³, the value of any additional error, including the temperature error, should not exceed the value preceding (in the series of accuracy classes) the value adopted as the accuracy class of the device. The temperature error of the transfer characteristic should be measured every 10 °C at an input signal of the non-electrical quantity equal to 0 %, 20 %, 40 %, 60 %, 100 % of the span for which the transducer has been calibrated.⁵

Considering the value of the temperature error of a given parameter over a population of transducers of a certain size, e.g. equal to the annual production of an industrial plant, one can distinguish a systematic (repeatable) part of the error and a random part, the ratio between these parts varying from zero (no repeatable part of the error) to a value close to 100 %. The greater the repeatability of the error, the easier it is to realize temperature compensation by simpler technical means within a given accuracy class of instruments.

Compensation of the temperature error in electrical transducers for non-electrical quantities can be realized in several ways: (a) by optimizing the manufacturing technology and the design of the transducing

² E.g. according to Polish Standard PN-74/M-42020, National System of Automation and Measurement POLMATIK — General requirements and tests — Additional errors are to be specified per 10 °C of change in the temperature of the ambient and of the measured medium. ³ Polish Standard PN-73/M-42024, Industrial automation — Analogue electrical elements and devices — Requirements and tests.

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element [3–24], e.g. a strain gauge. With this method one most often stops at the compensation of one parameter (zero) of the transfer characteristic of transducers made using highly repeatable transducing elements and with not very demanding requirements as to the compensation accuracy. It usually requires the use of several transducing elements in the sensor for the non-electrical quantity, enabling the use of a special electronic circuit, e.g. a bridge; (b) by means of a special non-electrical construction producing an additional, temperature-dependent value of the non-electrical quantity being converted [25–31]. Owing to great difficulties of

execution and low compensation accuracy, this method is now of historical significance only; (c) by placing the compensation circuitry in the analog part of the electronic circuit conditioning the sensor signal. This way is at present the most widespread [1, 32–76], owing to:

- the worldwide tendency in automation towards the integration of the sensor with the electronic signal-conditioning circuit,
- the possibility of obtaining small temperature errors of the compensated transducers,
- the possibility of unambiguous compensation of the temperature errors of the electronic signal-conditioning circuit,
- the possibility of compensating transducers whose sensors have a temperature error that is not repeatable from one unit to another,
- the decided predominance, at the present time, of analog automatic control systems over digital control systems; The method is often used together with the compensation named in item (a), and more rarely with the simultaneous use of the compensation named in item (b); (d) by realizing the compensation in the digital part of the automation system [78, 79], by software or by hardware. At the present time such a

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method is expensive, but nevertheless it allows the best measurement performance to be obtained. In the author's opinion, this method will supersede all other compensation methods in automation transducers once there is a decisive fall in the prices of microprocessors and a reduction in the supply current they draw, together with an increase in their level of integration and the introduction of cheap, easily programmable read-only memories (ROM) in which an individual correction program would be stored; (e) by thermostatic control of the sensor. Such a method eliminates the need for temperature compensation. It is, however, used only in very accurate laboratory instrumentation, e.g. [80].

From the above classification of the methods in use it follows that in an accurate measuring transducer produced in series, whose price is not a matter of indifference, the only design for temperature compensation at present is variant "c" — the use of a compensation circuit in the analog part of the electronic normalizing circuit, possibly with the use of variant "a" or "b".

The known compensation designs [1, 32, 77] are characterized by a mutual dependence either of the settings of the compensation circuit for one parameter (e.g. zero) on the settings of the compensation circuit for the second parameter (e.g. span), or of the settings of the compensation circuit at different temperatures. As a result the compensation procedure is tedious, and carrying it out requires highly qualified personnel and, not infrequently, recourse to a computer program.

Very high requirements as to metrological parameters (stability, temperature coefficient) are usually imposed on the elements correcting the temperature error. The values of these elements are determined only after the completion of the compensation procedure, that is, in the last phase of production. Allowing for the individual spread of temperature errors in each unit of the transducer requires keeping a suitably large stock of components in store (e.g. for the Honeywell Class 41 transducers [33, 39, 40],

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10 components in the compensation circuit are changed, with values selected from a set of about 130 values) or making them in-house [33].⁶

Translator's notes

1. original reads "którą oznaczymy przez U" for the sensor output, although equation (1) and the following paragraph use u for the sensor output and U for the transducer output; kept as printed.
2. original reads "0...6 mA"; elsewhere in the thesis the standard current signal is 0 to 5 mA. Kept as printed.
3. in items (a) and (b) the original says "płaszczyzny określonej zależnością (2)" (the plane defined by relation (2)), although the same paragraph has just called the graph of (2) a surface ("powierzchnia"); translated literally as "plane".
4. original reads "błąd zanikowy /ang. temperature decay/"; the author's own English term is kept. In item (e) the original ends page 12 with a comma and resumes page 13 with a stray full stop before "zwłaszcza" (especially); read as one sentence.
5. "additional error" (błąd dodatkowy) is the Polish-standard term for the error due to an influence quantity such as temperature; IEC usage would be "variation". The percentage series is printed as "0%, 20%, 40%, 60%, 100%" — 80 % is absent; kept as printed.
6. original reads "dopiero do zakończeniu procedury kompensacji" (page 16); "do" (until) is a typist's slip for "po" (after), translated as "after".

3. REVIEW OF METHODS OF COMPENSATING THE EFFECT OF TEMPERATURE USING COMPENSATION CIRCUITRY IN THE ANALOG PART OF THE SIGNAL-CONDITIONING CIRCUIT

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3.1. Introduction

The known circuit-compensation designs [1, 32–77] may be divided into three groups. The first group consists of designs in which the sensor for a non-electrical quantity is used at the same time as a temperature sensor. The second group is formed by designs in which, in order to sense the temperature of the sensor, components with a temperature-dependent resistance are used. In the third group of designs the temperature of the sensor is sensed by junction semiconductor devices.

Within the second and third groups we may further make a division according to the technology in which the temperature-sensitive elements are made, namely the use of discrete and of integrated components.

In the further part of this work examples of the most interesting designs will be presented.

3.2. Method using the pressure sensor as a temperature sensor

The method [61] developed at IAP PW (Institute of Industrial Automation, Warsaw University of Technology) was applied to the measurement of hydrostatic pressure, and of the temperature in the region in which that pressure acts, by means of a single sensor consisting of a semiconductor p-n junction with an arbitrary breakdown mechanism, supplied with an alternating square-wave current. The forward voltage U_p and the reverse voltage U_z are expressed by the following relations:

$$\begin{aligned}U_p &= U_{po} \cdot [1 + \alpha_p \cdot (p - p_o) - \beta_p \cdot (T - T_o)] \\U_z &= U_{zo} \cdot [1 + \alpha_z \cdot (p - p_o) + \beta_z \cdot (T - T_o)]\end{aligned}$$

where U_{po} and U_{zo} denote respectively the forward voltage

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and the reverse voltage at the lower-range pressure p_o and the reference temperature T_o , α_p and α_z denote the pressure sensitivity of the junction in the forward and in the reverse direction respectively, while β_p and β_z denote respectively the temperature coefficient of the voltage in the forward and in the reverse direction respectively.¹

The sign "+" or "-" of the pressure sensitivities of the junction depends on the material from which the junction is made. The sign "+" or "-" of the temperature coefficient β_z of the reverse voltage depends on the breakdown mechanism (Zener or avalanche). The sign of the temperature coefficient β_p of the forward voltage is always negative. The coefficients α_p , α_z , β_p , β_z are a function of the current flowing through the junction.

By forming, with the aid of an electronic circuit with memory (Fig. 3), the sum U^+ and the difference U^- of the forward and reverse voltages with the appropriate proportionality coefficients k_p , k_z respectively, one obtains the possibility of making this sum or difference insensitive to changes of pressure or to changes of temperature

$$\frac{\partial U^+}{\partial T} = 0 \quad \text{or} \quad \frac{\partial U^+}{\partial p} = 0$$

and

$$\frac{\partial U^-}{\partial T} = 0 \quad \text{or} \quad \frac{\partial U^-}{\partial p} = 0$$

In the case where α_p , α_z , β_p , β_z are not a function of temperature and pressure, two of the four relations above can be satisfied, and one obtains a pressure-compensated temperature transducer or a temperature-compensated pressure transducer.

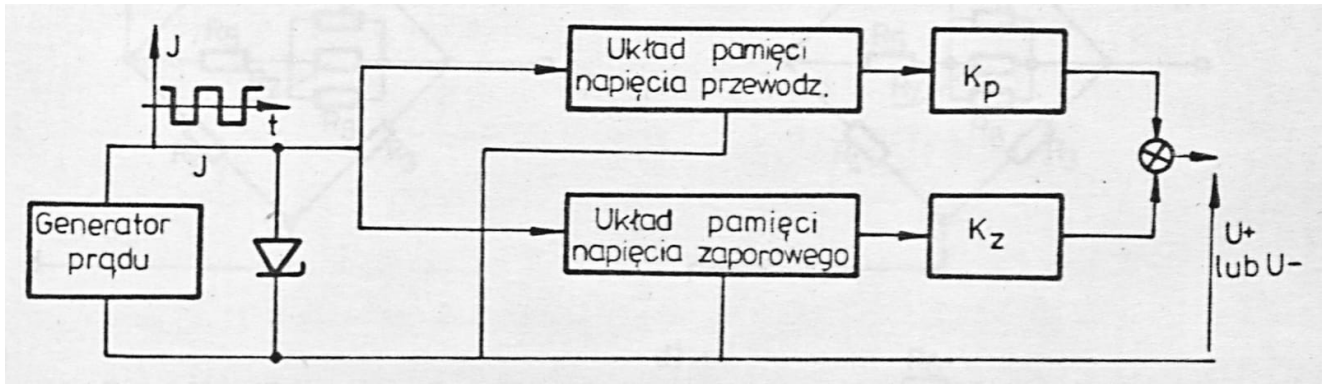


Fig. 3. Circuit for applying the method developed at IAP PW [61]

Labels: *Układ pamięci napięcia przewodzą.* = forward-voltage memory circuit; *Generator prądu* = current generator; *Układ pamięci napięcia zaporowego* = reverse-voltage memory circuit; *lub* = or

3.3. Method using discrete variable-resistance components to sense temperature

The compensation method presented in [71], proposed by Statham (USA), consists in connecting two-terminal networks with a temperature-dependent resistance in series with the arms of the strain-gauge bridge, or in parallel with them, in order to compensate the zero drift, and in connecting analogous two-terminal networks in series with the bridge, or in series-parallel with it, in order to compensate the span.

Figs. 4a, 4b, 4c and 4d show variants of the temperature compensation of the span. The resistances of the strain gauges are denoted by R_1 to R_4 . The compensating two-terminal network in Fig. 4a is built from the resistive components R_5 to R_8 , where the resistor R_6 is temperature-compensated, the resistance value of the component R_7 increases as a function of temperature, while that of the component R_8 decreases. The compensation consists in a variable loading of the bridge output. The circuit in Fig. 4b was modified by introducing a stronger division of the output signal by means of the resistor R_5 .

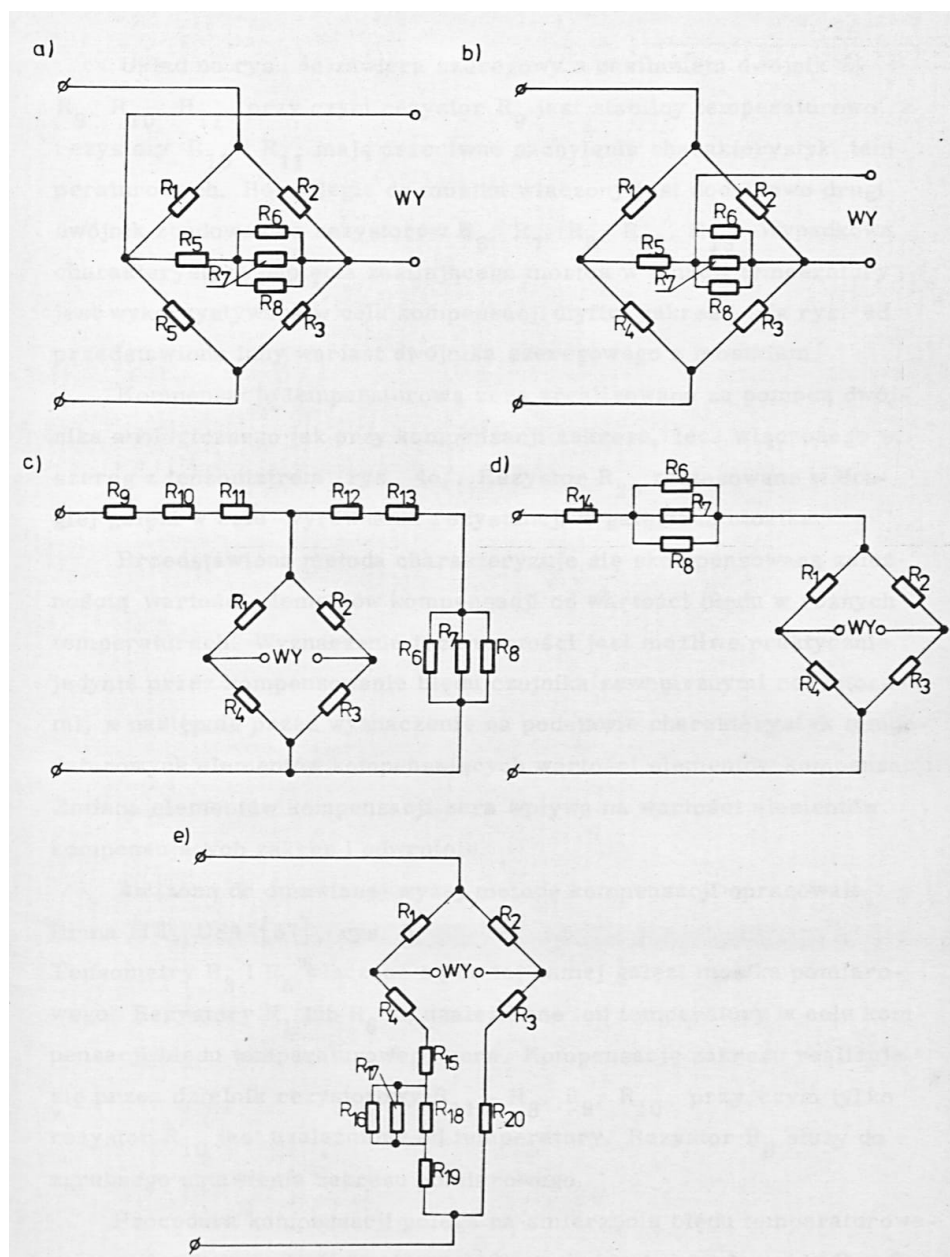


Fig. 4. Compensation circuit of Statham (USA) [71]; a, b, c, d - span compensation; e - zero compensation

Labels: WY = output (wyjście)²

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The circuit in Fig. 4c contains, in series with the supply, the two-terminal network R_9 , R_{10} , R_{11} , where the resistor R_9 is temperature-stable and the resistors R_{10} and R_{11} have temperature characteristics of opposite slopes. In parallel with the bridge a second two-terminal network, built from the resistors R_6 , R_7 , R_8 , R_{12} , R_{13} , is additionally connected. The resultant characteristic of the bridge excitation voltage as a function of temperature is used to compensate the span drift. Fig. 4d shows another variant of the two-terminal network in series with the bridge.

The temperature compensation of the zero was realized by means of a two-terminal network analogous to that used for the span compensation, but connected in series with a strain gauge (Fig. 4e). The resistor R_{20} was used in the second arm in order to equalize the resistances in the arms of the bridge.

The method presented is characterized by a complicated dependence of the values of the compensation components on the values of the error at the various temperatures. Determining these values is in practice possible only by compensating the sensor error with external resistors, and then by determining the values of the compensation components on the basis of the temperature characteristics of the compensating components. A change of the zero-compensation components affects the values of the components compensating the span, and vice versa.³

A compensation method close to the one discussed above was developed by ITT (USA) [57], Fig. 5. The strain gauges R_3 and R_5 are connected in the same arm of the measuring bridge. The resistors R_1 or R_6 are made temperature-dependent in order to compensate the temperature error of the zero. The span compensation is realized by the resistive divider $R_{11} - R_8, R_9, R_{10}$, where only the resistor R_{10} is temperature-dependent. The resistor R_8 serves for the coarse span setting.

The compensation procedure consists in measuring the temperature error of the zero and of the span, and then in calculating the values of the components R_1, R_6, R_8, R_{10} , which coarsely calibrate the value of the signal at the beginning and at the end of the measuring range at the reference temperature and ensure two-point temperature compensation.

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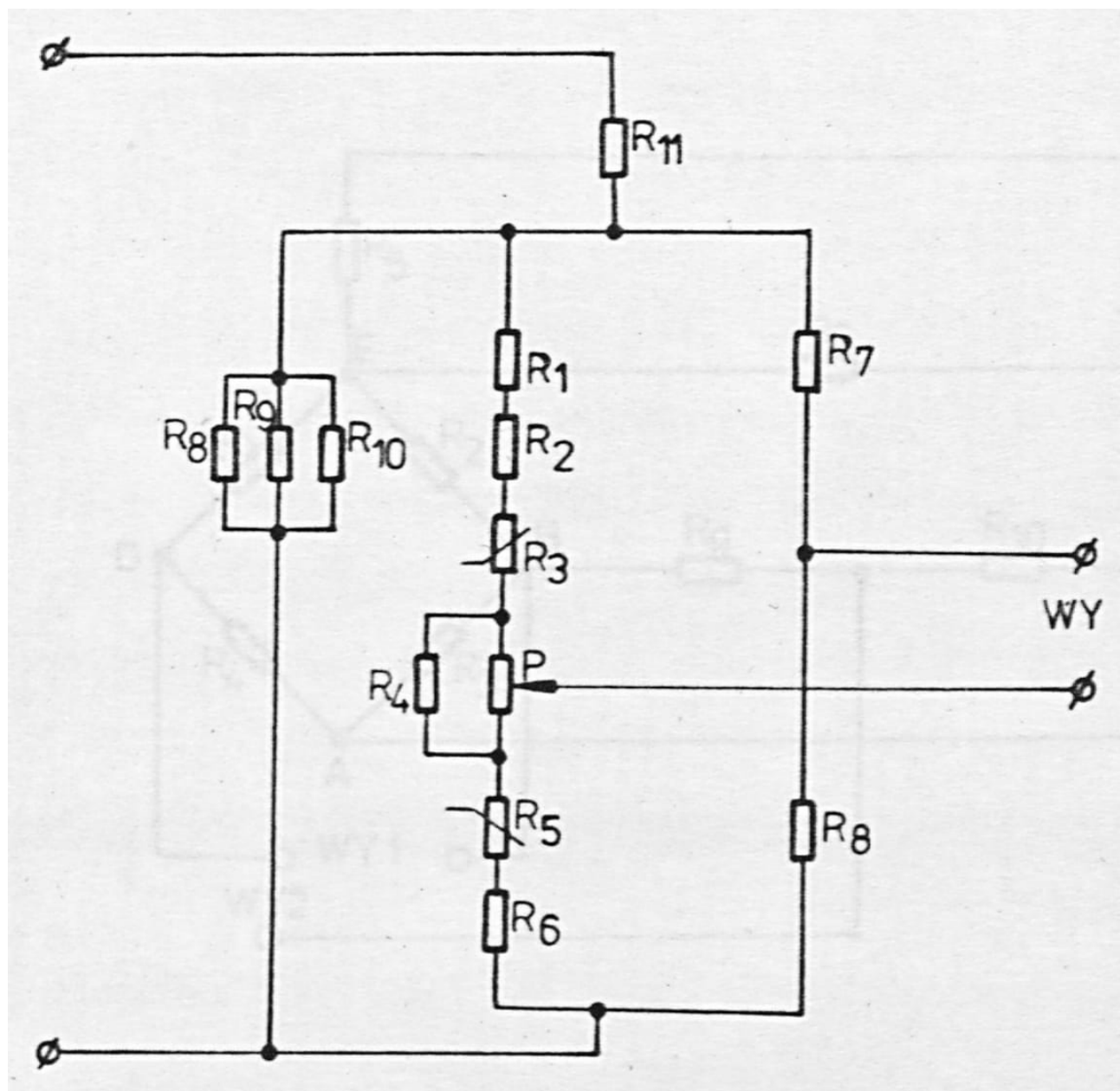


Fig. 5. Compensation circuit of ITT (USA) [57]

Labels: WY = output (wyjście)

The main drawback of the method is the complicated dependence of the values of the compensating components on the values of the errors.

Another design of the compensation method was introduced by Kulite (USA) [77], Fig. 6.

In order to temperature-compensate the zero of the strain-gauge bridge built from the strain gauges R_1 to R_4 , the voltage between the points A and C is equalized at the reference temperature with the voltage between the points A and B. Under these conditions the current flowing through the resistors R_9 and R_{10} is equal to zero and the value of these resistances does not affect the voltage

across the diagonal DB of the strain-gauge bridge. By making the voltage between the points A and C temperature-dependent by means of the resistors R_6, R_7, R_8, R_{11} , one obtains the possibility of producing, across the diagonal of the strain-gauge bridge, a change of voltage which compensates the zero drift. The value of the required current flowing through the resistors R_9 and R_{10} depends on the value of their resistance and does not change the balance condition of the strain-gauge bridge at the reference temperature.

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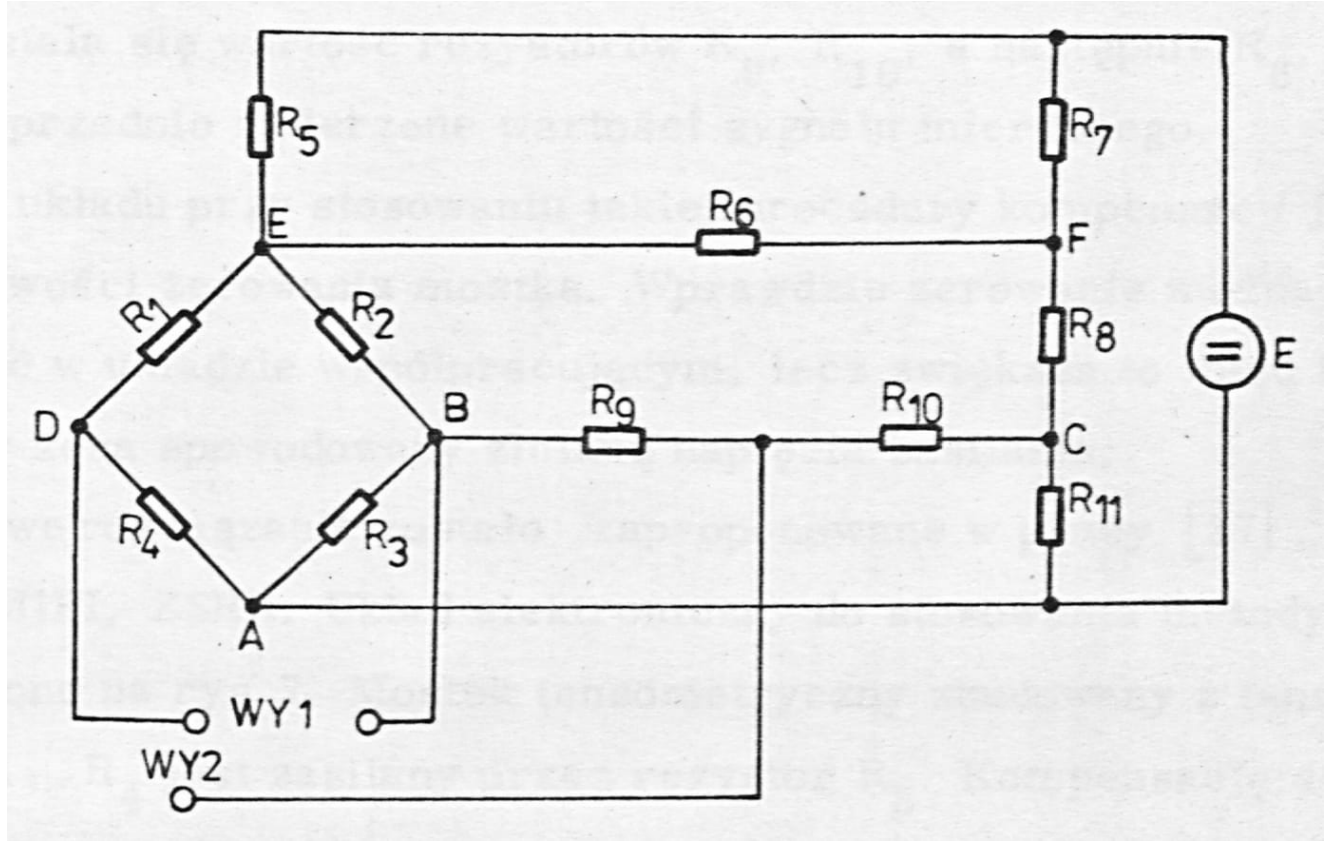


Fig. 6. Compensation circuit developed by Kulite (USA) [77]

Labels: WY1 = output 1; WY2 = output 2

Two outputs of the circuit are proposed. The output WY_1 is connected directly across the diagonal DB of the strain-gauge bridge, while the output WY_2 additionally contains the divider R_9-R_{10} , which modifies the course of the compensating signal.⁴

The span compensation was obtained by changing the bridge excitation voltage. If at the reference temperature the voltage between the points A and E is equal to the voltage between the points A and F, then the value of the resistance R_6 does not affect the values of these voltages. If at another temperature these voltages differ, a current flows through R_6 , and by selecting the temperature characteristic of the voltage AF by means of the resistors R_7, R_8, R_9 and the characteristic of the resistor R_5 one obtains the possibility of compensating the span, i.e. of the required increase or decrease of the voltage AE across the bridge.

The advantage of the circuit is the possibility of using a simple compensation procedure. At the reference temperature the voltages are equalized

$$U_{AB} = U_{AC}$$

$$U_{AE} = U_{AF}$$

s. 25

and the value of the voltage at the output of the circuit is measured at the lower and at the upper value of the range of the measured pressure. At the compensation temperature the values of the resistors R_9, R_{10} , and then R_6 , are set so as to obtain the previously measured values of the measured signal.

The drawback of the circuit, when such a compensation procedure is used, is the lack of any possibility of nulling the bridge. Admittedly the nulling can be realized in an associated circuit, but this increases the temperature error of the zero caused by the

change of the supply voltage.

An interesting design was proposed in [37], developed at MIFI (Moscow Engineering Physics Institute), USSR. The electronic circuit for applying the method is shown in Fig. 7. The strain-gauge bridge built from the strain gauges R_1 to R_4 is supplied through the resistor R_5 . The compensation of the zero drift is carried out by means of the auxiliary bridge M containing the thermistor RT . At the reference temperature the voltage across the diagonal AB of the bridge is equal to zero (which is obtained by means of the potentiometer P_1), and the zero adjustment of the transducer is performed with the potentiometer P_1 . At the compensation temperature the output signal of the amplifier W_1 is brought back to its previous value by adding to the sensor signal the output signal of the amplifier W_2 with a weighting factor set by the resistor R_{12} or R_{13} . The output signal of the amplifier W_2 is made temperature-dependent by means of the auxiliary bridge M.

The span compensation is realized by means of the resistor R_5 and by making use of the variable resistance of the strain gauges R_1 to R_4 as a function of temperature, which causes changes of the voltage U_{AB} across the bridge.

The method allows a relatively simple two-point compensation of the zero drift and a coarse compensation of the span. It requires, however, the use of an additional operational amplifier, which is its drawback.

s. 26

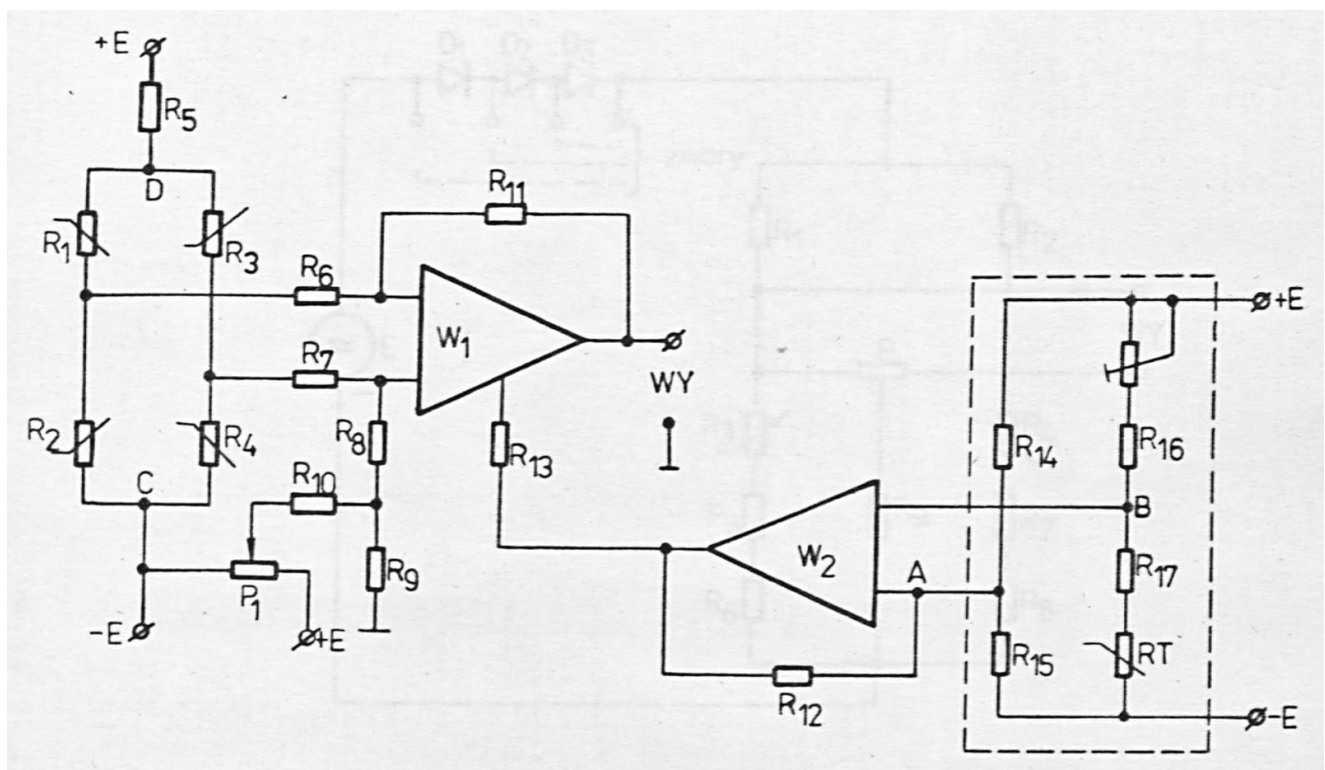


Fig. 7. Compensation circuit developed at MIFI, USSR [37]

Labels: WY = output (wyjście)

3.4. Methods using discrete junction semiconductor devices as temperature sensors.

The designs presented below make use of the linear dependence on temperature of the forward voltage of a diode or of the base-emitter voltage of a transistor. At the same time, variable-resistance components may be used for the compensation.

In the method used at Mera-Pnefal (Poland) [33], the compensation of the zero drift is realized by means of resistive components (Fig. 8). In the measuring bridge two strain gauges R_3 and R_4 are placed in opposite arms. The values of the resistors R_5 and R_7 are made independent of temperature, while the values of the resistors R_6 and R_8 have a positive temperature coefficient of resistance. By measuring the total resistance $R_5 + R_6$ and $R_7 + R_8$ required for nulling the bridge at two temperatures one obtains the information necessary to calculate the resistors R_5 to R_8 , where one of the resistors R_7 , R_8 is always equal to zero. The potentiometer P serves for the precise nulling of the bridge.

s. 27

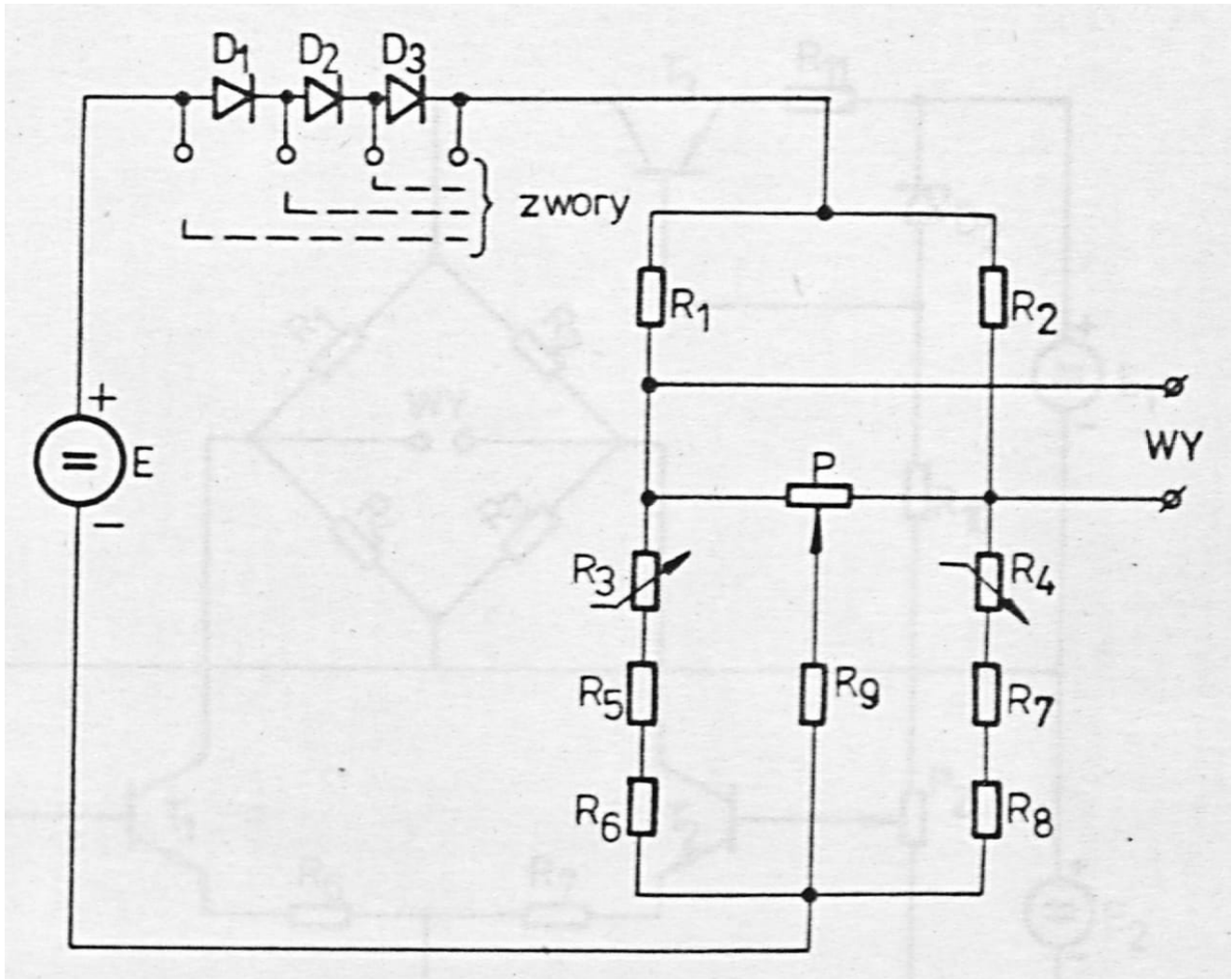


Fig. 8. Compensation circuit used at Mera-Pnefal [33]

Labels: *zwory* = jumpers; WY = output (wyjście)

The span compensation is obtained, similarly to the designs of Bell & Howell (USA) [60], by means of diodes connected in series with the bridge. The voltage across the diodes decreases with increasing temperature, which causes an increase of the voltage across the measuring bridge, which compensates the decrease of the pressure sensitivity. The number of diodes must be calculated on the basis of a measurement of the value of the span drift with temperature.

The compensation method [72] developed by Honeywell (USA) uses the diode D1 (Fig. 9) as the temperature-sensing element. The balance of the measuring bridge built from the strain gauges R_1 , R_2 , R_3 , R_4 depends on the values of the currents produced by the current sources built on the transistors T1 and T2. The mean value of these currents can compensate the span drift with temperature by changing the resultant voltage across the bridge. In order to compensate the zero drift of the sensor, the value of the necessary change of the difference of the currents of the two sources is changed first with the potentiometer P1, and then the bridge is nulled with the potentiometer P2.

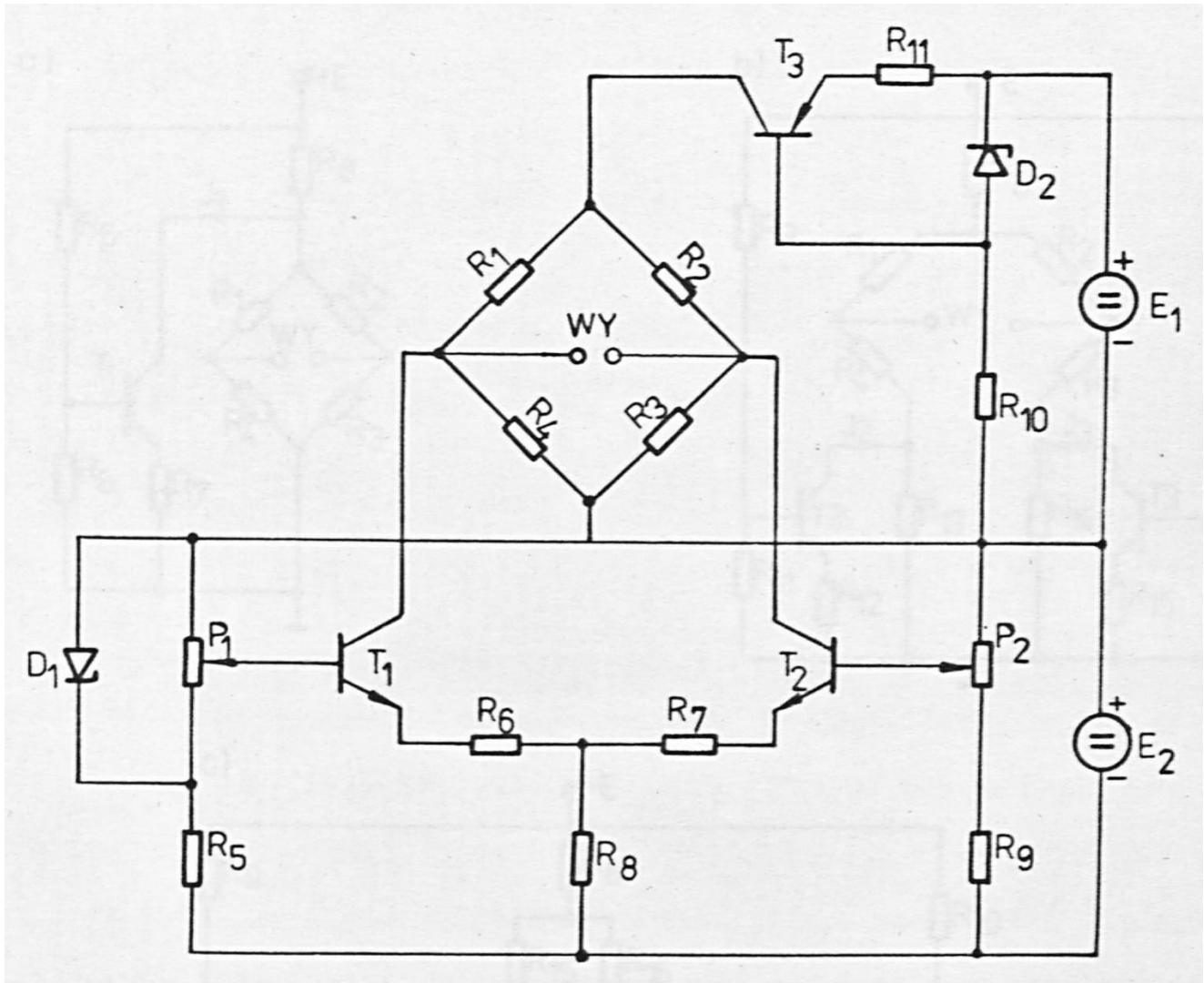


Fig. 9. Circuit developed by Honeywell (USA) [72]

Labels: WY = output (wyjście)

The compensation of the span drift with temperature can also be obtained by making the current produced by the transistor T3 temperature-dependent, by selecting the temperature coefficient of the diode D2 or by using a temperature-dependent resistor R_{11} .

The settings of the potentiometers P1 and P2 which ensure temperature compensation are mutually dependent in this circuit.

An interesting temperature-compensation design [32, 73] was proposed by Bell & Howell (USA). The method uses the base-emitter junctions of transistors as temperature sensors.

The compensation of the span drift is shown in Fig. 10a. As a result of the decrease of the base-emitter voltage of the transistor T1 with increasing temperature, the current I_1 increases, causing a decrease of the voltage across the measuring bridge containing the strain gauges R_1 to R_4 .

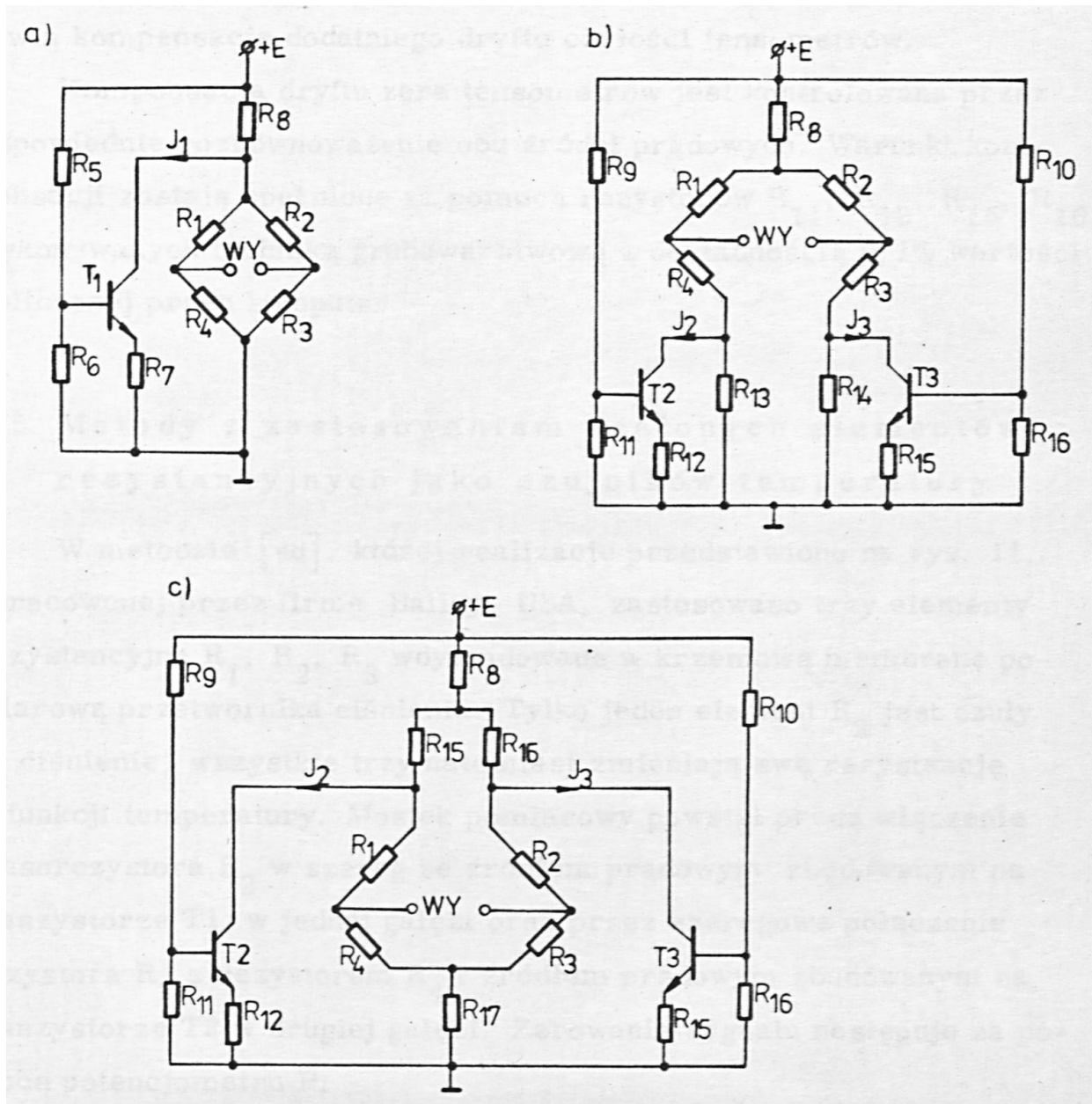


Fig. 10. Compensation circuit developed by Bell & Howell (USA) [32, 73]

Labels: WY = output (wyjście)⁵

Figs. 10b and 10c show the circuit proposed for the simultaneous compensation of the span and of the zero. A simultaneous increase of the currents I_2 and I_3 delivered by the current sources built on the transistors T2 and T3 causes:

- in the circuit of Fig. 10b: an increase of the voltage across the measuring bridge, which makes it possible to compensate a negative sensitivity drift of the strain gauges,

s. 30

- in the circuit of Fig. 10c: a decrease of the voltage across the bridge, which makes it possible to compensate a positive sensitivity drift of the strain gauges.

The compensation of the zero drift of the strain gauges is controlled by an appropriate unbalance of the two current sources. The compensation conditions are satisfied by means of the resistors R_{11} , R_{12} , R_{15} , R_{16} , made in thick-film technology to an accuracy of 0.1 % of the value calculated by a computer.

3.5. Methods using integrated resistive components as temperature sensors

In the method [48], whose realization is shown in Fig. 11, developed by Bailey (USA), three resistive components R_1 , R_2 , R_3 , diffused into the silicon sensing diaphragm of the pressure transducer, are used. Only one component, R_2 , is sensitive to pressure, whereas all three change their resistance as a function of temperature. The measuring bridge was formed by connecting the piezoresistor R_2 in series with the current source built on the transistor T1 in one arm, and by the series connection of the resistor R_3 with the resistor R_4 and the current source built on the transistor T2 in the other arm. The signal is zeroed by means of the potentiometer P.⁶

The temperature compensation of the zero drift was accomplished by selecting an appropriate value of the temperature-stable resistor R_4 , which sets the resultant temperature coefficient of the voltage in the right-hand arm of the bridge equal to the temperature coefficient of the voltage across the strain gauge. Since in the bridge it is the absolute voltage increments that compensate one another, the voltage increments in the two arms also depend on the ratio of the currents produced by the transistors T1 and T2. This makes it possible to compensate the zero drift of the transducer both when the strain gauge R_2 changes more strongly as a function of temperature than the resistor R_3 , and in the opposite case.

The compensation of the span drift with temperature was obtained as a result of making temperature-dependent the voltage controlling the source current of the

s. 31

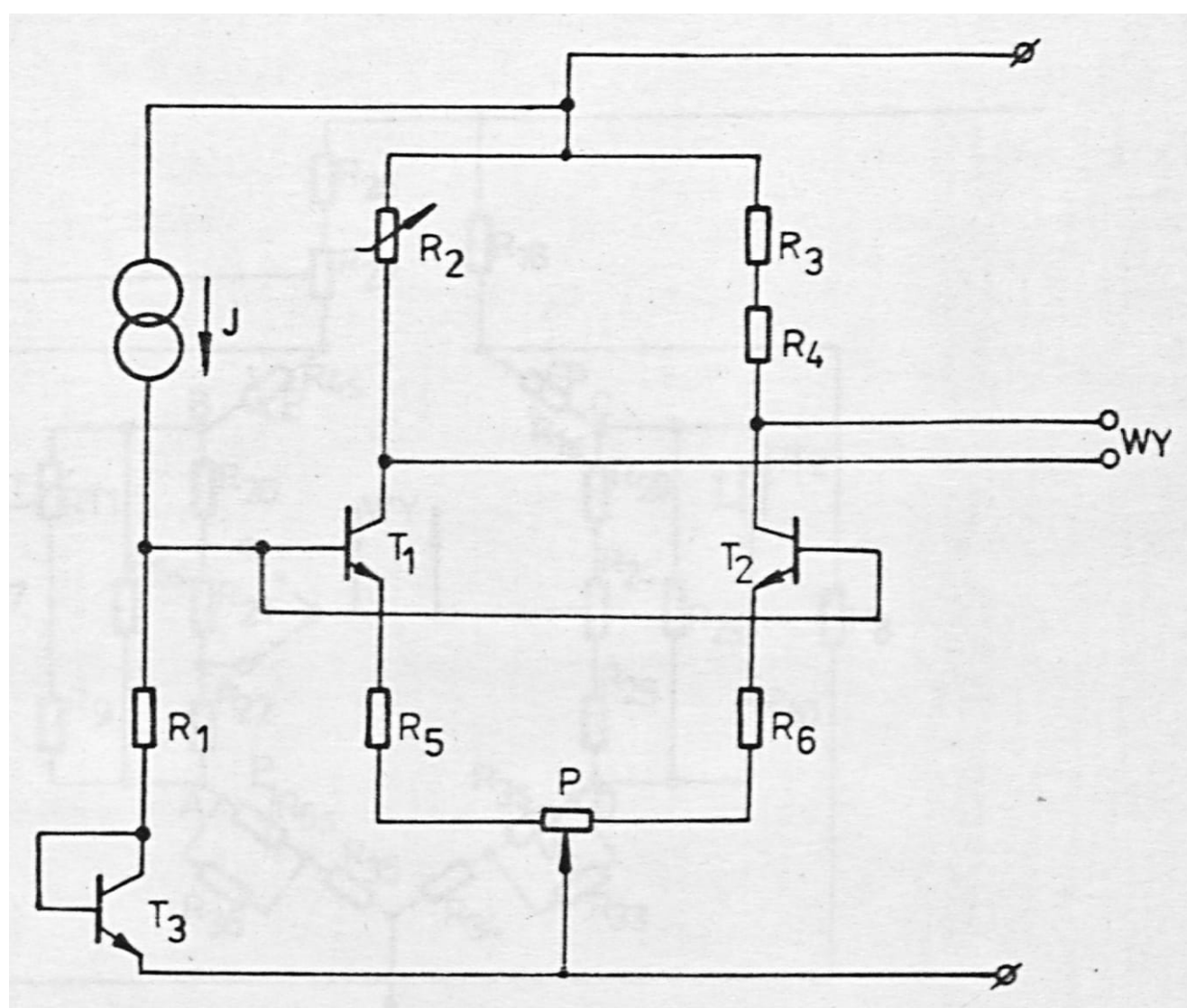


Fig. 11. Compensation circuit developed by Bailey (USA) [48]

Labels: WY = output (wyjście)

current sources on the transistors T1, T2. This dependence was obtained by making use of the diffused resistor R_1 , supplied by the temperature-stable current source I, to produce the said control voltage. The diode-connected transistor T3 compensates the

temperature changes of the base-emitter voltages of the transistors T1 and T2.

A very elaborate temperature-compensation method [33, 39, 40] was developed by Honeywell (USA) for a family of industrial transducers of pressure and derived quantities based on an integrated silicon piezoresistive sensor made in planar technology. The compensation circuit is shown in Fig. 12. It performs the following functions:

- it compensates the temperature error of the zero
- it compensates the temperature error of the span
- it compensates the zero-suppression voltage, which shifts the starting point of the transfer characteristic within the region of $\pm 100\%$ of the measuring range.

s. 32

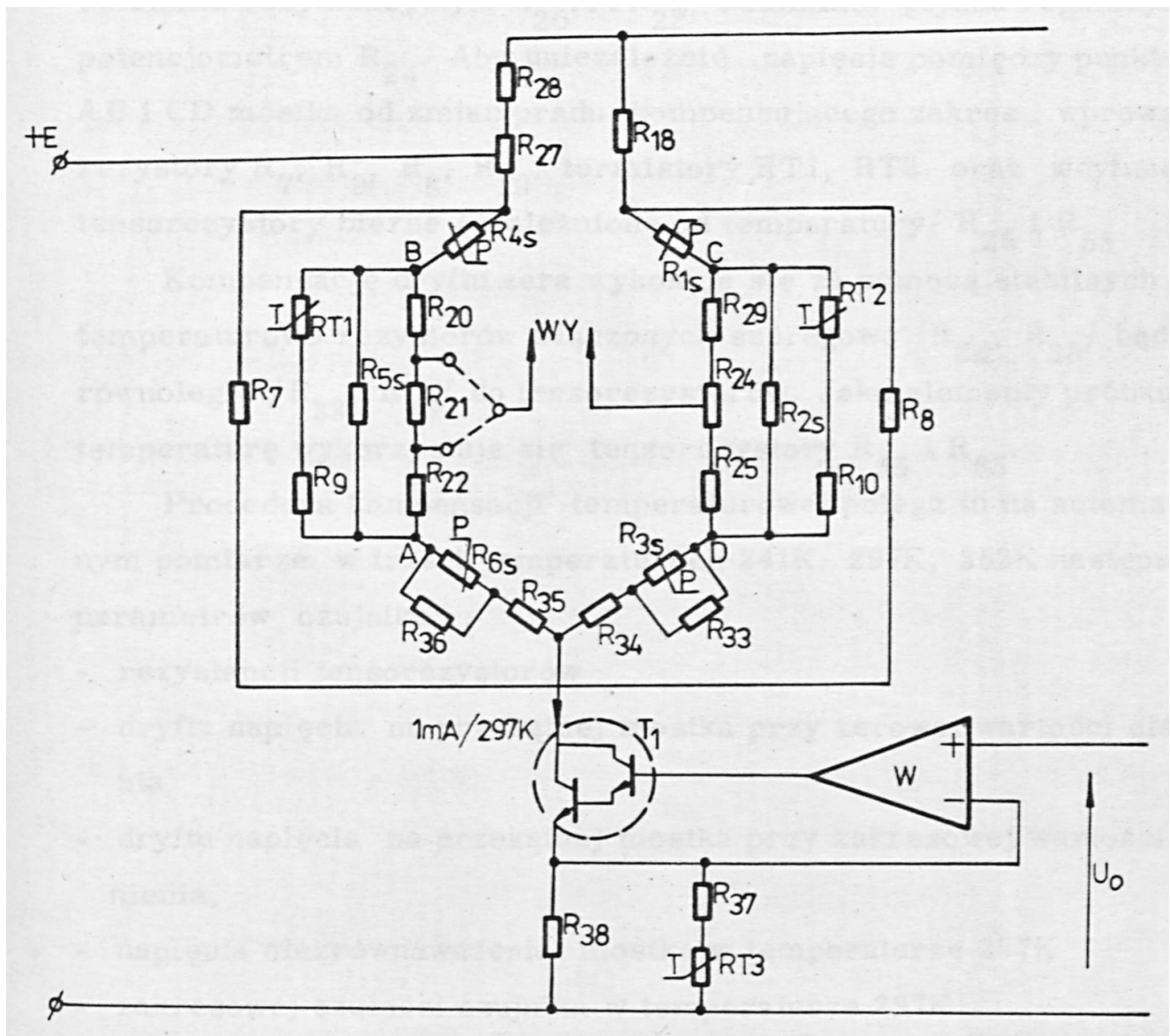


Fig. 12. Compensation circuit used by Honeywell (USA) [33, 39, 40]

Labels: WY = output (wyjście); W = amplifier (wzmacniacz)

The sensor is built from six resistors R_{1s} to R_{6s} diffused into the silicon sensing diaphragm. Two of these resistors, R_{1s} and R_{6s} , decrease their resistance with increasing pressure, the next two, R_{3s} and R_{4s} , increase it, and the remaining two, R_{2s} and R_{5s} , are not sensitive to pressure.⁷

The temperature compensation of the span is realized by making temperature-dependent the current produced by the current source built on the Darlington pair T1 and the amplifier W. The dependence is obtained by means of a two-terminal network built from the thermistor

s. 33

RT3 and the resistors R_{37} and R_{38} .

The stepped zero offset is obtained by means of the voltage across the resistive divider R_{20} to R_{22} , while the continuous zero adjustment is by the potentiometer R_{24} . In order to make the voltage between the points AB and CD of the bridge independent of changes of the span-compensating current, the resistors R_7 , R_9 , R_8 , R_{10} and the thermistors RT1, RT2 were introduced, and the passive (pressure-insensitive, temperature-dependent) piezoresistors R_{25} and R_{55} were diffused in.⁸

The compensation of the zero drift is performed by means of temperature-stable resistors connected in series (R_{34} , R_{35}) or in parallel (R_{33} , R_{36}) with the piezoresistors. The piezoresistors R_{35} and R_{65} are used as the temperature-sensing elements.

The temperature-compensation procedure here consists in the automatic measurement, at three temperatures 241 K, 297 K, 352 K, of the following parameters of the sensor:

- the resistance of the piezoresistors
- the drift of the voltage across the bridge diagonal at zero pressure
- the drift of the voltage across the bridge diagonal at the full-scale pressure,
- the bridge unbalance voltage at the temperature 297 K
- the full-scale sensitivity of the sensor at the temperature 297 K
- the temperature hysteresis
- the pressure hysteresis.

On the basis of the measured parameters of the sensor a computer calculates the values of the compensation components. The values of the components compensating the span drift and the drift of the zero-suppression voltage are coupled with one another. Depending on the parameters of the sensor, one of three sets of values of these components is used, which suffices to keep the errors of the transducer at the level of 0.07 %/10 K.

The total number of possible values of the resistors R_{33} to R_{36} compensating the span drift which may occur in practice is 110, these values being quantized so as to obtain a resultant zero drift at the level of 0.07 %/10 K.

s. 34

The method presented has a fundamental drawback: it requires stocking a large number of components, of which only an insignificant percentage will be used in the production process.

The advantage of designs using integrated temperature-sensing elements is the smaller temperature gradients between these elements and the sensor, resulting from the small thermal resistance between these elements.

3.6. Method using integrated semiconductor devices as temperature sensors

The conceptually most interesting compensation method was developed by National Semiconductor (USA) [1, 42, 70]. This method is closely tied to the integrated pressure sensor also developed at that company. This sensor is built from four strain gauges R_1 , R_2 , R_3 , R_4 (Fig. 13) diffused into the silicon sensing diaphragm. Between these strain gauges the transistor T4 is diffused. Into the same silicon chip, outside the region of the diaphragm, the transistors T1, T2, T3 and the operational amplifier W are also diffused. All the diffused components are located close to one another, owing to which the thermal resistance between them is very small.⁹

The transistor T4 is used as a heater controlled by a square wave from a drive generator. The rise time of the temperature from 298 K to 423 K of all the diffused components, with the exception of the amplifier W, is about 200 ms (thermal time constant approx. 100 ms, thermal resistance approx. 300 K/W). As a result it becomes possible to change the temperature of the diffused components at a frequency of the order of a few Hz.

The first element subjected to temperature compensation in the sensor circuit is the supply voltage between the points A and B. This voltage is supplied by a Zener diode formed by the reverse-biased base-emitter junction of the transistor T2, with a voltage of approx. 6.4 V and a temperature coefficient of approx. +2.5 mV/K. The temperature compensation is obtained by means of the so-called " $n \cdot V_{BE}$ " circuit (a V_{BE} multiplier) - a voltage

s. 35

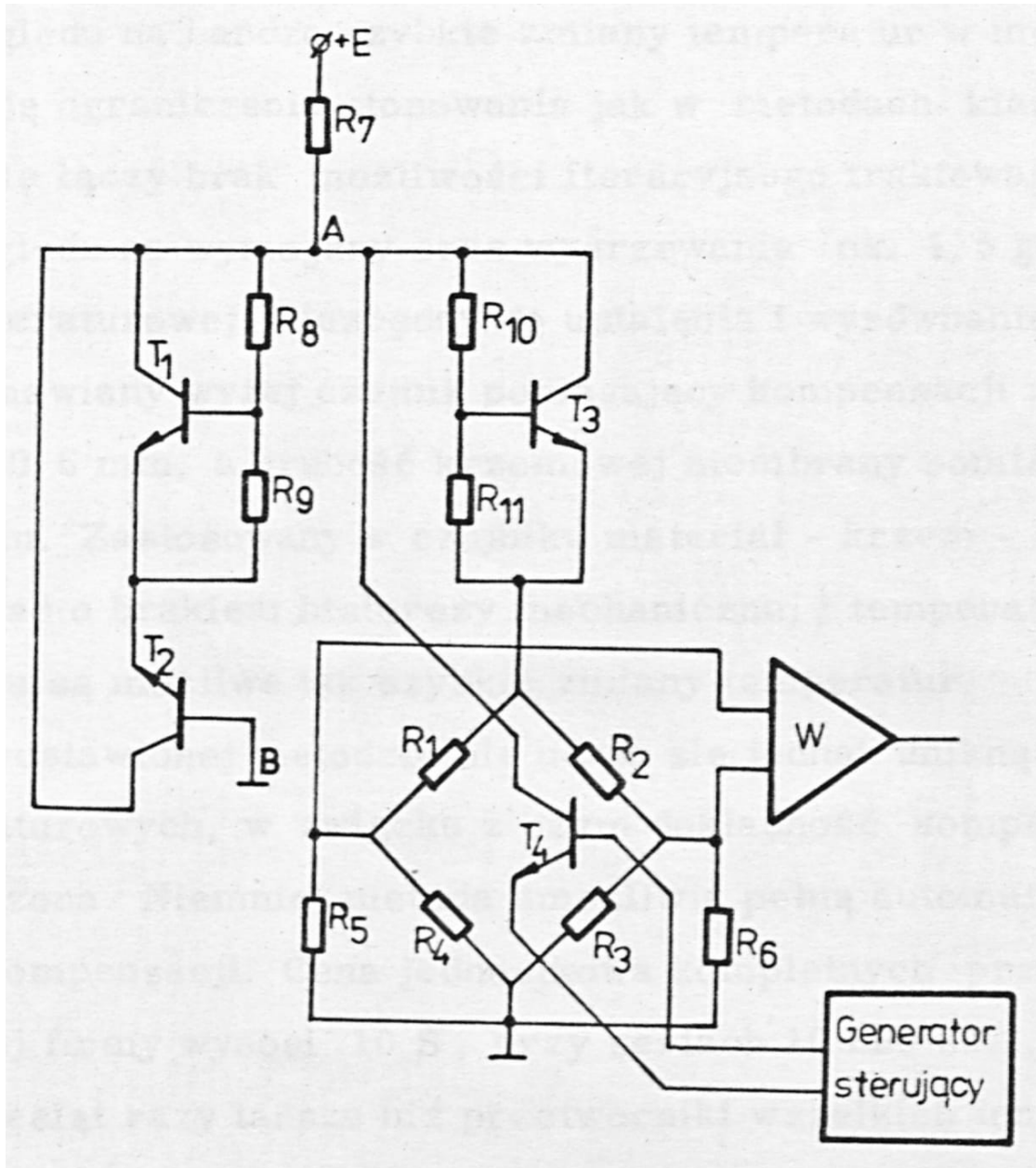


Fig. 13. Compensation circuit developed by National Semiconductor (USA) [1, 42, 70]

Labels: W = operational amplifier (wzmacniacz); Generator sterujący = drive generator

source with a voltage equal to "n" times the base-emitter voltage of the transistor T1. By changing the temperature of the components periodically, the changes of the supply voltage are observed, and in an automatic computer-controlled cycle the value of the thick-film resistor R_9 is corrected with a laser trimmer until these changes are equal to zero.

After applying the lower-range pressure, the change of the voltage across the diagonal of the strain-gauge bridge resulting from the changes of temperature is brought to zero in the manner given above, by changing the values of the thick-film resistors R_5/R_6 .

After the lower range value has been compensated, the full-scale pressure is applied and, again observing the changes of the voltage across the diagonal of the strain-gauge bridge, they are brought to zero by means of the second

s. 36

" $n \cdot V_{BE}$ " circuit on the transistor T3 and the resistors R_{10} , R_{11} .

Owing to the very rapid changes of temperature, this method is free of the limitations of application found in the classical methods, which are bound up with the impossibility of treating the compensation iteratively because of the required thermal soak time (approx. 1.5 h) in the temperature chamber, necessary for the temperatures to settle and equalize. The sensor discussed above which is subjected to compensation has the dimensions $2.9 \times 4.2 \times 0.6$ mm, and the thickness of the silicon sensing diaphragm is $25 \mu\text{m}$.

The material used in the sensor - silicon - is moreover characterized by the absence of mechanical and temperature hysteresis, owing to which such rapid changes of temperature are possible.

In the method presented, however, temperature gradients cannot be avoided, in consequence of which the compensation accuracy is limited. Nevertheless the method makes possible the full automation of the compensation procedure. The unit price of this company's complete pressure transducers is \$10 in lots of 10 000 units, so they are several tens of times cheaper than the transducers of all other competing companies.

3.7. Summary

The known temperature-compensation methods presented above may be characterized as follows: (a) none of the known methods makes complete compensation of the temperature errors possible. In almost all the methods only one compensation temperature is used, with the exception of the Honeywell method with three-point compensation, i.e. with two temperatures; (b) only one method, developed by Kulite, ensures unidirectional independence in setting the compensation conditions, since the values of the resistors R_6 , R_9 , R_{10} (Fig. 4) adjusted at the compensation temperature do not affect the signal of the transducer at the reference temperature; (c) in each of the methods presented, the number of values of the compensating components necessary to compensate all the sensors

s. 37

in a production lot is large. In all the designs in which the compensating components are connected in series with the strain gauges, great difficulties arise, either in making or in purchasing stable components with values of the order of a few ohms or fractions of an ohm, which always go together with the use of low-resistance gauges (e.g. 100 Ω); (d) the compensation procedure based on all the known methods, with the exception of the method developed by Kulite, is difficult and burdensome under production conditions; (e) the conceptually most interesting method, that of National Semiconductor, requires repeating the temperature cycles many times, which, because of the time required, is unfeasible if another technology of manufacturing the transducer is used, and also because of the temperature gradients that occur if the requirements as to the compensation accuracy are raised.¹⁰

In view of the above, in the author's opinion it appears expedient to develop a new method of compensation of the effect of temperature in semiconductor pressure transducers, one which eliminates the drawbacks of the methods known and used hitherto.

Translator's notes

1. the symbol U_p denotes the forward voltage in this section only; from Section 4 onward U_p is the transducer output at the lower range value. Both uses are kept as printed.
2. original caption reads "Statham, USA 71" with the reference brackets not drawn in; evidently reference [71]. In panel (a) the lower-left bridge arm is lettered "R5" as printed; evidently R_4 , as rendered in the label list.
3. original reads "skompensowaną zależnością" ("a compensated dependence"); evidently "skomplikowaną" ("complicated"), as in the wording used for the ITT method below.
4. WY_1 , WY_2 are the outputs labelled OUT1, OUT2 in Fig. 6 ("WY" = Polish "wyjście", output); the printed symbols are kept in the text.
5. the figures label the currents J ; the text writes them I_1 , I_2 , I_3 . Both are kept as printed.
6. the thesis spells the company "Balley"; this is evidently Bailey (Bailey Meter Co.), the assignee of reference [48]. Corrected here and in the caption of Fig. 11.
7. original reads " $R_{15}...R_{65}$ ", " R_{13} i R_{65} ", " R_{35} i R_{45} ", " R_{25} i R_{55} "; the subscript "s" (sensor) is typed as "5", and "13" is a mis-strike for "1s". Rendered according to the figure labels R_{1s} to R_{6s} .
8. original reads " R_{25} i R_{55} " and, in the next paragraph, " R_{35} i R_{65} "; as these are described as piezoresistors, they are evidently the diffused resistors R_{2s} , R_{5s} and R_{3s} , R_{6s} of Fig. 12 (the same "s"/"5" confusion as on the preceding page). Kept as printed, since R_{35} is also the label of a separate compensation resistor in Fig. 12.
9. the thesis writes "National Semiconductors"; the company is National Semiconductor Corp. Corrected here, in the caption of Fig. 13 and in Section 3.7.
10. in (a) the original reads "stosuje się tylko temperaturę kompensacji" ("only compensation temperature is used"), the numeral being omitted; evidently "only one". In (b) the original cites "rys. 4"; the Kulite circuit with the resistors R_6 , R_9 , R_{10} is Fig. 6.

4. A NEW METHOD OF COMPENSATION OF TEMPERATURE ERRORS

s. 38

4.1. Introductory remarks

The new method of compensation of temperature errors proposed below [81, 82] eliminates the drawbacks of the known methods, while at the same time making it possible to reduce the temperature error of the transducer identically to zero.

In order to make the considerations presented below unambiguous, restrictions will be stated for the class of transducers whose compensation will be analysed: (a) the subject of the considerations will be transducers with a linear transfer characteristic from pressure to an electrical signal, (b) it is assumed that the only source of the temperature errors of the transducer is the sensor. If it is required to take into account the temperature drifts of other units of the transducer located at the same temperature as the sensor (e.g. the electronic signal-conditioning circuit), they should be referred to the level of the sensor, and the equivalent sensor error (in the sense of Section 2 of this thesis) should be subject to compensation, (c) additivity of the value of the measured parameter and of the value of the temperature error is assumed, i.e. it is assumed that the value of the parameter under consideration at an arbitrary temperature is described by the sum of the value of the parameter at the reference temperature and the temperature error, (d) the subject of the considerations will be errors in temperature steady states; the effect of temperature in the transient state will not be analysed, because this error is inseparably linked with the design of the transducer.

s. 39

4.2. Sufficient conditions for the temperature compensation of the transfer characteristic of the transducer

Let the transfer characteristic (2) of the transducer be described by a linear relation (Fig. 14):

$$U = U_p + \alpha_1 X \quad (3)$$

where: U_p - the lower range value of the transducer output signal, at the lower range value X_p of the non-electrical quantity α_1 - the sensitivity¹

The changes of the output signal under the effect of temperature are determined by the partial differential equation

$$\frac{\partial U}{\partial T} = \frac{\partial U_p}{\partial T} + X \frac{\partial \alpha_1}{\partial T} \quad (4)$$

In order to satisfy the condition of complete temperature compensation of the output signal

$$\frac{\partial U}{\partial T} = 0 \quad (5)$$

two solutions of equation (4) are obtained

a.

$$\frac{\partial U_p}{\partial T} = -X \frac{\partial \alpha_1}{\partial T} \quad (6)$$

b.

$$\begin{cases} \frac{\partial U_p}{\partial T} = 0 \\ \frac{\partial \alpha_1}{\partial T} = 0 \end{cases} \quad (7)$$

s. 40

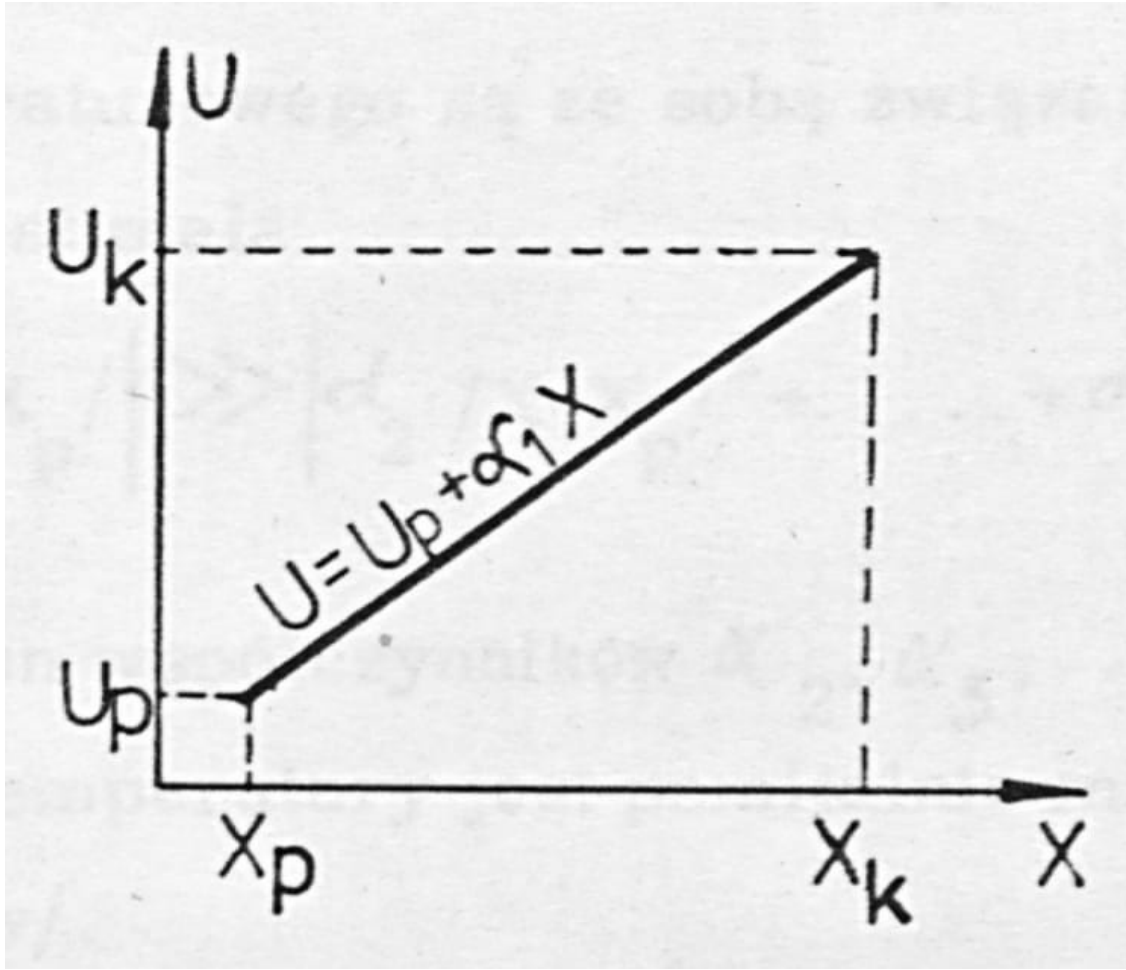


Fig. 14. Transfer characteristic of the transducer

Condition a. has no practical significance, because of the changes as a function of the measured value of pressure.

The temperature compensation of most measuring transducers is based on condition b., which we may define as follows:

A sufficient condition for the temperature compensation of the transfer characteristic (3) is making the lower range value U_p and the sensitivity α_1 independent of temperature. We may modify this condition: for the temperature compensation of the transfer characteristic (3) it is sufficient to make the lower range value U_p and the upper range value U_k of the measuring range of the transducer independent of temperature. This is obvious, since the upper range value U_k is a function of the lower range value and of the sensitivity:

$$U_k = U_p + \alpha_1(X_k - X_p) \quad (8)$$

In reality the transfer characteristic also exhibits a certain nonlinearity ¹

$$U = U_p + \alpha_1(X - X_p) + \alpha_2(X - X_p)^2 + \alpha_3(X - X_p)^3 + \dots + \alpha_n(X - X_p)^n \quad (9)$$

¹ Weierstrass approximation theorem (proved in 1885 [83]): for every function $P(X)$ continuous on the interval X_p, X_k and every $\varepsilon > 0$ there exists a polynomial

$$U(X) = \alpha_0 + \alpha_1 X + \dots + \alpha_n X^n$$

s. 41

as a result of which two-parameter compensation does not ensure ideal compensation of the effect of temperature on the output signal of the transducer. Since, however, both the permissible value of the nonlinearity and that of the temperature error are related to each other ², the value of the nonlinearity terms is small

$$|U_p + \alpha_1 \cdot (X - X_p)| \gg |\alpha_2 \cdot (X - X_p)^2 + \dots + \alpha_n \cdot (X - X_p)^n| \quad (10)$$

and the effect of the changes of the coefficients $\alpha_2, \alpha_3, \dots, \alpha_n$ caused by the action of temperature is negligibly small (as a higher-order small quantity).

Let us consider the block diagram of the transducer from the point of view of the needs of compensation (Fig. 14). The sensor C produces a signal u , dependent on the value of the measured non-electrical quantity X and on the temperature T through relation (1). The compensation circuit D produces a compensating signal k , dependent on temperature by means of the function $H(T)$:²

$$k = H(T) \quad (11)$$

The output signal U of the transducer is formed in the normalizing circuit N, which sums the signals of the sensor and of the compensation circuit with the appropriate proportionality coefficients (gains) b_1, b_2 and with the offset b_3 of the lower range value of the output signal

of degree $n(\varepsilon)$ such that:

$$\max |U(X) - P(X)| < \varepsilon$$

and therefore an arbitrary characteristic of real sensors can be described to arbitrary accuracy by relation (9).

² According to PN-73/M-42024 the maximum permissible value of the nonlinearity of the transfer characteristic is one position higher in the series of accuracy classes than the maximum permissible value of the temperature error, expressed in percent of the change of the measuring-range value per 10 K. For example: for a transducer of class 0.4 % a nonlinearity of 0.4 % is permitted, together with a temperature zero drift and span drift of 0.25 %/10 K.

s. 42

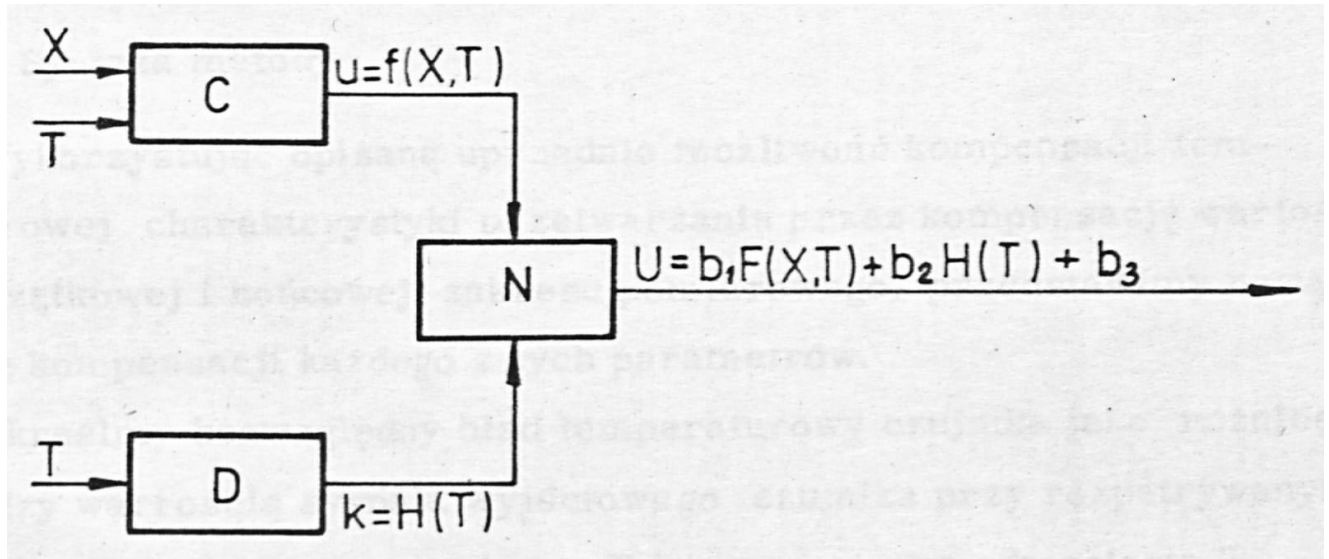


Fig. 15. Block diagram of the transducer from the point of view of the needs of compensation

$$U = b_1 \cdot f(X, T) + b_2 \cdot H(T) + b_3 \quad (12)$$

where: b_1, b_2, b_3 are independent of temperature (their temperature drift is included in the equivalent temperature error of the sensor) and of the measured value.

Differentiating and transforming (3) we obtain expressions for the lower range value U_p and the sensitivity α_1 :

$$\begin{cases} U_p = U - X \frac{\partial U}{\partial X} \\ \alpha_1 = \frac{\partial U}{\partial X} \end{cases} \quad (13)$$

Substituting expression (12) into (13) one obtains the equations:

$$\begin{cases} U_p = b_1 \left[f(X, T) - X \frac{\partial f(X, T)}{\partial X} \right] + b_2 \cdot H(T) + b_3 \\ \alpha_1 = b_1 \frac{\partial f(X, T)}{\partial X} \end{cases} \quad (14)$$

which make the lower range value U_p and the sensitivity α_1 dependent on the functions $f(X, T)$ and $H(T)$. In order to determine the restrictions on these functions, and in connection with the adoption of the linear model of the transfer characteristic

s. 43

determined by relation (3), we shall check for (14) the conditions of temperature compensation (7). These conditions lead to two second-order partial differential equations:

$$\begin{cases} \frac{\partial H(T)}{\partial T} = \frac{b_1}{b_2} \cdot \left[X \cdot \frac{\partial^2 f(X, T)}{\partial X \partial T} - \frac{\partial f(X, T)}{\partial T} \right] \\ \frac{\partial^2 f(X, T)}{\partial X \cdot \partial T} = 0 \end{cases} \quad (15)$$

after solving which we have the sought conditions for the functions $H(T)$ and $f(X, T)$:

$$H(T) = \frac{b_1}{b_2} \cdot \left[X \cdot \frac{\partial f(X, T)}{\partial X} - f(X, T) \right] + f_1(X) + C_1 \quad (16)$$

$$f(X, T) = f_2(X) + f_3(T) + C_2 \quad (17)$$

where f_1, f_2, f_3 - arbitrary functions of one variable C_1, C_2 - arbitrary constants

Thus the function $H(T)$ must have a course opposite to the temperature error of the sensor, determined by the first term of relation (16), and may be augmented by an arbitrary function of the measurand $f_1(X)$ and also by an arbitrary constant C_1 . The function $f(X, T)$, on the other hand, may only be a sum of independent functions of pressure $f_2(X)$ and of temperature $f_3(T)$, augmented by an arbitrary constant.

Relation (17) therefore expresses the condition of additivity of the value of the measured parameter and of the temperature error, formulated in Section 4.1 (c).

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4.3. The essence of complete temperature compensation

4.3.1. Synthesis of the method

Making use of the possibility, described above, of temperature compensation of the transfer characteristic by compensation of the lower and upper range values of the measuring range, we shall present a new method of compensation of each of these parameters.

Let us define the absolute temperature error of the sensor as the difference between the value of the sensor output signal at the pressure X under consideration at a given temperature T and at the reference temperature T_o , denoting it by $\delta(T)$:

$$\delta(T) = f(X, T) - f(X, T_o) \quad (18)$$

Let us denote the maximum absolute value of the error 18 by δ_m ³

$$\delta_m = |\delta(T)|_{\max} \quad (19)$$

In an analogous way we shall define the absolute temperature error of the transducer $\Delta(T)$

$$\Delta(T) = g(X, T) - g(X, T_o) \quad (20)$$

and the maximum absolute value of the error (20) by Δ_m

$$\Delta_m = |\Delta(T)|_{\max} \quad (21)$$

If we denote by U_p and U_k respectively the values of the sensor output signal corresponding to the lower and upper range values of the measured pressure X , then the effect of the action of the compensation circuit will be a reduction of the maximum relative measurement error of the transducer in comparison with the maximum relative error of the sensor (Fig. 16):

$$\frac{\delta_m}{|U_k - U_p|} > \frac{\Delta_m}{|U_k - U_p|} \quad (22)$$

s. 45

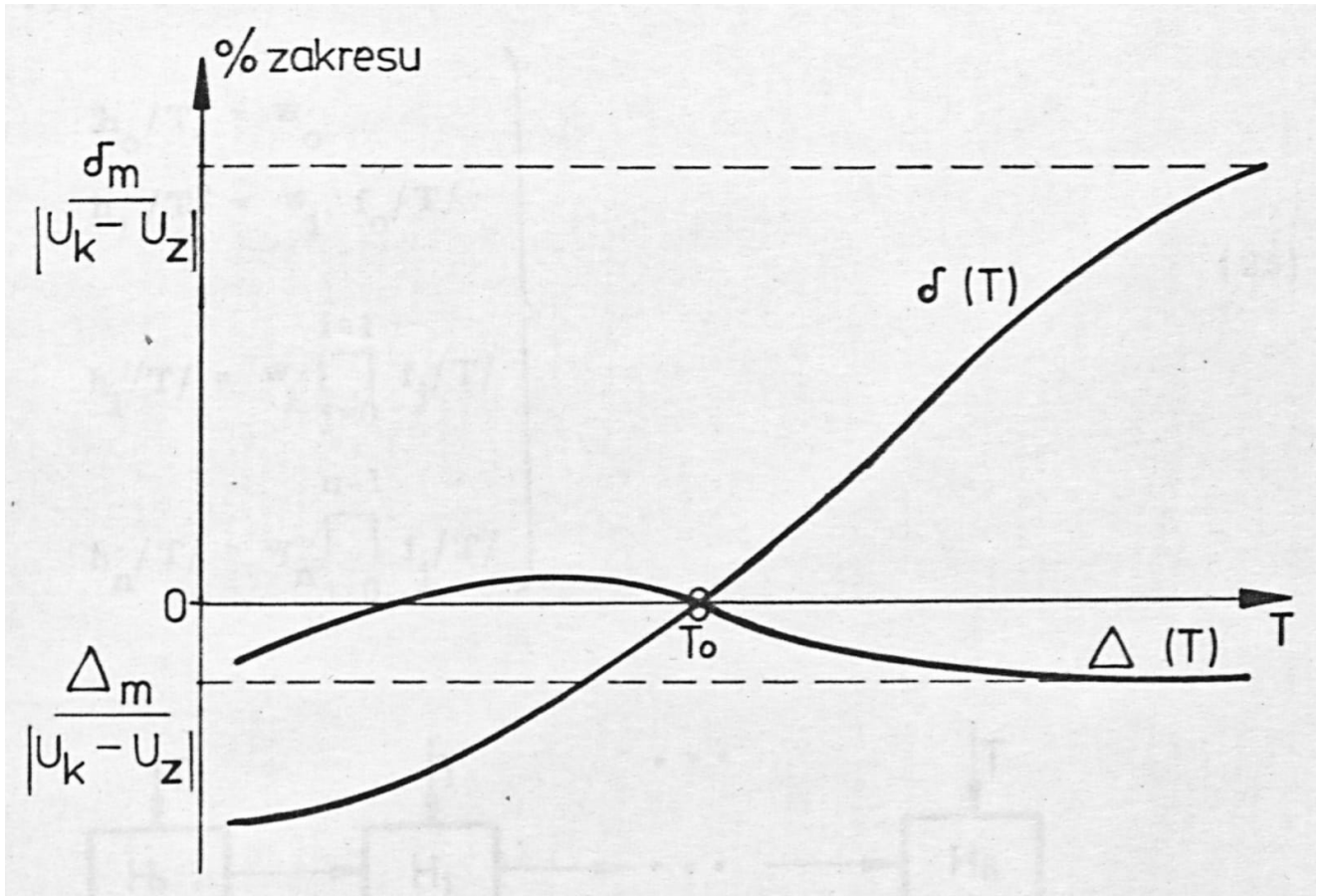


Fig. 16. Illustration of the action of the compensation circuit

Labels: % zakresu = % of the measuring range⁴

Substituting expression (12) into relation (20), taking (18) into account, we obtain the definition of the temperature error of the transducer in the form

$$\Delta(T) = b_1 \cdot \delta(T) + b_2 \cdot H(T) \quad (23)$$

Let the compensation circuit D (Fig. 15) be built of $(n+1)$ generators $H_0, H_1, \dots, H_n$ (Fig. 17). Each of the generators produces the compensating signals $h_0(T), \dots, h_n(T)$ respectively. The output signal $H(T)$ of the compensation circuit constitutes the sum of these signals:

$$H(T) = \sum_{i=0}^n h_i(T) \quad (24)$$

Let us assume that the compensating signals $h_0(T), \dots, h_n(T)$ are mutually related by means of the component functions⁵

s. 46

$f_0(T), \dots, f_n(T)$, dependent on temperature, in the following way⁶

$$\left. \begin{aligned} h_0(T) &= w_0 \\ h_1(T) &= w_1 \cdot f_0(T) \\ h_i(T) &= w_i \cdot \prod_{j=0}^{i-1} f_j(T) \\ h_n(T) &= w_n \cdot \prod_{j=0}^{n-1} f_j(T) \end{aligned} \right\} \quad (25)$$

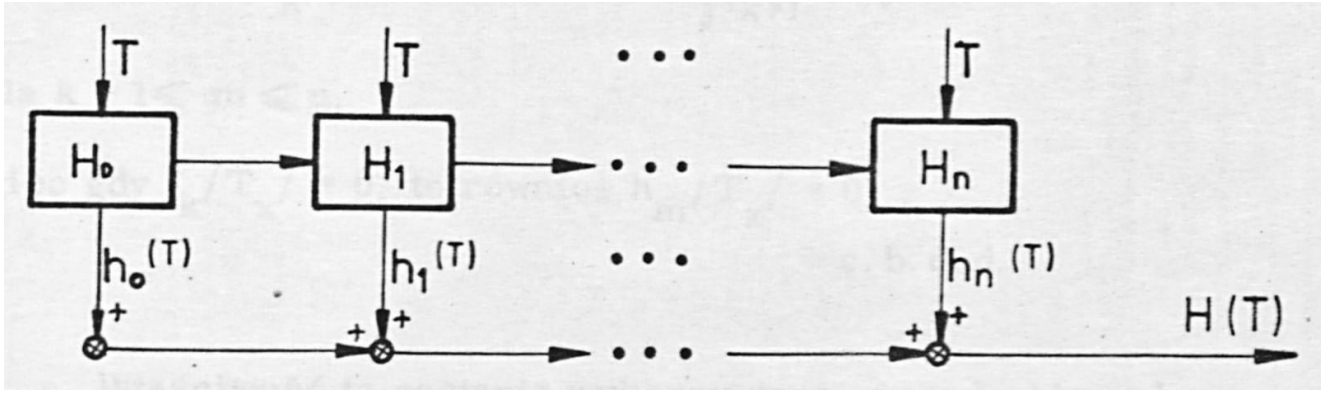


Fig. 17. Block diagram of the compensation circuit

where: $w_0, w_1, \dots, w_n$ - constants i, j, n - natural numbers

Taking (25) and (24) into account, the expression describing the temperature error of the transducer (23) takes the form

$$\Delta(T) = b_1 \cdot \delta(T) + b_2 \cdot w_0 + b_2 \cdot \sum_{i=1}^n \left[w_i \cdot \prod_{j=0}^{i-1} f_j(T) \right] \quad (26)$$

Such a relationship between the compensating signals is characterised by the following property:

THEOREM 1

If at some temperature T_x the value of the component function $f_k(T_x) = 0$,⁷

s. 47

where k is a natural number $k < n$, and the value of the constant $w_k \neq 0$, then the compensating functions $h_m(T_x) = 0$ for natural m in the interval $k + 1 \leq m \leq n$, where n is the number of component functions appearing in (25).

Proof: on the basis of (25) let us write

$$\frac{h_m(T_x)}{h_k(T_x)} = \frac{w_m}{w_k} \cdot f_k(T_x) \cdot \prod_{j=k+1}^m f_j(T_x)$$

whence

$$h_m(T_x) = \frac{w_m}{w_k} \cdot f_k(T_x) \cdot h_k(T_x) \cdot \prod_{j=k+1}^m f_j(T_x)$$

for $k + 1 \leq m \leq n$,

so that when $f_k(T_x) = 0$, then also $h_m(T_x) = 0$

Q.E.D.

This property will be used to make the settings of the compensation circuit at different temperatures unidirectionally independent of one another. To this end let us make the component functions $f_j(T)$ dependent on the reference temperature T_o and on the compensation temperatures $T_1, \dots, T_{n-1}$ as follows:

$$f_j(T) = a_j(T - T_j) \quad (27)$$

where a_j - constants $j = 0, 1, \dots, n - 1$

The adopted form (27) of the component functions $f_j(T)$ has the property of taking identically the value zero at the temperatures T_j

$$f_j(T_j) \equiv 0 \quad (28)$$

s. 48

Taking (27) into account, the expression describing the temperature error of the transducer (26) takes the form

$$\Delta(T) = b_1 \cdot \delta(T) + b_2 w_o + b_2 \cdot \sum_{i=1}^n w_i \cdot \prod_{j=0}^{i-1} [a_j(T - T_j)] \quad (29)$$

4.3.2. Compensation procedure

Let us now carry out the nulling of the temperature error of the transducer at the temperatures $T_0, \dots, T_n$ by changing the values of the coefficients w_i , where for simplicity of the considerations we shall use relation (26) describing the temperature error of the transducer. We obtain in turn:⁸ $T = T_o$; the reference temperature

Using (28) we find

$$f_o(T_o) = 0$$

and taking (26) into account we obtain the value of the temperature error

$$\Delta(T_o) = b_1 \cdot \delta(T_o) + b_2 \cdot w_o$$

Since by assumption $\delta(T_o) = 0$, the vanishing of the error $\Delta(T_o)$ will occur for

$$w_o = 0 \quad (30)$$

The coefficient w_o could therefore be omitted from the further analysis. Since, however, at the reference temperature the standardization of the points of the transfer characteristic under consideration should be carried out, e.g. zero adjustment or setting the required value of the full-scale signal, in the further considerations the coefficient w_o has been retained as a symbol of bringing the transfer error (and not the temperature error) to zero.

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$T = T_1$: the first compensation temperature

At this temperature

$$f_1(T_1) = 0$$

as a result of which the temperature error (26), after taking into account the condition for w_o obtained at $T = T_o$, is determined:

$$\Delta(T_1) = b_1 \cdot \delta(T_1) + b_2 \cdot w_1 \cdot f_o(T_1)$$

The vanishing of the error $\Delta(T_1)$ is obtained for the value w_1 :⁹

$$w_1 = -\frac{b_1 \delta(T_1)}{b_2 f_o(T_1)} \quad (31)$$

The required value of w_1 depends only on the ratio of the value of the sensor error $\delta(T)$ to the value of the component function $f_o(T)$ at this temperature, modified by the coefficients b_1, b_2 of the normalizing circuit

$T = T_2$: the second compensation temperature

Analogously to the above we obtain

$$f_2(T_2) = 0$$

and taking (26) into account we obtain the expression for the temperature error

$$\Delta(T_2) = b_1 \cdot \delta(T_2) + b_2 \cdot [w_o + w_1 \cdot f_o(T_2) + w_2 \cdot f_o(T_2) \cdot f_1(T_2)]$$

whence, after equating to zero and substituting the conditions (30) and (31) for the constants w_o and w_1 , one obtains the condition for the constant w_2 ¹⁰

$$w_2 = -\frac{b_1}{b_2} \cdot \frac{\delta(T_2) - \frac{\delta(T_1)}{f_o(T_1)} \cdot f_o(T_2)}{f_o(T_2) \cdot f_1(T_2)} \quad (32)$$

s. 50

Thus the value of the constant w_2 required to null the temperature error of the transducer at the temperature T_2 depends on the values of the sensor error at the first and second compensation temperatures ($\delta(T_1)$ and $\delta(T_2)$ respectively) and on the values of the

component functions $f_o(T)$, $f_1(T)$ at both temperatures. It does not, however, depend on the values of the sensor error and the values of the component functions at the subsequent compensation temperatures.¹¹
At the same time it should be emphasised that fixing the value of the constant w_2 at the temperature T_2 does not affect the value of the constant w_1 , fixed at the first compensation temperature T_1 .

$T = T_3.....T_k....T_{n-1}$: the subsequent compensation temperatures

Proceeding in a manner analogous to that presented above, one obtains at each of the compensation temperatures T_k a condition for the constant w_k ($k = 3, 4, ..., n-1$) in the general form

$$w_k = - \frac{b_1 \cdot \delta(T_k) + b_2 \cdot w_o + b_2 \cdot \sum_{i=1}^{k-1} w_i \cdot \prod_{j=0}^{i-1} f_j(T_k)}{b_2 \cdot \prod_{j=0}^{k-2} f_j(T_k)} \quad (33)$$

As before, the value of the constant w_k necessary to obtain a zero value of the temperature error of the transducer at the temperature T_k depends on the values of the constants $w_o, ..., w_{k-1}$ fixed at the previous temperatures and on the values of the component functions $f_o(T), ..., f_{k-1}(T)$ at the temperature T_k , and on the values of the coefficients b_1, b_2 of the normalizing circuit. The value of the constant w_k does not, however, depend on the values of the constants $w_{k+1}, ..., w_{n-1}$ and of the component functions $f_k(T), ..., f_{n-2}(T)$ at the subsequent compensation temperatures $T_{k+1}, ..., T_{n-1}$.

Making use of this property for the practical application of the method presented, we find that there exists a unidirectional independence of the settings of the elements fixing the values of the constants $w_o, ..., w_{n-1}$.

s. 51

$T = T_n$: the last compensation temperature

At the previous temperatures the properties (28) of the vanishing of all the existing component functions $f_j(T)$, ($j=0, 1, ..., n-1$), have been exhausted in fixing the values of the constants w_i , ($i = 1, 2, ..., n-1$), necessary for compensating the error. Let us now choose the constant w_n so as to obtain, for the last time, a zero value of the error $\Delta(T_n)$

$$\Delta(T_n) = b_1 \cdot \delta(T_n) + b_2 \cdot w_o + b_2 \cdot \sum_{i=1}^{n-1} w_i \cdot \prod_{j=0}^{i-1} f_j(T_n) + b_2 \cdot w_n \cdot \prod_{j=0}^{n-2} f_j(T_n)$$

whence

$$w_n = - \frac{b_1 \cdot \delta(T_n) + b_2 \cdot w_o + b_2 \cdot \sum_{i=1}^{n-1} w_i \cdot \prod_{j=0}^{i-1} f_j(T_n)}{b_2 \cdot \prod_{j=0}^{n-2} f_j(T_n)} \quad (34)$$

Condition (34) has a form and properties analogous to expression (33), with the sole difference that there are no subsequent compensation temperatures. As a result of applying the method presented, one obtains a zero value of the temperature error of the point of the characteristic of the measuring transducer under consideration at n temperatures $T_1, T_2, ..., T_n$, which means that at these temperatures the value of the point of the characteristic under consideration is equal to its value at the reference temperature T_o .

In the graphical interpretation of the action of the compensation method presented, the graph representing the dependence of the sensor-error component $b_1 \delta(T)$ in the transducer output signal will intersect the graph of the compensating-signal component $b_2 H(T)$ with reversed sign at $(n+1)$ temperature points (Fig. 18).¹²

s. 52

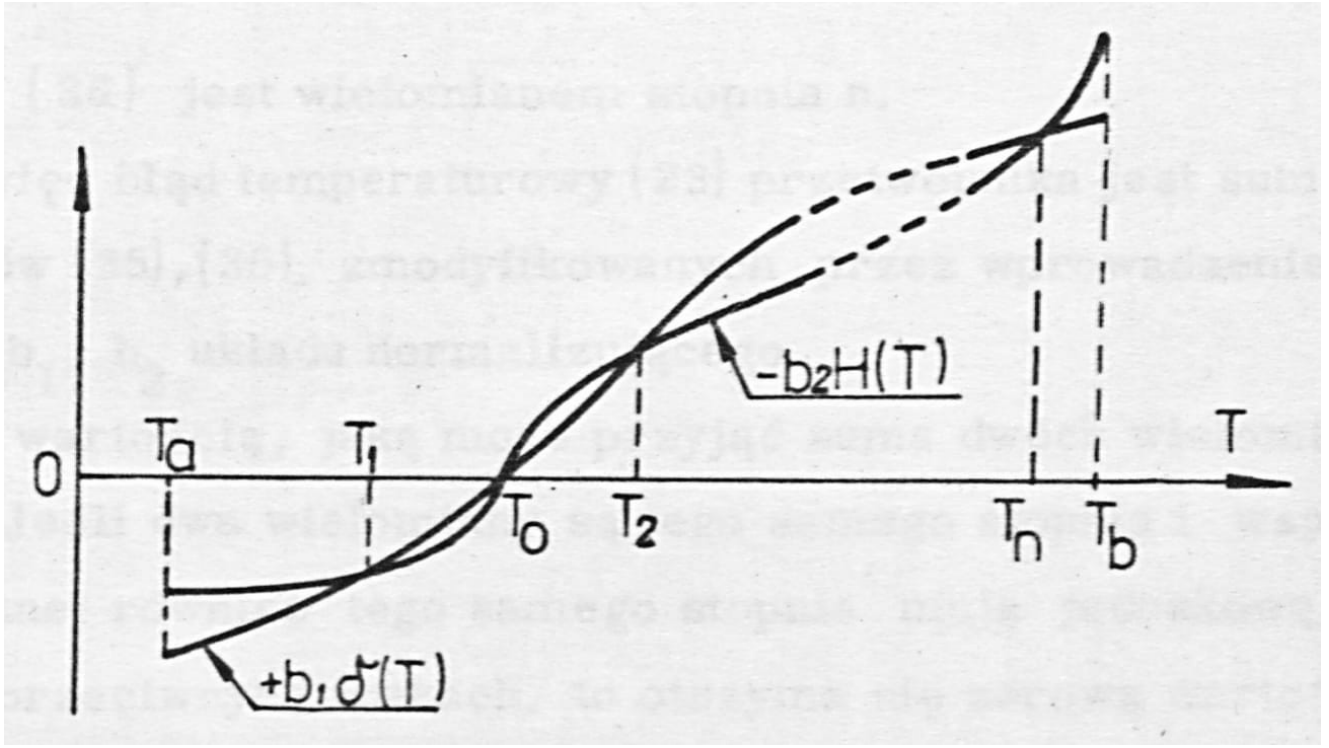


Fig. 18. Graphical interpretation of the action of n-point compensation

4.3.3. Sufficient conditions for complete temperature compensation

The condition of zero temperature error of the transducer at n compensation temperatures is not sufficient to determine its maximum value. For this, knowledge of the value of the error over the whole operating temperature range under consideration is necessary. We shall now consider the sufficient conditions for complete temperature compensation in the sense of minimization of the value of the temperature error.

Let us introduce the following description of the temperature error of the sensor $\delta(T)$

$$\delta(T) = c_0 + c_1T + c_2T^2 + \dots + c_sT^s \quad (35)$$

where $c_0, \dots, c_s$ - constants

By virtue of the Weierstrass approximation theorem [83] (see Section 4.2), expression (35) approximates any continuous curve sufficiently accurately, the degree s of the approximating polynomial being a function of the accuracy of approximation. Let us therefore assume that the description (35) of the temperature error of the sensor is a sufficiently accurate representation of the real error (18) of the sensor. Comparing expressions (29) and (23) we may determine the compensating signal as follows

s. 53

$$H(T) = w_0 + \sum_{i=1}^n w_i \cdot \prod_{j=0}^{i-1} a_j \cdot (T - T_j) \quad (36)$$

Expression (36) is a polynomial of degree n . Thus the temperature error (23) of the transducer is the sum of two polynomials (35), (36), modified by the introduction of the coefficients b_1, b_2 of the normalizing circuit. The minimum value that the sum of two polynomials can take is zero. If two polynomials are of the same degree and the coefficients of the variable of the same degree likewise have equal absolute values and opposite signs, then a zero value of the sum of these polynomials is obtained irrespective of the value of the variable. We may therefore formulate the conclusion that the optimum condition of temperature compensation that interests us is the attainment of the identity

$$b_1 \cdot \delta(T) + b_2 \cdot H(T) \equiv 0 \quad (37)$$

A necessary condition for attaining (37) is the equality of the degrees of the polynomials (35) and (36):

$$n = s \quad (38)$$

which is equivalent to equating the number n of compensation temperatures with the degree s of the polynomial approximating the temperature error of the sensor. As a result of carrying out the compensation in accordance with Section 4.3.2, one obtains $(n+1)$

zeros of the equation:

$$\Delta(T) = 0$$

Since through $(n+1)$ points only one curve of degree n can be drawn, this means that the compensation procedure leads unambiguously to the identity (37). This is equivalent to the identical vanishing of the temperature error of the transducer over the whole operating temperature range, irrespective of the choice of the compensation temperatures.

In the analysis carried out above it was assumed that the compensating-signal generators $H_1 \dots H_n$ produce signals linearly dependent on temperature. The resultant compensating signal is produced

s. 54

by establishing an appropriate combination of products of these signals, giving as a result a polynomial of degree n . Let us now assume that we wish to obtain a polynomial of degree n with a smaller number of compensation temperatures. To this end let us make the component functions $f_j(T)$ dependent on temperature in the following way:

$$f_j(T) = (T - T_j) \cdot \sum_{p=0}^{m-1} a_{jp} \cdot (T - T_j)^p \quad (39)$$

where a_{jp} - constants $j = 0, 1, \dots, n - 1$
 m - a natural number

Expression (39) is a polynomial of degree m and, by virtue of the Weierstrass approximation theorem [83] (see Section 4.2), it can describe any continuous function, the degree m of the polynomial depending on the required accuracy of approximation of that function. The adopted form (39) of the component functions $f_j(T)$ also has the property (28) of vanishing identically at the temperatures T_j .

Let us assume in turn that a certain number R of properties of relation (35) approximating the temperature error of the sensor is known in advance. Let the degree m of the component function (39) be determined as follows

$$m = R + r \quad (40)$$

where r is a natural number

By raising the degree m one obtains a compensating polynomial $H(T)$ of degree $n(R + r)$. In order to obtain the identity (37) the relation

$$s = n(R + r) \quad (41)$$

must be satisfied, whence one obtains the required number n of compensation temperatures in the case of adopting $r = 0$, that is, in the case of maximum use of the R known properties:

$$n = \frac{s}{R} \quad (42)$$

s. 55

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Conclusions: the optimum conditions of complete temperature compensation can be achieved either by producing component functions $f_j(T)$ linear as a function of temperature and carrying out the compensation at a number of temperatures equal to the degree of the polynomial describing the temperature error of the sensor (condition 38), or else by raising the degree of the polynomial describing the component function $f_j(T)$, relying on properties of the temperature error of the sensor known in advance, and reducing the number of compensation temperatures (condition 42).

An example of advance information on the character of the temperature error of the sensor is information on the ratio of the values of the errors at certain temperatures. Thus in integrated pressure sensors [40] the temperature span drift is approximated by a fourth-order curve, and the quotient of the values of the temperature error at the temperatures 352 K and 241 K is a function of the substrate resistivity. In such a case it may prove sufficient to produce a function $f_j(T)$ compensating the temperature error of one sensor, which will then make it possible to compensate all the sensors by multiplying (dividing) the value of the compensating signal by an appropriate proportionality coefficient.

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The method will now be explained by examples.

Example 1

Let the sensor error be determined by the quadratic relation

$$\delta(T) = B \cdot (T - T_o) \cdot (T + T_x)$$

where T_x - a constant and let $b_1 = b_2 = 1$

We shall realise two variants of the compensation circuit for $m \cdot n = 2$; subjecting them next to compensation, we shall carry out the compensation procedures for them

variant (a) $n = 2$ $m = 1$, so

$$f_o = a_1 \cdot (T - T_o)$$

$$f_1 = a_2 \cdot (T - T_1)$$

and after substitution into (26) we obtain

$$\Delta(T) = B \cdot (T - T_o) \cdot (T + T_x) + w_o + w_1 \cdot a_1 \cdot (T - T_o) - w_2 \cdot a_1 \cdot a_2 \cdot (T - T_o) \cdot (T - T_1)$$

Compensation procedure:

$$T = T_o; \quad \Delta(T_o) = w_o$$

and hence we obtain the condition for the vanishing of the error $\Delta(T_o)$ ^{13 14}

$$w_o = 0$$

$$T = T_1; \quad \Delta(T_1) = B \cdot (T_1 - T_o) \cdot (T_1 + T_x) + w_1 \cdot a_1 \cdot (T - T_o)$$

and the condition for the vanishing of the error $\Delta(T_1)$ ¹⁵

$$w_1 = -\frac{B \cdot (T_1 + T_x)}{a_1}$$

$$T = T_2;$$

$$\Delta(T_2) = B \cdot (T_2 - T_o) \cdot (T_2 + T_x) + B \cdot (T_1 + T_x) \cdot (T_2 - T_o) - a_1 \cdot a_2 \cdot w_2 \cdot (T_2 - T_o) \cdot (T_2 - T_1)$$

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and finally the condition for the vanishing of the error $\Delta(T_2)$

$$w_2 = -\frac{B}{a_1 \cdot a_2}$$

Substituting the values w_o , w_1 , w_2 obtained in this way into expression (26), one obtains the identity

$$\Delta(T) \equiv 0$$

variant (b) $n = 1$, $m = 2$

$$f_o(T) = (T - T_o) \cdot (a_{o1} + a_{o2}T)$$

After substitution into (26) we obtain

$$\Delta(T) = B \cdot (T - T_o) \cdot (T + T_x) + w_o + w_1 \cdot (T - T_o) \cdot (a_{o1} + a_{o2} \cdot T)$$

Compensation procedure¹⁶

$$T = T_o; \quad \Delta(T_o) = w_o \quad \text{whence}$$

$$w_o = 0$$

$$T = T_1; \quad \Delta(T_1) = B \cdot (T_1 - T_o) \cdot (T_1 + T_x) + w_1 \cdot (T_1 - T_o) \cdot (a_{o1} + a_{o2} \cdot T_1)$$

whence¹⁷

$$w_1 = -\frac{B \cdot (T_1 + T_x)}{a_{o1} + a_{o2} \cdot T_1}$$

Taking into account the values of w_o and w_1 obtained, we obtain

$$\Delta(T) = B \cdot (T - T_o) \cdot \left[T + T_x - \frac{(T_1 + T_x) \cdot (T + \frac{a_{o1}}{a_{o2}})}{T_1 + \frac{a_{o1}}{a_{o2}}} \right]$$

The value of $\Delta(T)$ obtained is identically equal to zero under the additional

s. 58

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condition, relating its sensor-error characteristic to the characteristic of the compensating signal, in the form

$$T_x = \frac{a_{o1}}{a_{o2}}$$

This is obvious, since complete compensation of an error described by a quadratic function requires three degrees of freedom (balancing of the three coefficients T_o , T_x , B), whereas in the compensation procedure of variant b we have only two degrees of freedom, namely the coefficients w_o and w_1 . The procedure presented according to variant a is based on three degrees of freedom - the coefficients w_o , w_1 and w_2 - and consequently no additional condition was required.

4.4. The essence of incomplete temperature compensation

We shall now consider the value of the error (26) of the transducer under the assumption of incomplete compensation. By incomplete compensation will be understood a limitation of the number of compensation temperatures in comparison with the values obtained from relations (38) or (42).

$$m \cdot n < s \quad (43)$$

For simplicity this compensation will be shown for the case of the degree s of the polynomial approximating the temperature error of the sensor equal to two and three, which practically exhausts almost all the cases met with in practice. In the case $s = 1$ the temperature error is reduced identically to zero by a compensation circuit with the parameters $m = 1$, $n = 1$.

4.4.1. Case: $s = 2$, $m = 1$, $n = 1$

In this case the sensor error is described by the relation

$$\delta(T) = B \cdot (T - T_o) \cdot (T + T_x) \quad (44)$$

where T_o - the reference temperature B , T_x - constants

s. 59

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On the basis of (27) we have $f_o = a_o \cdot (T - T_o)$ and using (26) we shall write the error $\Delta(T)$ of the transducer in the form

$$\Delta(T) = b_1 \cdot B \cdot T^2 + [b_1 \cdot B \cdot (T_x - T_o) + b_2 \cdot w_1 \cdot a_o] \cdot T - b_1 \cdot B \cdot T_o \cdot T_x - b_2 \cdot w_1 \cdot a_o \cdot T_o$$

The compensation procedure is as follows:

a. $T = T_o$; $\Delta(T_o) = 0$

b. $T = T_1$;

$$\Delta(T_1) = b_1 \cdot B \cdot [T_1^2 + (T_x - T_o) \cdot T_1 - T_o \cdot T_x] - w_1 \cdot b_2 \cdot a_o \cdot (T_o - T_1)$$

In order to bring the error $\Delta(T_1)$ to zero the value w_1 is necessary:

$$w_1 = \frac{b_1 \cdot B \cdot [T_1^2 + (T_x - T_o) \cdot T_1 - T_o \cdot T_x]}{b_2 \cdot a_o \cdot (T_o - T_1)} \quad (45)$$

Introducing the value w_1 obtained into (45), we obtain the relation describing the temperature error of the compensated transducer¹⁸

$$\Delta(T) = b_1 \cdot B \cdot (T - T_o) \cdot (T - T_1) \quad (46)$$

Let us impose an additional condition, requiring that the values of the error (73) at the limits T_a, T_b of the operating temperature range be equal to each other and that they be equal - with opposite sign - to the value of the error at the temperature T_m at which the extremum of the function occurs (Fig. 19a):¹⁹

$$\Delta(T_a) = \Delta(T_b) = -\Delta(T_m) \quad (47)$$

it can therefore easily be shown that

$$T_m = \frac{T_o + T_1}{2} \quad (48)$$

and

$$\Delta(T_m) = -\frac{b_1 \cdot B \cdot (T_o - T_1)^2}{4} \quad (49)$$

Assuming $T_a < T_b, T_o < T_1$, the value of the reference temperature T_o will be determined by the relation

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$$T_o = T_a + \frac{\sqrt{2} - 1}{2\sqrt{2}} \cdot (T_b - T_a) \quad (50)$$

while the first compensation temperature T_1 :

$$T_1 = T_b - \frac{\sqrt{2} - 1}{2\sqrt{2}} \cdot (T_b - T_a) \quad (51)$$

The error-reduction factor η of the temperature error of the sensor will be determined as follows:

$$\eta = \left| \frac{\delta m}{\Delta m} \right| = \left| \frac{T_b + T_x}{b_1 \cdot (T_b - T_1)} \right| \quad (52)$$

As can be seen, condition (47) unambiguously makes the values of the reference temperature and of the first compensation temperature dependent on the limit temperatures of operation, irrespective of the parameters of the sensor and of the compensation circuit (which should merely lead to condition 47).

The value of the maximum temperature error of the transducer is also in such a case independent of the parameters of the compensation circuit. For, substituting (50) and (51) into (49), we obtain the value of the extreme error of the transducer $\Delta(T_m)$:

$$\Delta(T_m) = -\frac{b_1 \cdot B}{8} \cdot (T_b - T_a)^2 \quad (53)$$

and so this value depends only on the width of the operating temperature range and on the uncompensated constant B of the sensor-error characteristic, and on the constant b_1 of the normalizing circuit.

Example 2

The transducer is to operate in the temperature range 253 K to 333 K. On the basis of (51) and (52) we calculate: $T_o = 264.7$ K, $T_1 = 321.3$ K. The sensor error referred to the temperature T_o we shall describe by the relation (expressed²⁰

s. 61

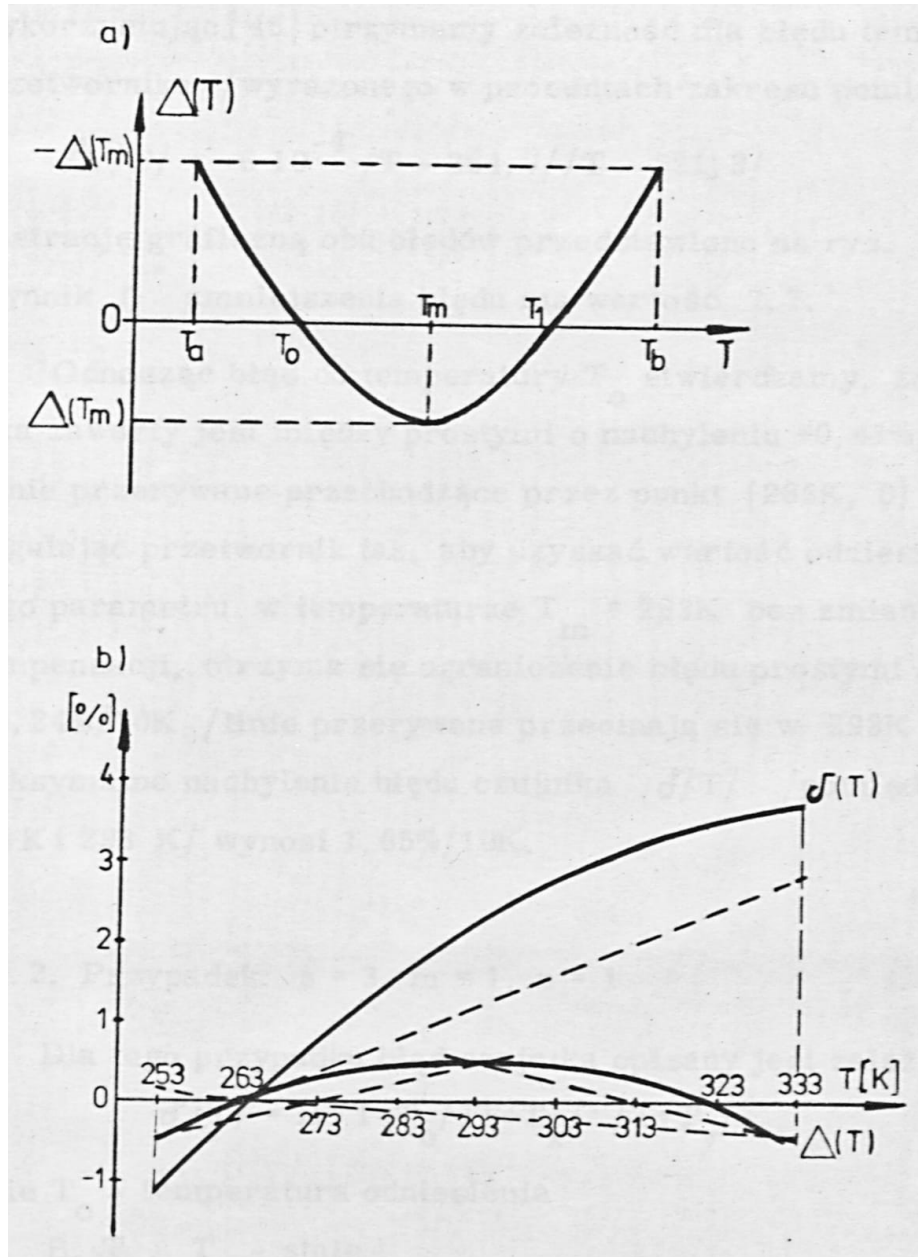


Fig. 19. Temperature error of the sensor $\delta(T)$ and of the transducer $\Delta(T)$ in the case $s = 2$

s. 62

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as a percentage of the measuring range):²¹

$$\Delta(T) = -6 \cdot 10^{-4} \cdot (T - 264.7) \cdot (T - 423)$$

and for simplicity we shall adopt the parameters of the normalizing circuit $b_1 = b_2 = 1$. Using (46) we obtain the relation for the temperature error of the transducer (expressed as a percentage of the measuring range):

$$\Delta(T) = -6 \cdot 10^{-4} \cdot (T - 264.7) \cdot (T - 321.3)$$

A graphical illustration of both errors is presented in Fig. 19b. The error-reduction factor η has the value 7.7.

Referring the error to the temperature T_0 , we find that the transducer error is contained between straight lines of slope $+0.41 \text{ } \%/10 \text{ K}$ and $0.07 \text{ } \%/10 \text{ K}$ (dashed lines passing through the point $(283 \text{ K}, 0)$ in Fig. 19b). Adjusting the transducer so as to obtain the reference value of the parameter under consideration at the temperature $T_m = 293 \text{ K}$ without changing the compensation parameters, one obtains a limitation of the error by straight lines of slope $\pm 0.24 \text{ } \%/10 \text{ K}$ (dashed lines intersecting at 293 K in Fig. 19b). The maximum slope of the sensor error $\delta(T)$ (between the temperatures 253 K and 293 K) amounts to $1.05 \text{ } \%/10 \text{ K}$.

4.4.2. Case: $s = 3, m = 1, n = 1$

For this case the sensor error is described by the relation:

$$\delta(T) = B \cdot (T - T_o) \cdot (T + T_x) \cdot (T + T_y) \quad (54)$$

where T_o - the reference temperature B, T_x, T_y - constants

On the basis of (27) we therefore write

$$f_o = a_o \cdot (T - T_o)$$

and taking $w_o = 0$ into account we obtain the transducer error in the form

$$\Delta(T) = b_1 \cdot B \cdot (T - T_o) \cdot (T + T_x) \cdot (T + T_y) + b_2 \cdot w_1 \cdot a_o \cdot (T - T_o)$$

s. 63

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The temperature compensation procedure is as follows:²²

$$T = T_o; \quad \Delta(T_o) = 0$$

$$T = T_1; \quad \Delta(T_1) = b_1 \cdot B \cdot (T_1 - T_o) \cdot (T_1 + T_x) \cdot (T_1 + T_y) + b_2 \cdot w_1 \cdot a_o \cdot (T_1 - T_o)$$

In order to bring $\Delta(T_1)$ to zero the value w_1 is required

$$w_1 = - \frac{b_1 \cdot B \cdot (T_1 + T_x) \cdot (T_1 + T_y)}{b_2 \cdot a_o} \quad (55)$$

Taking into account the value (55) obtained for w_1 , one obtains the relation for the error of the compensated transducer

$$\Delta(T) = b_1 \cdot B \cdot (T - T_o) \cdot [T^2 + (T_x + T_y) \cdot T - T_1^2 \cdot (T_x + T_y)] \quad (56)$$

It may be assumed that, from the point of view of the needs of compensation, it will be advantageous for relation (56) to be characterised by the following features: (a) that it should have 3 real roots; this will be satisfied when the discriminant D of the quadratic equation in square brackets in relation (56)

$$\Delta = (T_x + T_y + 2T_1)^2$$

is greater than zero, that is, for every T_1 satisfying the condition:

$$T_1 \neq - \frac{T_x + T_y}{2}$$

(b) that both roots of the equation in square brackets in relation (56) should lie within the operating temperature range: this condition cannot, however, be guaranteed with a single degree of freedom in the form of the constant T_1 .

The minimization of the error (56) for assumed spreads of the parameters T_x and T_y can be carried out most quickly by means of computer calculations of variants on the basis of the results of measurement of the sensor error.

Example 3

Operating temperature range from 253 K to 333 K. Sensor error

s. 64

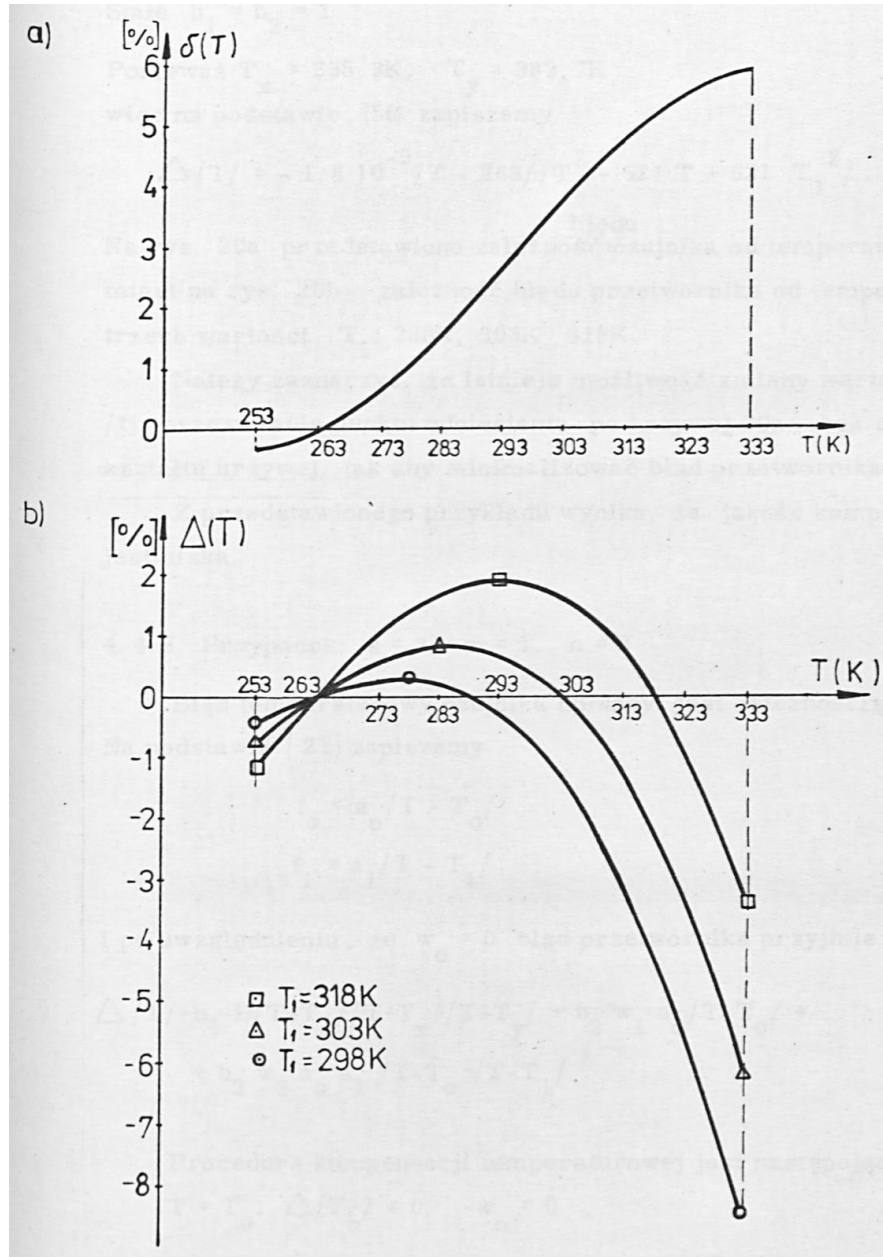


Fig. 20. Temperature error of the sensor $\delta(T)$ and of the transducer $\Delta(T)$ in the case $s = 3$, $m = 1$, $n = 1$.

s. 65

$$\delta(T) = -1.8 \cdot 10^{-5} \cdot (T - 263)(T - 238.3) \cdot (T - 382.7)$$

Constants $b_1 = b_2 = 1$

Since $T_x = 238.3$ K, $T_y = 382.7$ K on the basis of (56) we therefore write

$$\Delta(T) = -1.8 \cdot 10^{-5} \cdot (T - 263) \cdot (T^2 - 621 \cdot T + 621 \cdot T_1^2)$$

Fig. 20a presents the dependence of the sensor error on temperature, while Fig. 20b presents the dependence of the transducer error on temperature for three values of T_1 : 288 K, 303 K, 318 K.²³

It should be noted that there is the possibility of changing the value of T_o (i.e. shifting the reference point along the curve 20a) without changing the shape of the curve, so as to minimize the transducer error.

From the example presented it follows that the quality of the compensation is low.

4.4.3. Case: $s = 3$, $m = 1$, $n = 2$

The temperature error of the sensor is described by relation (54). On the basis of (27) we write

$$f_o = a_o \cdot (T - T_o)$$

$$f_1 = a_1 \cdot (T - T_1)$$

and taking into account that $w_o = 0$, the transducer error takes the form

$$\begin{aligned} \Delta(T) = & b_1 \cdot B(T - T_o) \cdot (T + T_x) \cdot (T + T_y) + b_2 \cdot w_1 \cdot a_o \cdot (T - T_o) + \\ & + b_2 \cdot w_2 \cdot a_o \cdot a_1 (T - T_o) \cdot (T - T_1) \end{aligned}$$

The temperature compensation procedure is as follows:

$$T = T_o; \quad \Delta(T_o) = 0, \quad w_o = 0$$

$$\begin{aligned} T = T_1; \quad \Delta(T_1) = & b_1 \cdot B(T_1 - T_o) \cdot (T_1 + T_x) \cdot (T_1 + T_y) + b_2 \cdot w_1 \cdot a_o \cdot (T_1 - T_o) + \\ & + b_2 \cdot w_2 \cdot a_o \cdot a_1 \cdot (T_1 - T_o) \end{aligned}$$

s. 66

The value w_1 bringing the error $\Delta(T_1)$ to zero we shall write

$$w_1 = - \frac{b_1 \cdot B(T_1 + T_x) \cdot (T_1 + T_y)}{b_2 \cdot a_o} \quad (57)$$

Taking into account the value of w_1 found, the expression for the transducer error takes the form

$$\begin{aligned} \Delta(T) = & b_1 \cdot B(T - T_o) \cdot (T + T_x) \cdot (T + T_y) - b_1 \cdot B(T_1 + T_x) \cdot (T_1 + T_y) \cdot (T - T_o) + \\ & + b_2 \cdot w_2 \cdot a_o \cdot a_1 \cdot (T - T_o) \cdot (T - T_1) \end{aligned}$$

$T = T_2$; determining the error analogously to the above, we obtain the value w_2 nulling it:

$$w_2 = - \frac{b_1 \cdot B(T_2 + T_x) \cdot (T_2 + T_y) - b_1 \cdot B(T_1 + T_x) \cdot (T_1 + T_y)}{b_2 \cdot a_o \cdot a_1 \cdot (T_2 - T_1)} \quad (58)$$

After substituting the values of w_1 and w_2 found, we obtain the relation describing the temperature error of the compensated transducer:²⁴

$$\Delta(T) = b_1 \cdot B(T - T_o) \cdot (T - T_1) \cdot (T - T_2) \quad (59)$$

This error depends on the value of the uncompensated constant B of the sensor error, on the values of the compensation temperatures T_1 and T_2 and of the reference temperature T_o , and is at the same time modified by the coefficient b_1 of the normalizing circuit. Relation (59) guarantees obtaining three zeros within the operating temperature range (Fig. 21). Imposing the condition of values of the error $\Delta(T)$ equal in absolute value at the extrema occurring at the temperatures T_c, T_d , one obtains a relation between the reference temperature and the compensation temperatures:

$$T_o = \frac{T_1 + T_2}{2} \quad (60)$$

The value of the maximum error can be shaped by changing the differences between the compensation temperatures and by changing the value of the reference temperature.

s. 67

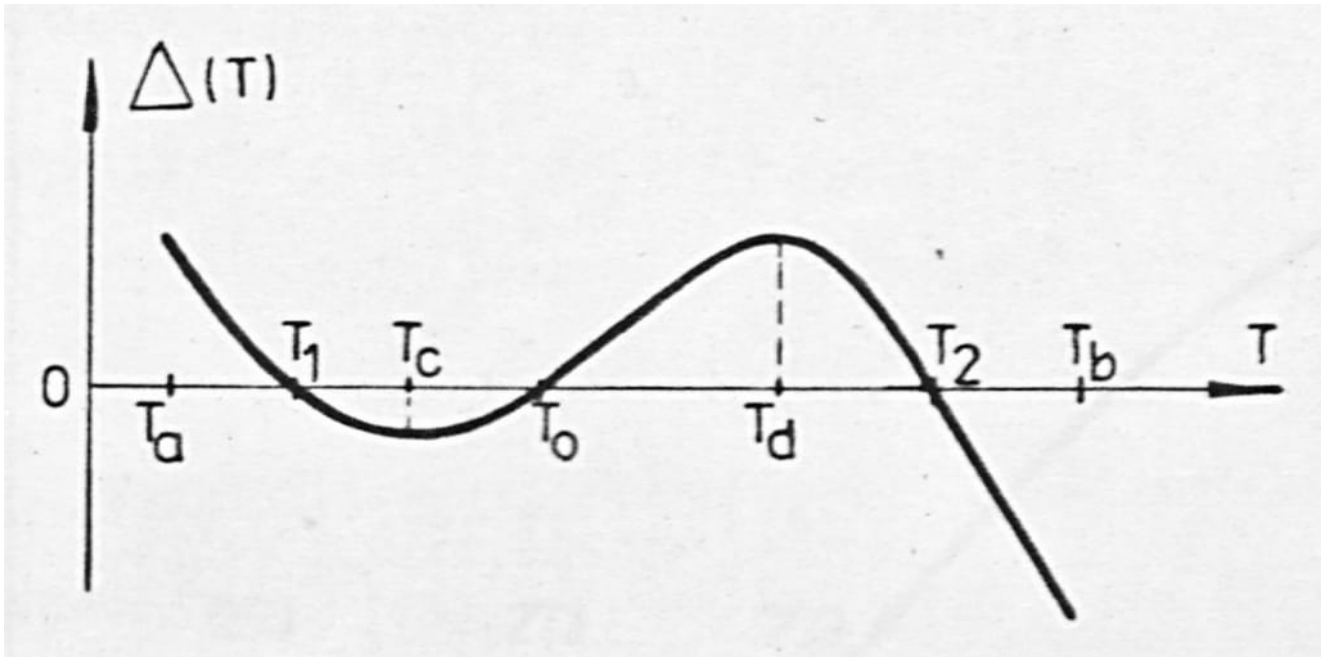


Fig. 21. Desired course of the transducer error in the case $s = 3$, $m = 1$, $n = 2$

Example 4

Operating temperature range from 253 K to 333 K The sensor error is described by the curve (Fig. 22)

$$\delta(T) = -1.8 \cdot 10^{-5} \cdot (T - 293) \cdot (T - 373) \cdot (T - 218)$$

constants $b_1 = b_2 = 1$

Thus, $T_x = -373K$, $T_y = -218K$, $B = -1.8 \cdot 10^{-5}$

The dependence of the error (59) of the compensated transducer on temperature depends on the choice of the compensation temperatures T_1 and T_2 :²⁵

$$\Delta(T) = -1.8 \cdot 10^{-5} \cdot (T - 293)(T + T_1) \cdot (T + T_2)$$

Graphs of this error for various pairs T_1 , T_2 satisfying (60), and for one pair not satisfying (60), are presented in Fig. 22b.

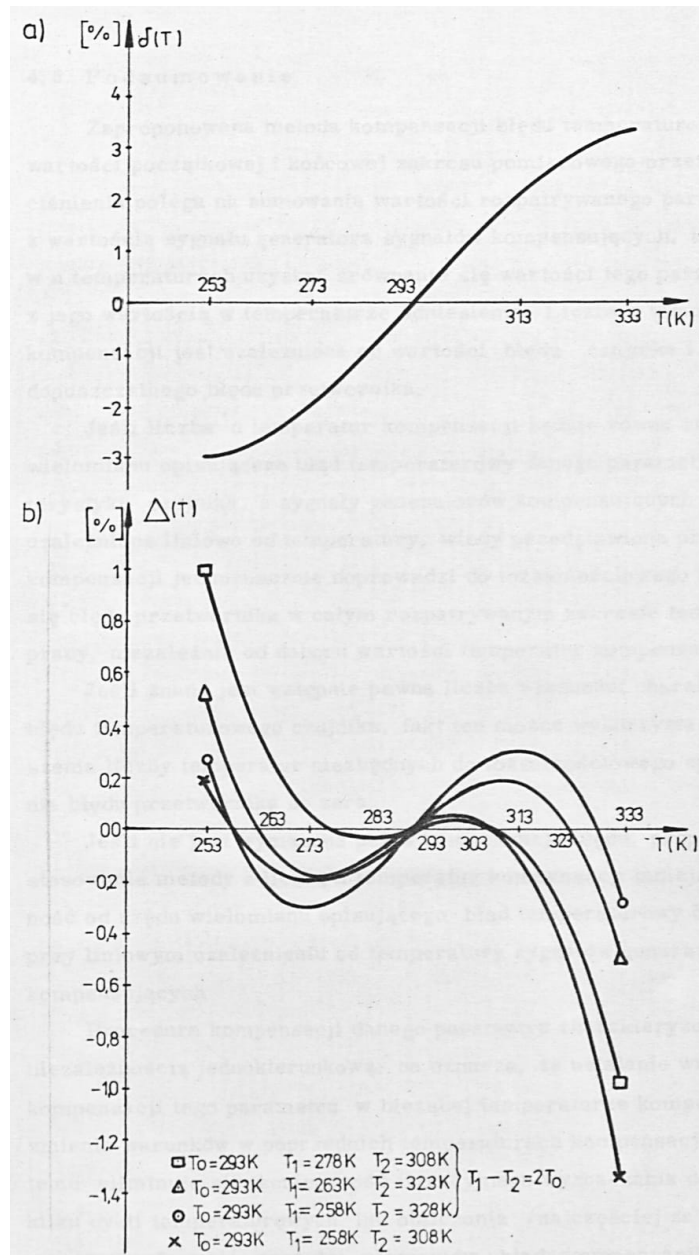


Fig. 22. Temperature error of the sensor $\delta(T)$ and of the transducer $\Delta(T)$ in the case $s = 3$, $m = 1$, $n = 2$

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s. 69

4.5. Summary

The proposed method of compensation of the temperature error of the lower and upper range values of the measuring range of a pressure transducer consists in summing the value of the parameter under consideration with the value of the signal of the compensating-signal generator, so that at n temperatures the value of this parameter becomes equal to its value at the reference temperature. The number n of compensation temperatures depends on the value of the sensor error and on the value of the permissible transducer error.

If the number n of compensation temperatures is equal to the degree of the polynomial describing the temperature error of the given parameter of the sensor characteristic, and the signals of the compensating generators are linearly dependent on temperature, then the compensation procedure presented leads unambiguously to the identical vanishing of the transducer error over the whole operating temperature range under consideration, irrespective of the choice of the values of the compensation temperatures.

If a certain number of properties of the temperature-error characteristic of the sensor is known in advance, this fact can be used to reduce the number of temperatures necessary for reducing the transducer error identically to zero.

If complete compensation of the error is not required, it is proposed to use the method with a number n of compensation temperatures smaller by one than the degree of the polynomial describing the temperature error of the sensor, with the signals of the compensating generators linearly dependent on temperature.

The compensation procedure for a given parameter is characterised by unidirectional independence, which means that establishing the compensation conditions for this parameter at the current compensation temperature does not change the conditions at the previous compensation temperatures. Thanks to this, the necessity is eliminated of iterative determination, which requires several temperature cycles, or of calculation (most often by means of a digital computer) of the values of the components of the compensation circuit necessary for compensating the temperature error of the parameter of the transducer characteristic

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under consideration.

Comparing the method presented with other known methods [1, 32–76], it must be stated that only the method presented in this thesis makes possible the identical reduction of the temperature error of the transducer to zero together with unidirectional independence of the establishment of the compensation conditions.

In the method presented, the change of the temperature characteristic of the compensating signal is effected by changing proportionality coefficients that are independent of temperature. In practical application the compensation method may consist in appropriately setting potentiometric dividers of the compensating signals. Since on such dividers only a signal of the order of the temperature errors of the sensor would then be present, that is, a small percentage of the full-scale signal, the metrological requirements imposed on these components could be relaxed.

The use of the potentiometric dividers mentioned would eliminate the necessity of stocking a large number of values of compensating components (which may potentially be used) or of manufacturing them after obtaining information on the sensor errors.

The method presented can be applied in measuring transducers of all types for non-electrical quantities satisfying the conditions listed in Section 4.1.

Fig. 23 presents schematically the course of the temperature error of a compensated transducer in the case of complete compensation and of incomplete compensation for the cases most frequently met with in practice.

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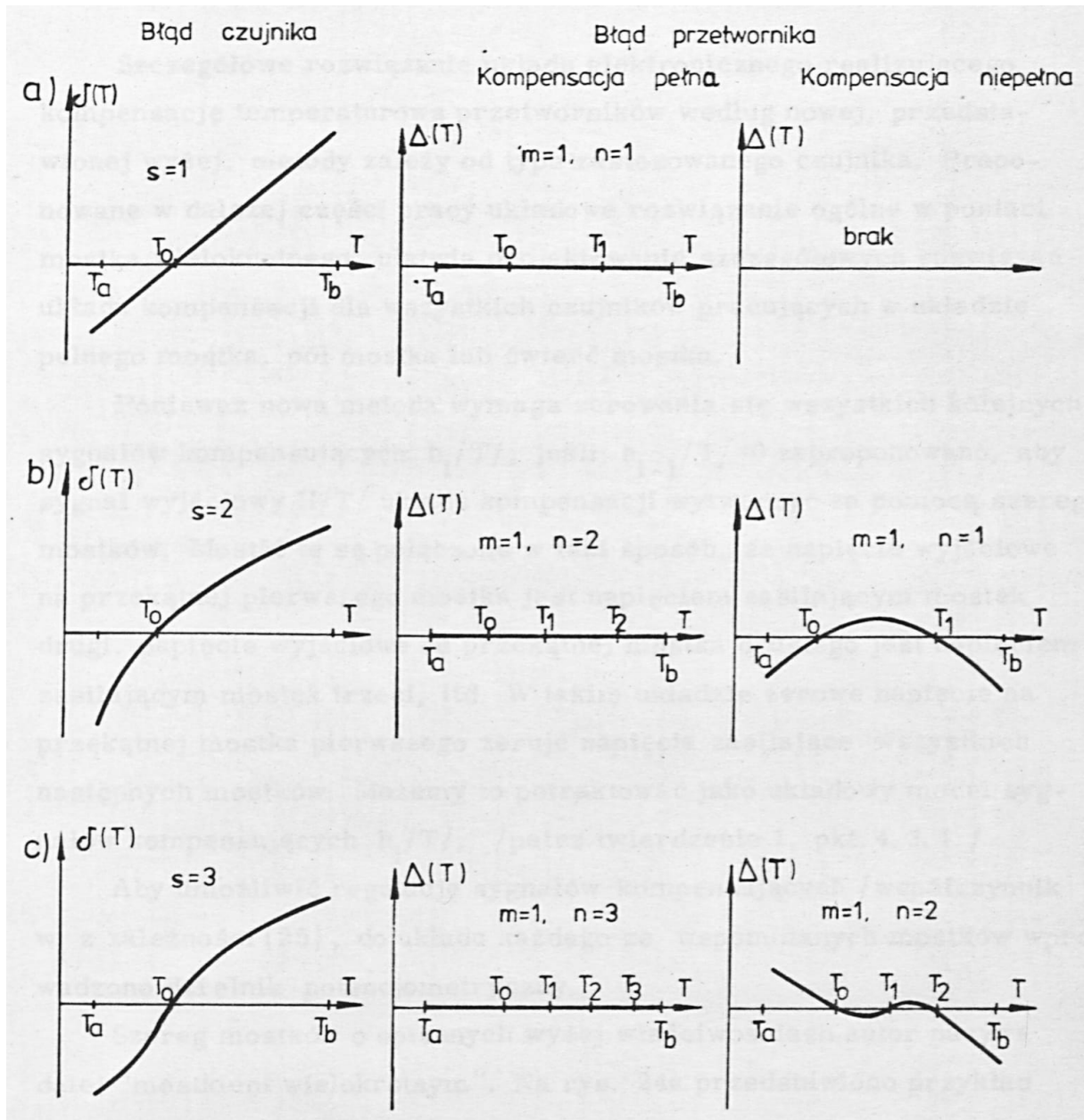


Fig. 23. Schematic shape of the temperature error $\Delta(T)$ of a compensated transducer in the case of complete and incomplete compensation; a. sensor error $\delta(T)$ described by a linear function; b. sensor error $\delta(T)$ described by a quadratic function; c. sensor error $\delta(T)$ described by a cubic function

Labels: Błąd czujnika = sensor error; Błąd przetwornika = transducer error; Kompensacja pełna = complete compensation; Kompensacja niepełna = incomplete compensation; brak = none (not applicable)

Translator's notes

1. from here on U_p denotes the output at the lower range value; in Section 3.2 the same symbol denoted the forward voltage of a p-n junction.
2. original reads "rys. 14"; the block diagram referred to is Fig. 15.
3. original reads only the subscript "m" here; the δ is missing in the typescript, evidently δ_m as in (19). "error 18" is printed without parentheses.
4. the figure labels read U_z where the text of (22) uses U_p for the lower range value; labels as printed.
5. original reads " $h_1(T)$ " for the last signal of the list; evidently $h_n(T)$.
6. original reads "i=1" as the upper limit of the product in the third line; evidently i-1, as in (26).
7. in Theorem 1 T_x denotes an arbitrary temperature; from Section 4.3.3 onward the same symbol denotes a constant of the sensor-error polynomial.
8. original reads " w_1 "; evidently w_i , the whole set of coefficients.
9. original reads " (T_1) " without the δ in the numerator of (31); the δ is missing in the typescript, evidently $\delta(T_1)$.
10. in (32) the inner numerator is typed " δT_1 " without the parentheses in the original; evidently $\delta(T_1)$.

11. original reads "tempe-" with the syllable "ra" typed and then overstruck by a hyphen at the line break ("temperaturowego"); a typing correction with no effect on the meaning.
12. original reads " $b_1(T)$ "; the δ is missing in the typescript, evidently $b_1 \delta(T)$.
13. original reads " W_o " with a capital W; evidently w_o .
14. " $(T - T_o)$ " in the last factor as printed; evidently $T_1 - T_o$, as in the $\Delta(T_2)$ line below.
15. original reads " $(T_1 + T_x)$ " — the closing parenthesis is missing in print and the "+" is overtyped; rendered with the parenthesis closed.
16. original reads " $(T_1 + T_o)$ " in the first factor; the "+" is as printed, evidently $T_1 - T_o$.
17. original reads " $(T_1 + T_x)$ " without the closing parenthesis, and the second denominator subscript is typed "02" (digit zero); evidently a_{o2} , as elsewhere in this variant.
18. "into (45)" as printed; the value of w_1 is evidently substituted into the expression for $\Delta(T)$ at the top of this page, not into (45) itself.
19. original reads "(73)"; the error referred to is evidently (46).
20. "(51) and (52)" as printed; the two temperatures follow from (50) and (51).
21. original reads " $\Delta(T)$ " on the left-hand side although this is the sensor error introduced in the preceding sentence; by the text it is $\delta(T)$.
22. the factor $(T_1 + T_x)$ is missing from the first term as printed; cf. the preceding expression for $\Delta(T)$ and (55).
23. the word "błądu" (error) in "the sensor error" is a handwritten insertion in the typescript. The first compensation temperature reads 288 K in the text; the legend of Fig. 20b reads $T_1=298K$.
24. original reads $(T + T_1) \cdot (T + T_2)$; the "+" signs are as printed, evidently "-" (the error vanishes at the compensation temperatures T_1, T_2).
25. $(T + T_1) \cdot (T + T_2)$ as printed, repeating the signs of (59) as printed; see the note at (59).
26. the bracketed legend label reads $T_1 - T_2 = 2T_0$ in the original; evidently $T_1 + T_2 = 2T_0$, i.e. condition (60).

5. PRACTICAL REALIZATION OF THE METHOD

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The detailed design of the electronic circuit that realizes the temperature compensation of transducers according to the new method presented above depends on the type of sensor used. The general circuit design proposed in the remainder of this work, in the form of a multiple bridge, simplifies the design of detailed compensation circuits for all sensors operating in a full-bridge, half-bridge or quarter-bridge configuration.

Since the new method requires that every successive compensating signal $h_i(T)$ vanish whenever $h_{i-1}(T) = 0$, it is proposed that the output signal $H(T)$ of the compensation circuit be generated by means of a chain of bridges. These bridges are connected in such a way that the output voltage on the diagonal of the first bridge is the supply voltage of the second bridge, the output voltage on the diagonal of the second bridge is the supply voltage of the third bridge, and so on. In such a circuit a zero voltage on the diagonal of the first bridge nulls the supply voltages of all the following bridges. We may treat this as a circuit model of the compensating signals $h_i(T)$ (see Theorem 1, Section 4.3.1).

In order to make the compensating signals adjustable (the coefficient w_i of equation (25)), a potentiometric divider has been introduced into the circuit of each of the bridges mentioned.

A chain of bridges with the properties described above is called by the author in what follows a "multiple bridge". Fig. 24a shows an example of the construction of such a bridge. The first bridge M_1 is built of four impedances Z_1, Z_2, Z_3, Z_4 (frequency- and/or temperature-dependent impedances). A potentiometric divider P_1 is connected across the bridge diagonal. The potential on one arm of this divider supplies the next bridge M_2 , built of analogous impedances. A potentiometric divider is connected across the diagonal of bridge M_2 . The potential of one of its arms supplies bridge M_3 , and so on. From the last bridge M_n the potential of the wiper of the potentiometric divider P_n is brought out.¹

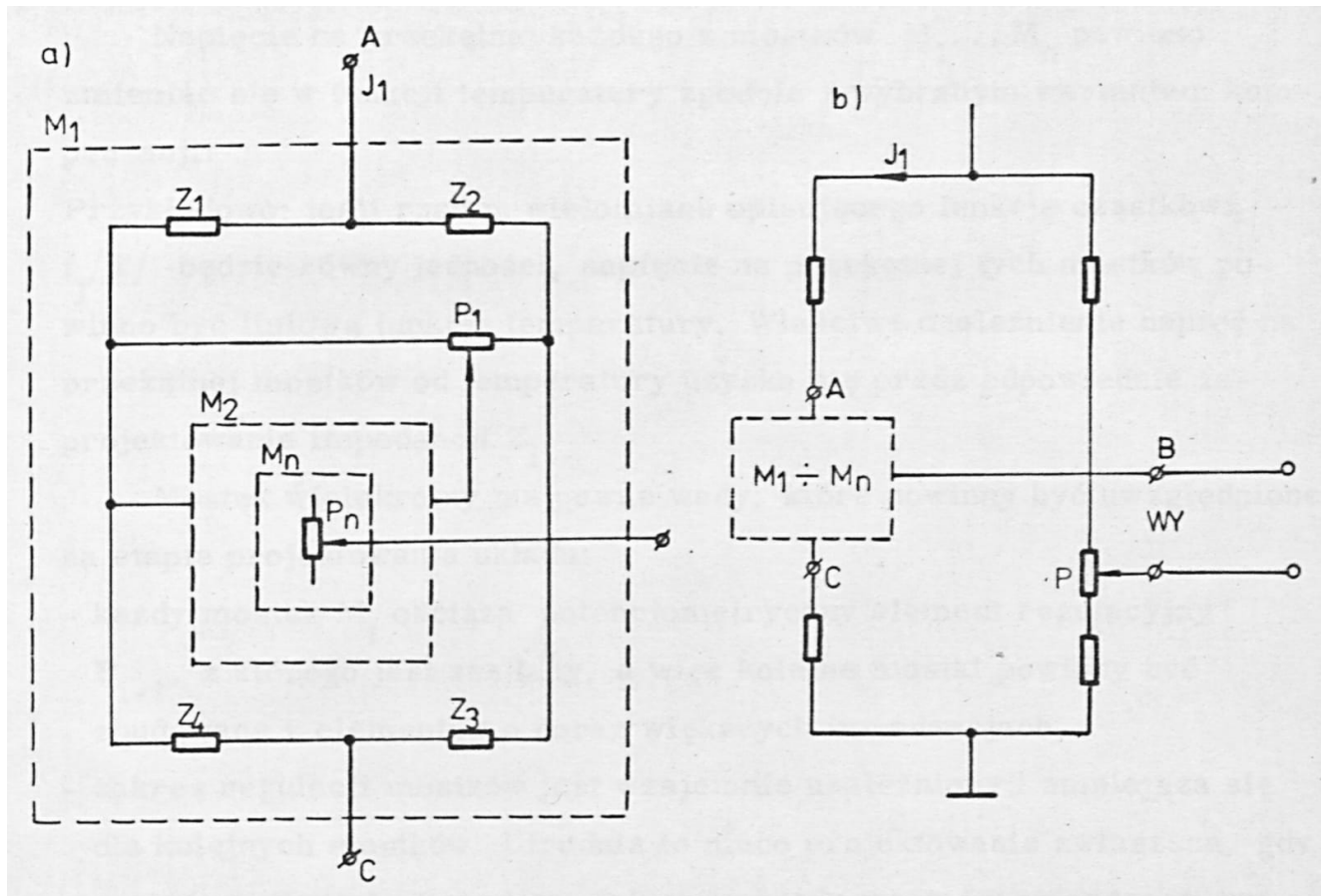


Fig. 24. a. General circuit of the multiple bridge b. Method of supplying the bridge

Labels: WY = output (wyjście)

The multiple bridge may be connected, for example, into one arm of the measuring bridge (the one containing the sensor) in the manner shown in Fig. 24b; in the other arm there will be a potentiometer P serving to null the bridge signal at the reference temperature. At the successive compensation temperatures the output voltage of the measuring bridge will be nulled by the potentiometric dividers $P_1 \dots P_n$.

The voltage on the diagonal of each of the bridges $M_1 \dots M_n$ should vary as a function of temperature in accordance with the chosen compensation variant: For example: if the degree m of the polynomial describing the component function $f_j(T)$ is equal to one, the voltage on the diagonal of these bridges should be a linear function of temperature. The proper dependence of the voltages on the bridge diagonals on temperature is obtained by suitable design of the impedances Z_i .

The multiple bridge has certain drawbacks which should be taken into account at the circuit design stage:

- each bridge M_i loads the potentiometric adjusting element P_{i-1} from which it is supplied, so the successive bridges should be built of components of ever greater impedance,
- the adjustment ranges of the bridges are mutually dependent and decrease for the successive bridges. This makes the design somewhat more difficult, especially when the whole is supplied with direct current and the change in the values of the impedances forming the bridge varies as a function of temperature. The use of a computer program for the calculations will then be required,
- the input current of the associated circuit of the multiple bridge produces a voltage drop across the equivalent output resistance of the bridge. This resistance changes as the adjusting elements $P_1, \dots, P_n$ are adjusted, so the condition for the vanishing of the voltages on the diagonals of the constituent bridges, when the measuring bridge is supplied with a constant voltage, is a function of the wiper position of these elements. To prevent such a dependence it suffices to use a suitably small bridge load current.

Because of the drawbacks listed, the bridge multiplicity is limited; nevertheless, obtaining a multiplicity of 1, 2, 3 presents no great difficulty. Below are discussed: the construction and properties of the triple bridge, and also the problem of the interaction between the compensation of the lower and the upper range value.

5.1. Triple bridge

By way of example let us consider a triple bridge (Fig. 25). It is built of three bridges $Z_1 - Z_4$, $Z_5 - Z_8$, $Z_9 - Z_{12}$. The adjusting elements P_1, P_2, P_3 are connected across their respective diagonals. Adopting the notation of Fig. 25, the output voltage of the bridge is determined by the relation:

$$\frac{u}{e} = a_8 + a_5 \cdot a_7 \cdot (a_9 - a_8) + a_2 \cdot a_4 \cdot a_7 \cdot (a_6 - a_5) \cdot (a_9 - a_8) + a_1 \cdot a_4 \cdot a_7 \cdot (a_3 - a_2) \cdot (a_6 - a_5) \cdot (a_9 - a_8) \quad (61)$$

where

$$e_1 = a_1 \cdot (e_3 - e_2)$$

$$e_2 = a_2 \cdot e_4$$

$$e_3 = a_3 \cdot e_4$$

$$e_4 = a_4 \cdot (e_6 - e_5)$$

$$e_5 = a_5 \cdot e_7$$

$$e_6 = a_6 \cdot e_7$$

$$e_7 = a_7 \cdot (e_9 - e_8)$$

$$e_8 = a_8 \cdot e$$

$$e_9 = a_9 \cdot e$$

where $a_1 \dots a_9$ denote the values of the respective division ratios.²

Comparing (61) with (25) we may write

$$f_o(T) = a_5 \cdot (a_9 - a_8) \cdot e$$

$$f_1(T) = \frac{a_2}{a_5} \cdot (a_6 - a_5) \cdot e$$

$$f_2(T) = \frac{1}{a_2} \cdot (a_3 - a_2) \cdot e$$

and

$$w_o = a_8 \cdot e$$

$$w_1 = a_7$$

$$w_2 = a_4 \cdot a_7$$

$$w_3 = a_1 \cdot a_4 \cdot a_7$$

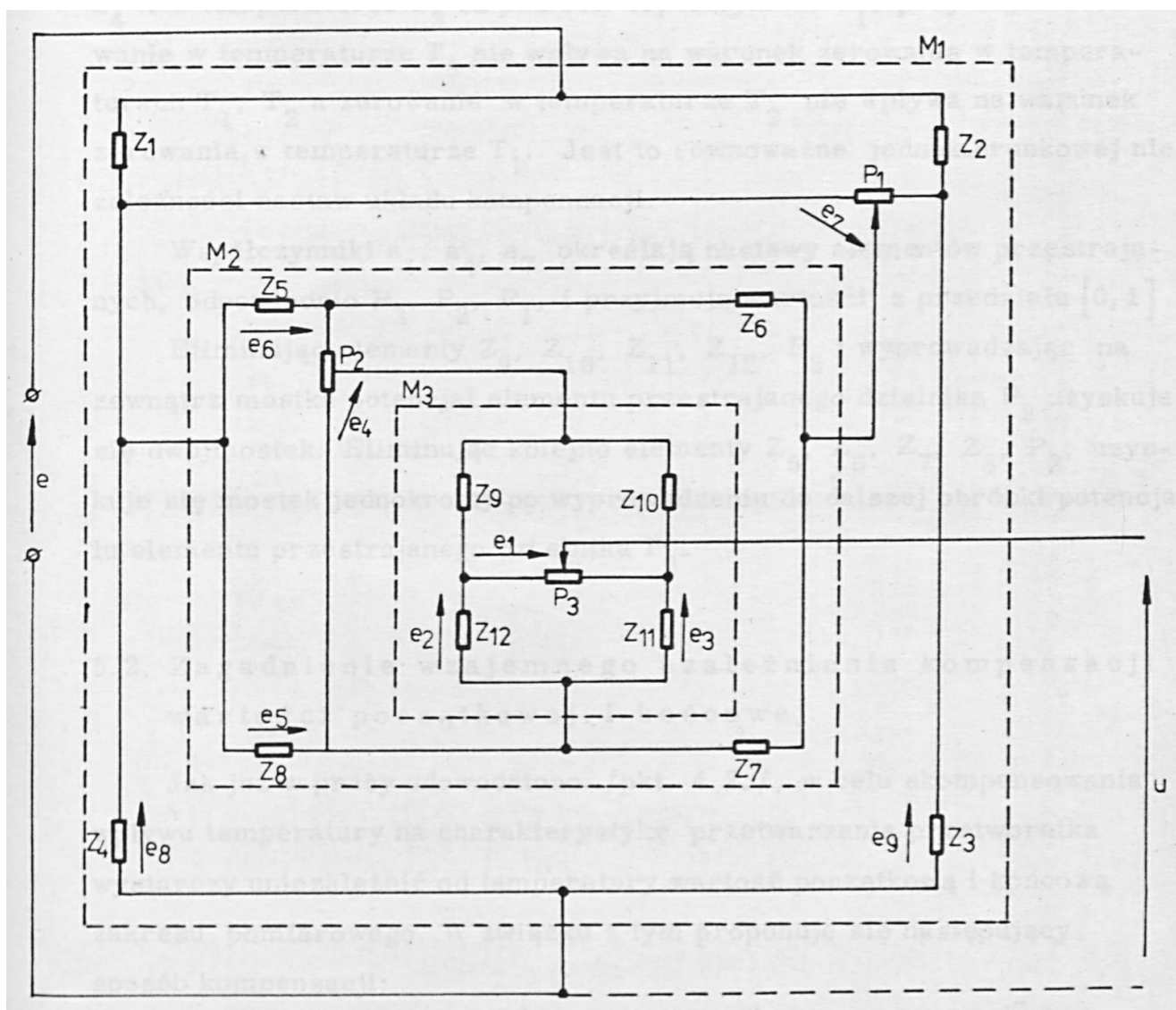


Fig. 25. General circuit of the triple bridge

Designing the circuit so that: for $T = T_0$:

$$a_9 - a_8 = 0$$

for $T = T_1$:

$$a_6 - a_5 = 0$$

for $T = T_2$:

$$a_3 - a_2 = 0$$

there arises the possibility of nulling the error successively at temperature T_1 by means of the coefficient a_7 , at temperature T_2 by means of the coefficient a_4 , and at temperature T_3 by means of the coefficient a_1 , where nulling at temperature T_3 does not affect the nulling condition at temperatures T_1, T_2 , and nulling at temperature T_2 does not affect the nulling condition at temperature T_1 . This is equivalent to the unidirectional independence of the settings of the compensation circuit. The coefficients a_1, a_4, a_7 determine the settings of the adjustable elements P_3, P_2, P_1 respectively, and take values from the interval $[0, 1]$. Eliminating the components $Z_9, Z_{10}, Z_{11}, Z_{12}, P_3$ and bringing the potential of the adjustable element of divider P_2 out of the bridge, one obtains a double bridge. Eliminating in turn the components Z_5, Z_6, Z_7, Z_8, P_2 , one obtains a single bridge, once the potential of the adjustable element of divider P_1 has been brought out for further processing.

5.2. The problem of the interaction between the compensation of the lower and the upper range value

As has already been proved in this work (Section 4.2), in order to compensate the effect of temperature on the transfer characteristic of the transducer it suffices to make the lower and the upper range value independent of temperature. In connection with this, the following manner of compensation is proposed:

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- compensation of the temperature drift of one of the values mentioned (the lower or the upper) by bringing the voltage on the diagonal of the measuring bridge to zero. Nulling at the reference temperature would be realized by components placed in one arm of the bridge, whereas nulling at the compensation temperatures would be realized by means of a multiple bridge connected into the other arm of the bridge (Fig. 24b).
- compensation of the temperature drift of the other of the values mentioned (the lower or the upper) would be carried out by making the voltage or current supplying the measuring bridge temperature-dependent. The value of this voltage or current would be adjusted by means of the signal from an analogous multiple bridge. Since the value of the output signal of the measuring bridge is proportional to the value of the supply voltage, and this voltage is used for the compensation of the upper range value, the lower value of the bridge output signal outside the compensation temperatures depends on the changes of the supply voltage. If we denote by $\Delta_1(T)$ the relation determining the changes of the voltage e supplying the measuring bridge that are necessary for the compensation of the error of the range value corresponding to bridge unbalance (e.g. the full-scale value):

$$e = e_o \cdot [1 + \Delta_1(T)] \quad (62)$$

where e_o - the value of the bridge supply voltage at the reference temperature T_o , then the error $\Delta'(T)$ of the value corresponding to bridge balance (e.g. the zero value) will be described by the relation

$$\Delta'(T) = \Delta(T) \cdot [1 + \Delta_1(T)] \quad (63)$$

Example 5

Considering Example 4 for $T_o = 293$ K, $T_1 = 258$ K, $T_2 = 328$ K and $\Delta_1(T) = 2.5 \cdot 10^{-3} \cdot (T - 293)$ (i.e. a span drift of -2.5 %/10 K), using relation (63) we obtain:³

$$\Delta'(T) = -1.8 \cdot 10^{-5} \cdot (T - 293) \cdot (T - 288) \cdot (T - 218) \cdot [1 + 2.5 \cdot 10^{-3} \cdot (T - 293)]$$

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The geometrical interpretation is given in Fig. 26. The effect of the changes of the supply voltage is small, since it is expressed by a quantity of second order of smallness.

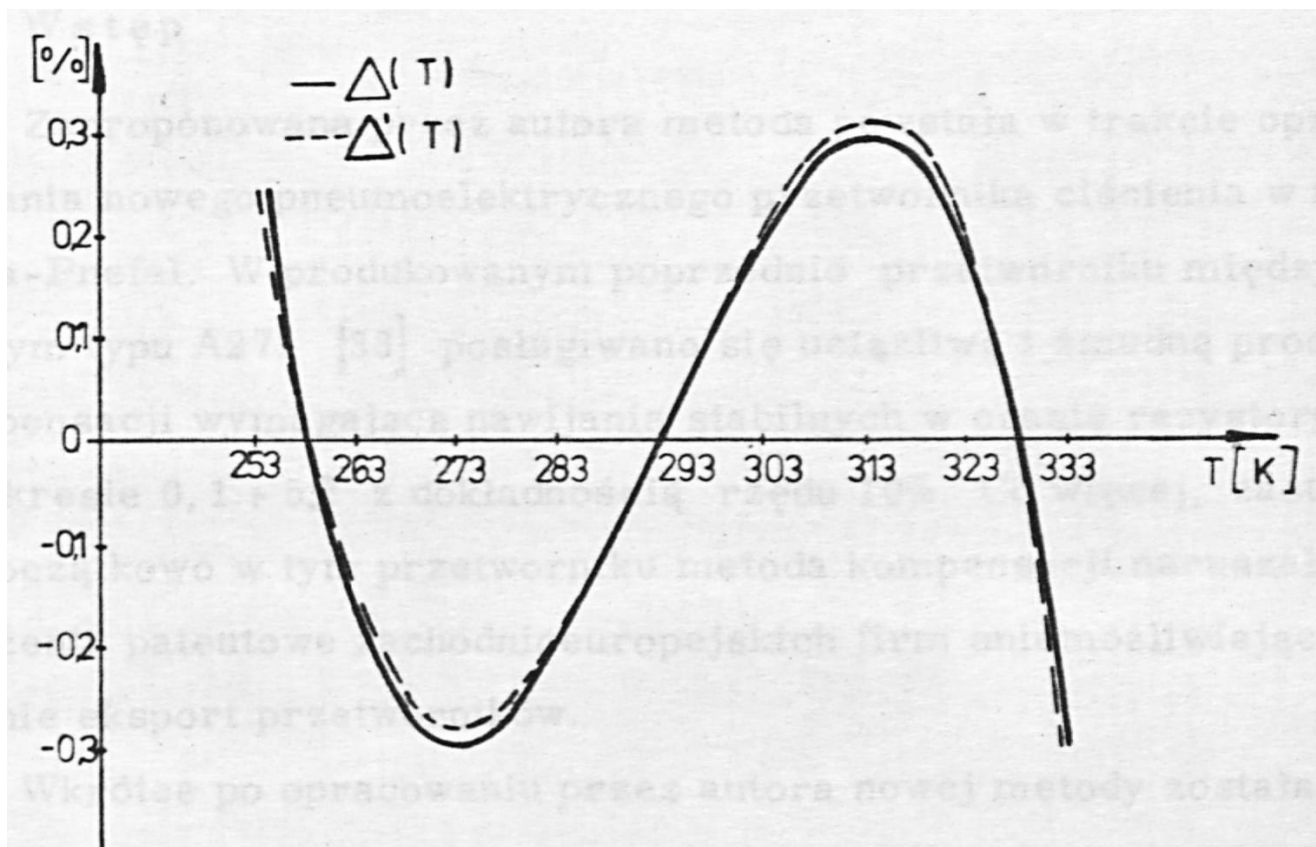


Fig. 26. Example of the temperature drift of the transducer zero $\Delta(T)$ and the change of this drift under the introduction of span compensation.

Translator's notes

1. "multiple bridge" (Polish "mostek wielokrotny") is the author's own term for this chain of Wheatstone bridges in which the output diagonal of each bridge supplies the next; a chain of two is called a "double bridge" ("dwójmostek", "mostek dwukrotny") and a chain of three a "triple bridge" ("mostek trójrotny"); a single stage is a "single bridge" ("mostek jednokrotny"). The "double bridge" of this thesis is unrelated to the Kelvin (Thomson) double bridge used for low-resistance measurement.
2. the symbols $a_1 \dots a_9$ here are division ratios of the dividers in Fig. 25, not the slope constants a_j of the component functions in Chapter 4.
3. factors as printed. (T-288) and (T-218) match neither the compensation temperatures $T_1 = 258$ K and $T_2 = 328$ K given in the same sentence nor the factors of $\Delta(T)$ in Example 4; the intended values cannot be established, so the expression is left as in the original.

6. APPLICATION OF THE NEW COMPENSATION METHOD IN A PIEZORESISTIVE PRESSURE TRANSDUCER

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6.1. Introduction

The method proposed by the author arose in the course of the development of a new pneumatic-to-electric pressure transducer at the Mera-Pnefal Industrial Automation Research and Development Centre (OBRAP). In the previously manufactured inter-system converter type A271 [33] a burdensome and laborious compensation procedure was used, requiring the winding of long-term stable resistors in the range 0.1 to 5 Ω with an accuracy of the order of 10 %. Moreover, the compensation method initially applied in that transducer infringed the patent claims of West European firms, practically preventing the export of the transducers.¹

Soon after the author had developed the new method, it was tested in the pneumatic-to-electric pressure transducer type A272, and then, after positive results of the prototype tests, by decision of the Technical Council it was introduced into series production at Mera-Pnefal. In 1978 the manufacture of a series of 1000 units of these transducers is planned.

In the remainder of this work there will be presented the required parameters of the transducer, the construction and properties of the pressure sensor, a design outline of the more interesting subassemblies of the transducer connected with the temperature compensation circuit, and finally some results of the tests of the prototypes of the pneumatic-to-electric transducer carried out by the Product Testing Laboratory of the Quality Control Department of the Mera-Pnefal Industrial Automation Enterprise and by the Mera-Pnefal Industrial Automation Research and Development Centre.

6.2. Required metrological parameters of the transducer.

a. The construction of the transducer should be based on the sensor discussed in Section 6.3. b. input signal 20 to 100 kPa c. output signal: one of those listed, according to the choice of the customer

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0 - 5 mA

0 - 20 mA

0 - 50 mA

4 - 20 mA

10 - 50 mA

1 - 5 V

0 - 10 V d. transfer characteristic - linear e. intrinsic error 0.4 % f. operating temperature range: standard version 273 K to 333 K

special version 253 K to 333 K g. supply voltage 25 V $\begin{smallmatrix} +0.5V \\ -1.5V \end{smallmatrix}$ with a common negative rail²

6.3. Sensor

6.3.1. Construction

The pressure sensor is built on the basis of silicon strain gauges. The input pressure is converted by means of the bellows assembly (Fig. 27) into a force producing stresses in the strain-gauge beam. The beam is rigidly fixed at one end, while at the other it is coupled to the bellows assembly. Two silicon strain gauges are bonded to the strain-gauge beam, one on each side. Under the action of the input pressure this beam deflects, which causes compressive stresses to arise in the upper gauge TS2 and tensile stresses in the lower gauge TS1, as a result of which an increase in the resistance value (of approx. 5 %) of gauge TS1 and a decrease in the resistance value of gauge TS2 are obtained. The beam is protected from overload by the beam travel stop. The gauge leads are soldered to the terminal board, from which the sensor signal is then conveyed by wires to the electronic

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signal-conditioning circuit.

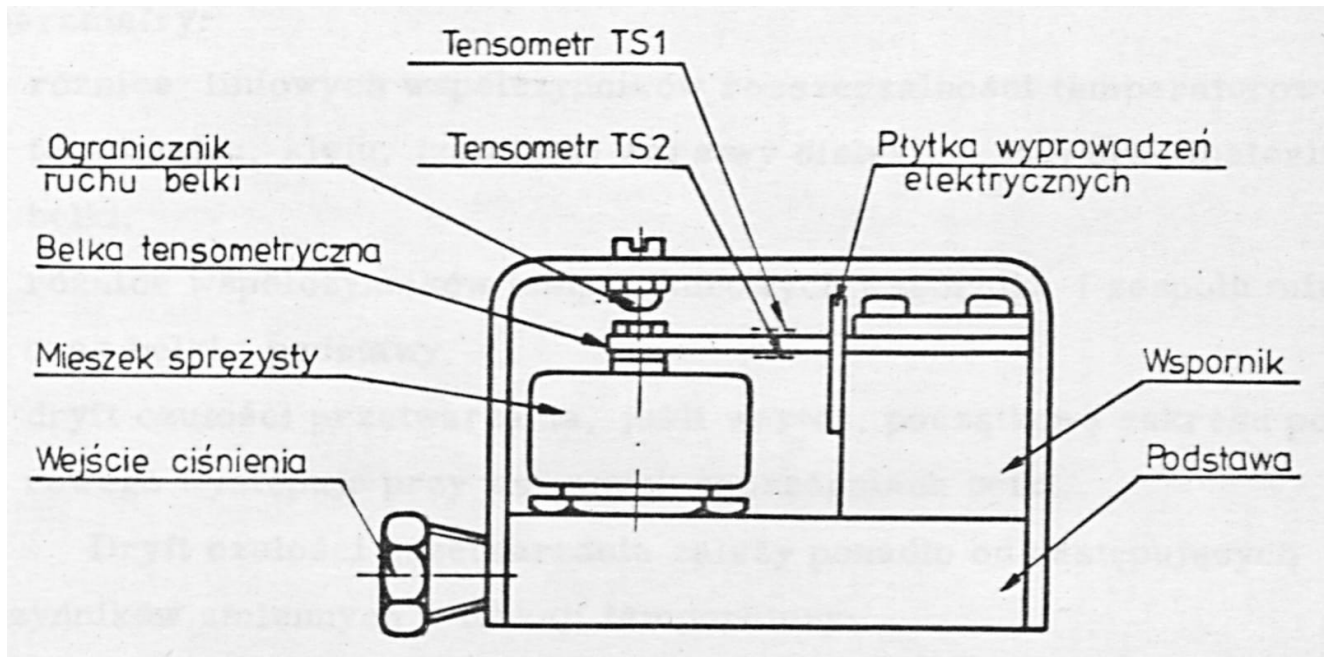


Fig. 27. Construction of the pressure sensor

Labels: *Tensometr TS1* = strain gauge TS1; *Ogranicznik ruchu belki* = beam travel stop; *Tensometr TS2* = strain gauge TS2; *Płyta wyprowadzeń elektrycznych* = terminal board; *Belka tensometryczna* = strain-gauge beam; *Mieszek sprężysty* = bellows; *Wspornik* = bracket; *Wejście ciśnienia* = pressure inlet; *Podstawa* = base

The basic technical data of the sensor are: a. initial resistance of the gauges at a temperature of 293 K, at atmospheric pressure - $110 \Omega \pm 11 \Omega$, b. spread of resistance of the gauges on one sensing beam 0 to 5Ω , the gauge in tension having the greater resistance, c. full-scale resistance change of the gauges (for a change of pressure from 20 kPa to 100 kPa) - 5.6Ω to 7.6Ω .

6.3.2. Sources of temperature errors.

The basic source of the temperature errors of the sensor is the strain gauges. Both the initial resistance and the sensitivity of the gauges change strongly with temperature. The change of the initial resistance at atmospheric pressure (without stress) as a function of temperature for the gauges used has the character of a second-order curve. The sensitivity is determined by the relation:

$$\frac{\Delta R}{R} = c_1 \varepsilon + c_2 \varepsilon^2$$

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where: c_1 , c_2 - constants

An additional influence on the drift of the lower range value is exerted by the following parameters:

- differences between the linear coefficients of thermal expansion of the gauge, the adhesive, the insulating dielectric layer and the beam material,
- differences between the temperature coefficients of the bracket and the bellows assembly, and of the beam and the base,
- the sensitivity drift, if the lower range value occurs with the beam under preload. The sensitivity drift depends moreover on the following factors that vary as a function of temperature:
 - the effective area of the bellows and its compliance
 - the Young's modulus of the strain-gauge beam
 - the thickness of the layers insulating the gauges from the beam.

6.3.3. Selection of the parameters of the temperature compensation circuit

In order to obtain information on the temperature errors of the sensor, temperature-pressure tests of 16 pressure sensors were carried out in the measuring setup shown in Fig. 28. The tests were carried out in the temperature range from 253 K to 333 K, every 20 K. At each of these temperatures the static characteristic was measured at five input pressures. The input pressure was measured with an Ashcroft digital pressure gauge with an accuracy of $\pm 0.05 \%$ on the 200 kPa measuring range. The output signal of the sensor was read on a Hewlett-Packard 3490A digital voltmeter, with an accuracy of $\pm 0.03 \%$. After analysis of the measurement results it was found that the temperature drift of the nonlinearity remains at the level of $0.007 \%/10 \text{ K}$, so that temperature compensation of this parameter is unnecessary. The following procedure for determining the temperature errors of the zero was applied:

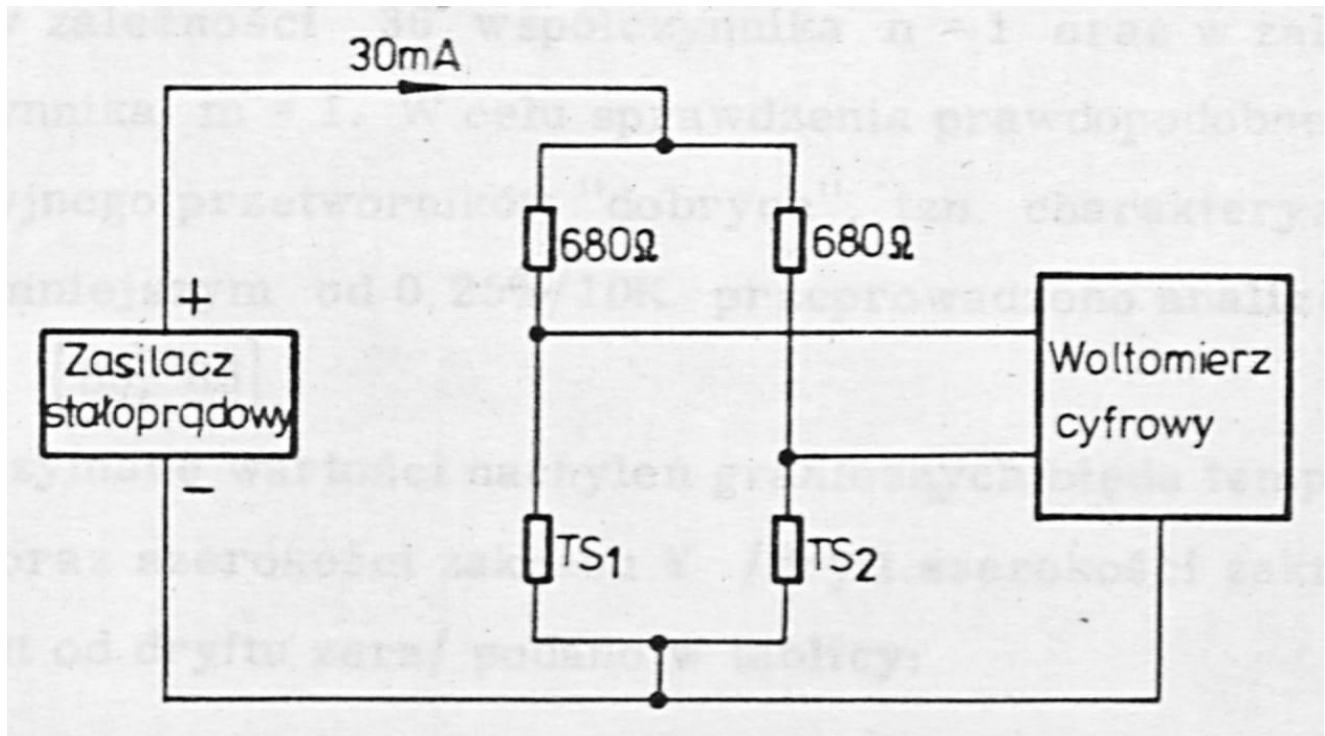


Fig. 28. Setup for measuring the sensor characteristic

Labels: Zasilacz stałoprądowy = DC power supply; Woltomierz cyfrowy = digital voltmeter

a. for each of these parameters a straight line was drawn intersecting the plot of the sensor error at the temperatures 278 K (reference) and 308 K (first compensation), (Fig. 29a); b. the straight line was shifted parallel to itself so that it intersected the plot of the sensor error at the temperature 293 K (Fig. 29b); c. the maximum slope of the error with respect to this straight line was sought, determining the error limit according to PN-74/M-42020 (see Section 2, Fig. 2b.)

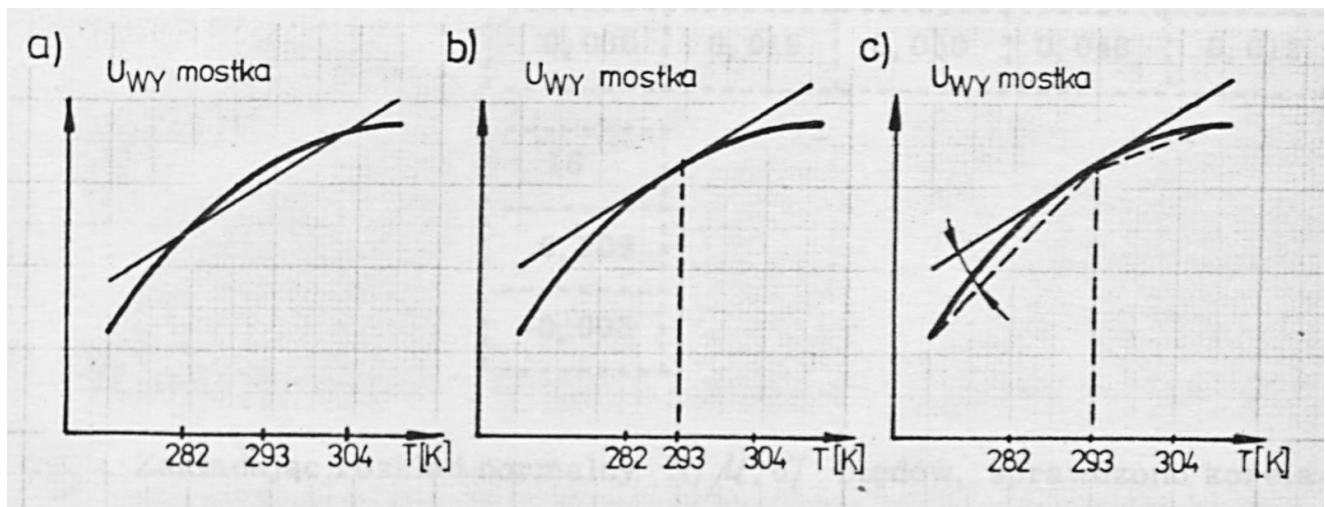


Fig. 29. Procedure for determining the temperature errors of zero and span

Labels: $U_{WY\ mostka}$ = bridge output voltage

The compensation procedure applied was equivalent to adopting in relation 36 the coefficient $n = 1$ and in relation 39 the coefficient $m = 1$. In order to check the probable production "yield" of "good" transducers, i.e. those characterized by an error smaller than 0.25 %/10 K, a statistical analysis of the results was carried out [83, 85].

The values obtained for the limiting slopes of the temperature error of the zero X and of the span Y (the span drift is made independent of the zero drift) are given in the table:

Sensor No.	X, %/10 K	Y, %/10 K
1	0.181	0.081
2	0.110	-0.033
3	0.176	0.013
4	0.051	0.074
5	0.083	-0.027
6	0.137	0.039
7	0.153	0.065
8	0.181	0.052
9	0.140	0.080
10	0.112	-0.015
11	0.175	0.086
12	0.183	0.019
13	0.144	0.050
14	0.134	0.048
15	0.192	0.012
16	0.209	-0.005 ³

Assuming a normal distribution $N(\mu, \sigma)$ of the errors, the correlation between the temperature drift of the zero and of the span was checked. The sample mean errors $\bar{X}$ and $\bar{Y}$ are

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$$\bar{X} = 0.148,$$

$$\bar{Y} = 0.034$$

whereas the sample standard deviations S_x and S_y :

$$S_x = 0.0414$$

$$S_y = 0.0381$$

The correlation coefficient r_{xy} is defined as follows:

$$r_{xy} = \frac{1}{n} \sum_{i=1}^n \frac{X_i - \bar{X}}{S_x} \frac{Y_i - \bar{Y}}{S_y}$$

where: n - the number of sensors X_i - the value of the zero drift of the i-th sensor Y_i - the value of the span drift of the i-th sensor

For the error values from Table 1 we obtain $r_{x,y} = 0.0162$. Taking $n = 16$ and assuming a confidence level of 0.95, one obtains the confidence interval for the unknown true value of the correlation coefficient $[-0.38, +0.6]$.⁴

Calculating the critical value of the correlation coefficient [85] we obtain

$$r_k = 0.4973$$

The value of the correlation coefficient observed in the sample batch of sensors, as determined by its confidence interval, is greater than the critical value, so there are no grounds for rejecting the hypothesis that the zero drift and the span drift are correlated with each other. Since, however, the value obtained for the correlation coefficient is small, it cannot be used as additional information on the sensor error in accordance with Section 4.3.3.

Observation of the scatter of the limiting zero and span drifts (Fig. 30) confirms this conclusion.

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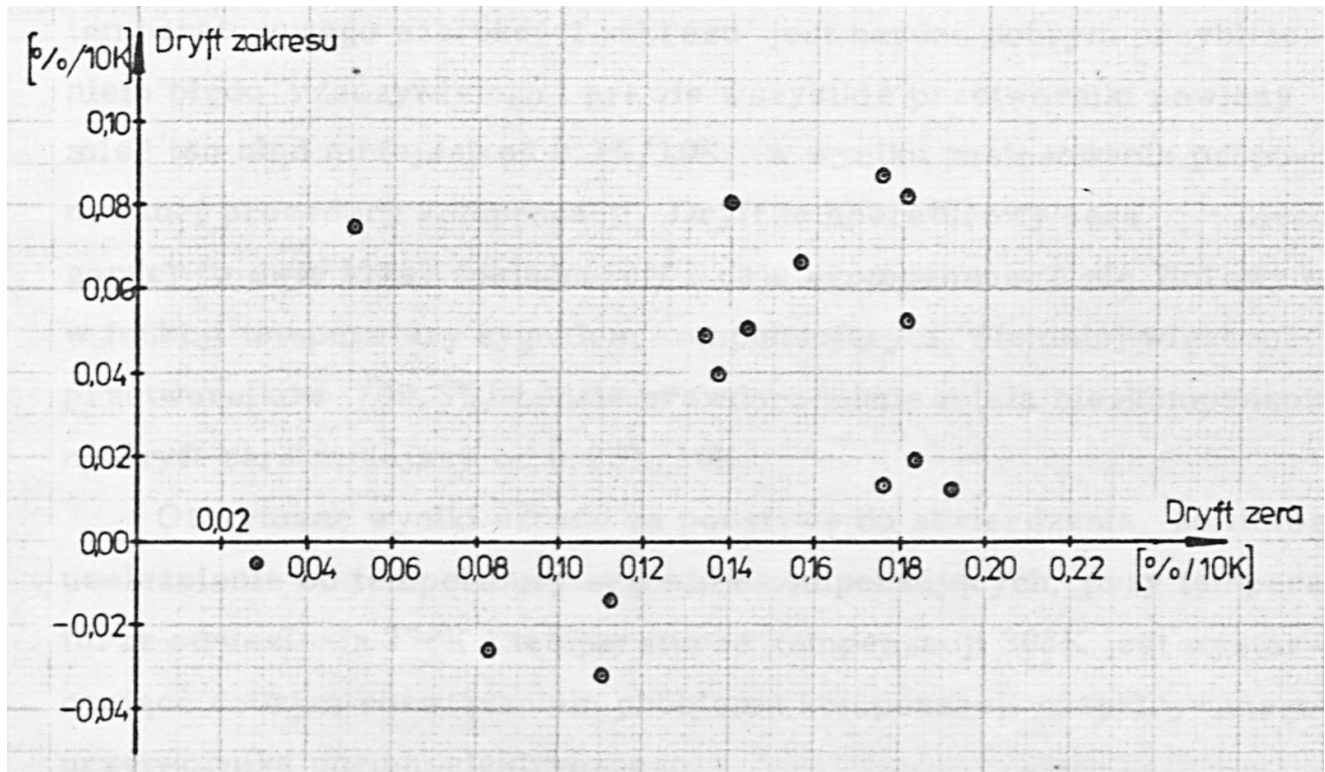


Fig. 30. Scatter of the temperature drifts of zero (X) and span (Y) for 16 pressure sensors

Labels: Dryft zakresu = span drift; Dryft zera = zero drift

Taking into account the values obtained for the mean error limits $\bar{X}$ and $\bar{Y}$ and the sample standard deviations, we may quantify the effects of applying the proposed temperature compensation procedure. Namely, we may calculate the probability of obtaining transducers with an uncompensated error smaller than: 0.05 %/10 K, 0.1 %/10 K, 0.16 %/10 K and 0.25 %/10 K. The results are presented in Table 2.

Table 2

A	0.05	0.1	0.16	0.25	%/10 K
$P(X < A)$	0.8	12.3	65.2	99.3	%
$P(Y < A)$	68.8	97.7	99.997	1	⁵

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From the above data it follows that the linear approximation of the temperature drift of the span is a very good approximation of the real error, and almost all transducers should have this error smaller than 0.1 %/10 K as a result of applying the proposed compensation procedure. The temperature drift of the zero lends itself somewhat less well (by two accuracy classes) to compensation by a compensating signal linear in temperature; nevertheless the majority of transducers (99.3 %) will probably have an uncompensated zero drift smaller than 0.25 %/10 K.

The results obtained were taken as the basis for stating that a linear temperature dependence of the compensating signals, with a reference temperature of 278 K and a compensation temperature of 308 K, is a sufficiently good solution of the compensation problem for the pneumatic-to-electric transducer under consideration.

6.4. Electronic circuit of the transducer

6.4.1. Block diagram

The block diagram of the transducer circuit design chosen by the author [87] is shown in Fig. 31. The transducer is built of six main assemblies

- the measuring bridge MP
- the single bridge MK_1 for the temperature compensation of the lower range value
- the voltage-difference-to-current converter W
- the current source I

- the single bridge MK_2 for the temperature compensation of the upper range value (span)
- the regulated power supply

The measuring bridge makes it possible to convert the change of resistance of the strain gauges TS into a change of voltage on the bridge diagonal. At the same time, as a result of the differential connection of the gauges, a preliminary compensation of the effect of temperature is realized. In addition the circuit makes it possible to null the voltage on the bridge diagonal at the lower range value and

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to add to the voltage signal from the gauges the voltage of the generator of the zero temperature-compensation signal, in the form of the single bridge MK_1 .

The single bridge MK_1 makes it possible to null the measuring bridge at the reference temperature independently of the setting of potentiometer P_4 , because on this potentiometer, connected across the diagonal of the compensation bridge MK_1 , there is zero voltage at the reference temperature. At the compensation temperature a voltage is produced on potentiometer P_4 , a part of which, set by the position of the potentiometer wiper, is used to null the measuring bridge again, i.e. to compensate the temperature drift of the lower range value.

The measuring bridge is supplied by the current source I. The source current of this source is controlled by the potential of the wiper of potentiometer P_1 , placed on the diagonal of the single bridge MK_2 . At the reference temperature there is zero voltage on this potentiometer and the source current is determined by the value of the potential of the end terminals of the potentiometer, independently of the position of its wiper. At the first compensation temperature a certain voltage is produced on the potentiometer, and consequently a change in the position of the potentiometer wiper changes the value of the current supplying the measuring bridge, which is used to compensate the temperature error of the upper range value.

The differential signal from the diagonal of the measuring bridge MP is converted by the circuit W, with an adjustable conversion factor, into the output current I_1 . To produce the voltage output signal of the transducer there serves a resistor R shunting the output terminals.

The voltage regulator S supplies two supply voltages:

- the internal supply reference voltage +19 V
- the auxiliary voltage for supplying the transducer circuit +21 V

The whole circuit is supplied from a single voltage with a nominal value of 25 V.

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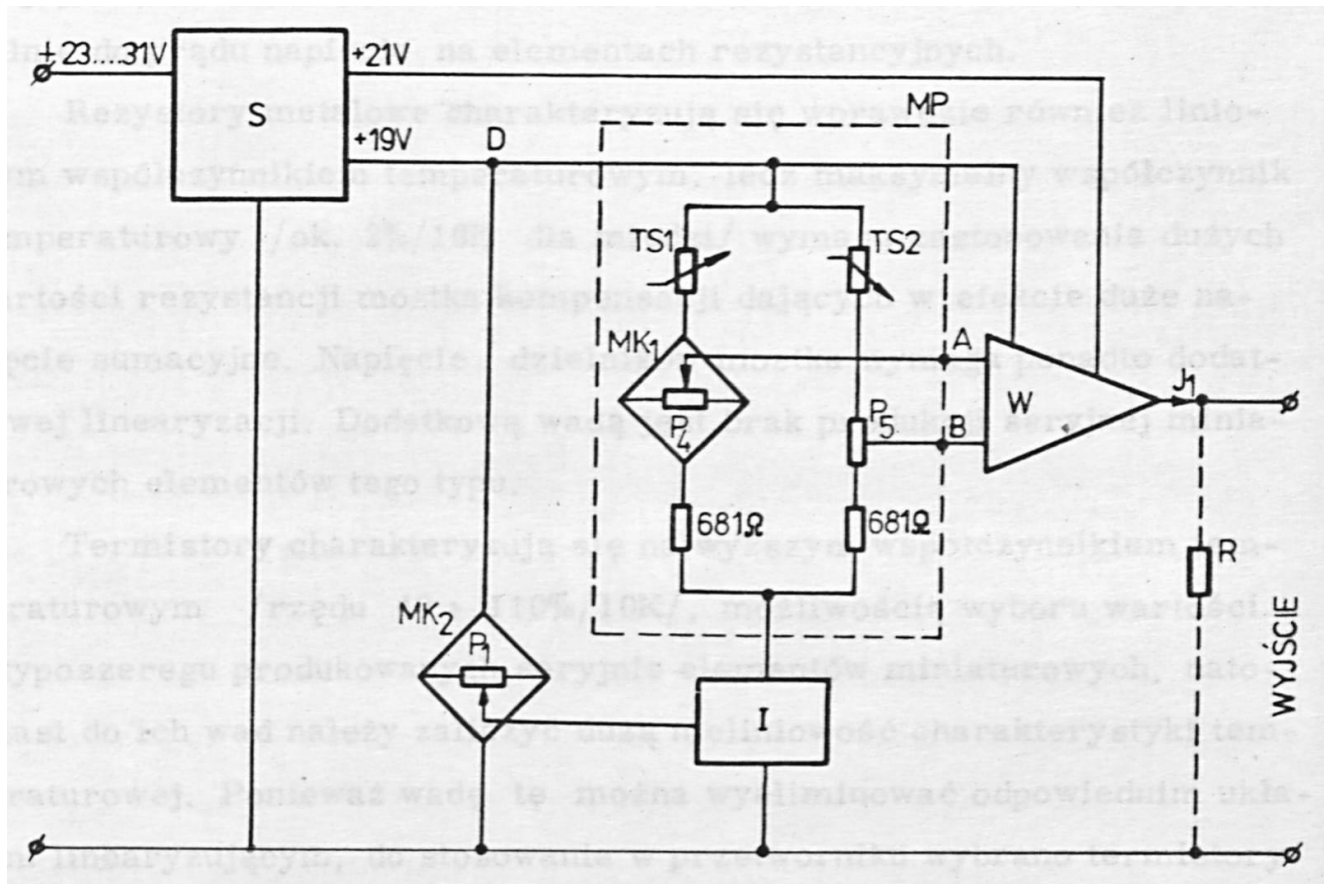


Fig. 31. Block diagram of the electronic circuit of the transducer.

Labels: WYJŚCIE = output (wyjście)

6.4.2. Choice of the temperature-sensing elements

The following components were considered as temperature-sensing elements:

- diodes
- transistors
- metal resistors
- thermistors

Diodes and transistors are characterized both by a large temperature coefficient of the forward or base-emitter voltage (approx. 3 %/10 K) and by a highly linear change of this voltage over a wide temperature range. Among the basic drawbacks of these components must be counted the large spread of the value of this voltage when discrete components are used, of the order of the full-scale signal of the sensor. Moreover, their use would increase the common-mode voltage of the sensor by several hundred

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millivolts. An additional argument that influenced the rejection of these components is the fact that if, in the state of bridge balance, the supply current were to change, this would cause bridge unbalance on account of the stabilizing characteristics of these components and of the voltage on the resistive components being proportional to the current.

Metal resistors, it is true, are also characterized by a linear temperature coefficient, but the maximum temperature coefficient (approx. 2 %/10 K for copper) requires the use of large values of resistance in the compensation bridge, giving in effect a large common-mode voltage. The voltage of the bridge dividers moreover requires additional linearization. An additional drawback is the absence of series production of miniature components of this type.

Thermistors are characterized by the highest temperature coefficient (of the order of 40 to 110 %/10 K), by the possibility of choosing the value from the standard value series of series-produced miniature components, whereas among their drawbacks must be counted the large nonlinearity of the temperature characteristic. Since this drawback can be eliminated by a suitable linearizing circuit, thermistors were chosen for use in the transducer. In the remainder of this work the circuits linearizing the characteristics of the thermistors are presented.

6.4.3. Optimization of the characteristics of the bridge compensating the zero drift

The circuit of the bridge compensating the temperature drift of the zero should provide a linear change of voltage with changes of temperature, adjustable in the range from -8 %/80 K to +8 %/80 K. It was decided to check the circuit of a single-thermistor voltage divider with regard to the possibility of obtaining a voltage on the bridge arms that is suitably linear as a function of temperature (Fig. 32). The bridge is built of two such dividers connected in opposition. As a result the voltage U_{AB} decreases, whereas the voltage U_{CB} increases with temperature.

In order to reduce the effect of changes of the bridge resistance on the voltage U_{DB} under constant-current excitation, a shunt resistor R was introduced.

For the linearization of the voltages U_{AB} and U_{CB} as a function of temperature, use was made of the nonlinear relation determining the value of the resultant resistance of the resistor R_2 and the thermistor RT connected in parallel, and of the nonlinear relation determining the division ratio of the resistive divider $R_1 - R_2/RT$.

The optimum values of the resistors R_1 , R_2 were calculated by means of a computer program. The calculations were carried out for 8 pairs of temperatures (reference temperature T_o - compensation temperature T_1), starting from 288 K - 298 K and ending at 274 K - 312 K, where at each successive step both temperatures were changed simultaneously by 2 K. The optimization consisted in minimizing the slope of the nonlinearity of the divider with respect to the temperature 293 K.

A thermistor of type NTC110 with a nominal resistance of 47 Ω at a temperature of 298 K was used here. The characteristics of the thermistors were determined experimentally by measuring the resistance values in the temperature range 253 K to 333 K every 20 K. A lack of agreement was found between the resistance of the thermistors in the measured temperature range and the generally accepted approximation $RT = A \exp(B/T)$. Since, however, this approximation was sufficiently accurate over an interval of 20 K, for determining the resistance of the thermistors at the compensation temperatures T_1 and reference temperatures T_o the above relation was used, the constants A and B being determined on the

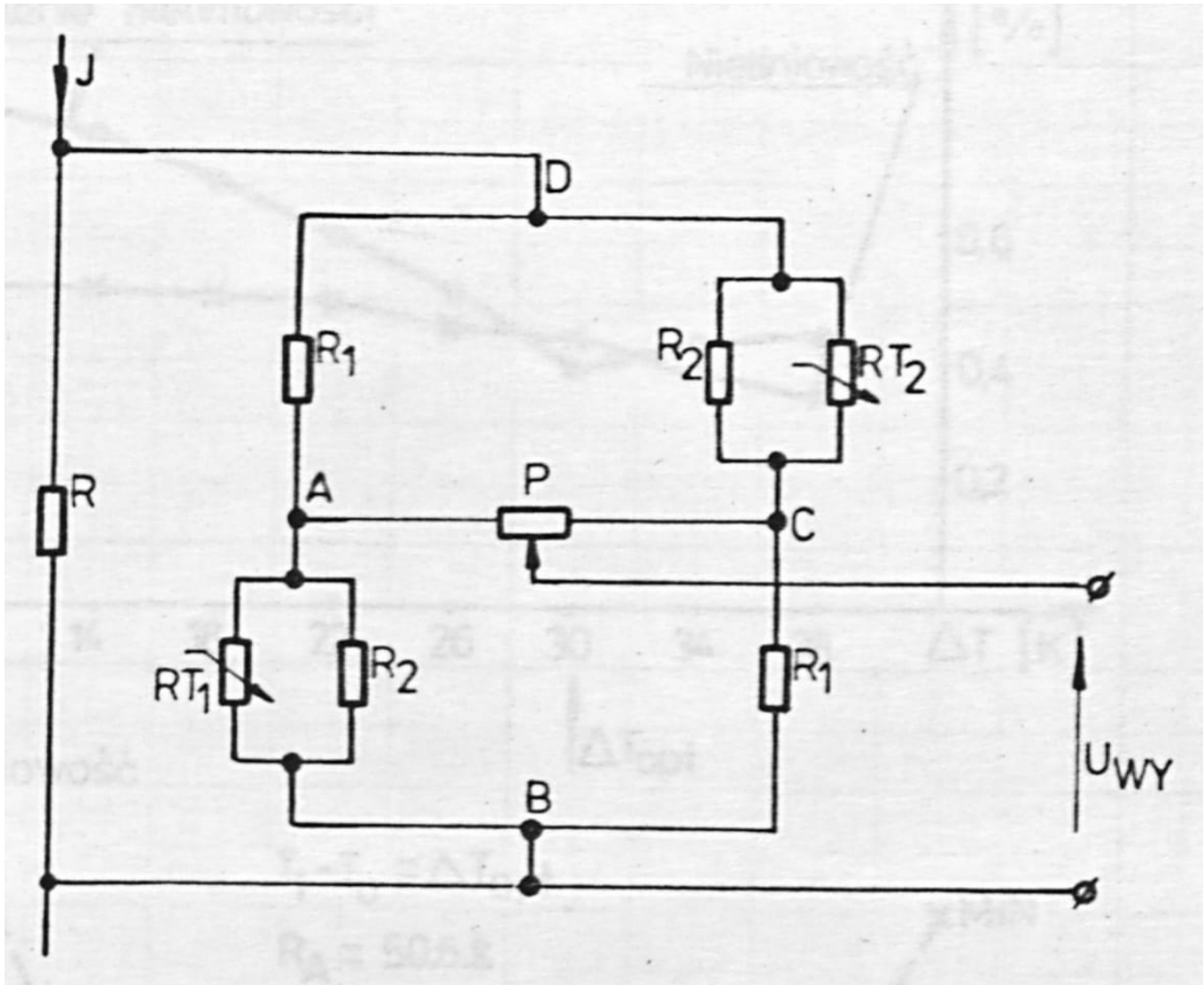


Fig. 32. Circuit of the bridge MK₁ compensating the zero drift

Labels: $U_{\text{sub} > \text{WY} < /sub >}$ = output voltage (WY = wyjście, output)

basis of the resistance values of the thermistor at the neighbouring temperatures.

On the basis of the measurement results for 6 thermistors the mean characteristic was determined, and the optimization was carried out for this characteristic; the nonlinearity as a function of temperature was then checked for the mean characteristic and for the extreme characteristics of the thermistors, i.e. the maximum and minimum characteristics.

The results of the calculations are presented in Fig. 33. The minimum value of the slope M , equal to 0.089 %/10 K, was obtained for the pair of temperatures $T_o = 278$ K, $T_1 = 308$ K (Fig. 33a.) The smallest value of the nonlinearity (the difference D) was obtained for the pair of temperatures 274 K - 312 K. Since in accordance with PN-74/M-42020 it is the slope of the error that is assessed, it was decided to choose the reference temperature $T_o = 278$ K and the compensation temperature $T_1 = 308$ K.

At these temperatures the optimum resistor values $R_1 = 50.6 \Omega$ and $R_2 = 109.4 \Omega$ provide a change of the division ratio of 42.2 % for a change of temperature from 253 K to 333 K.

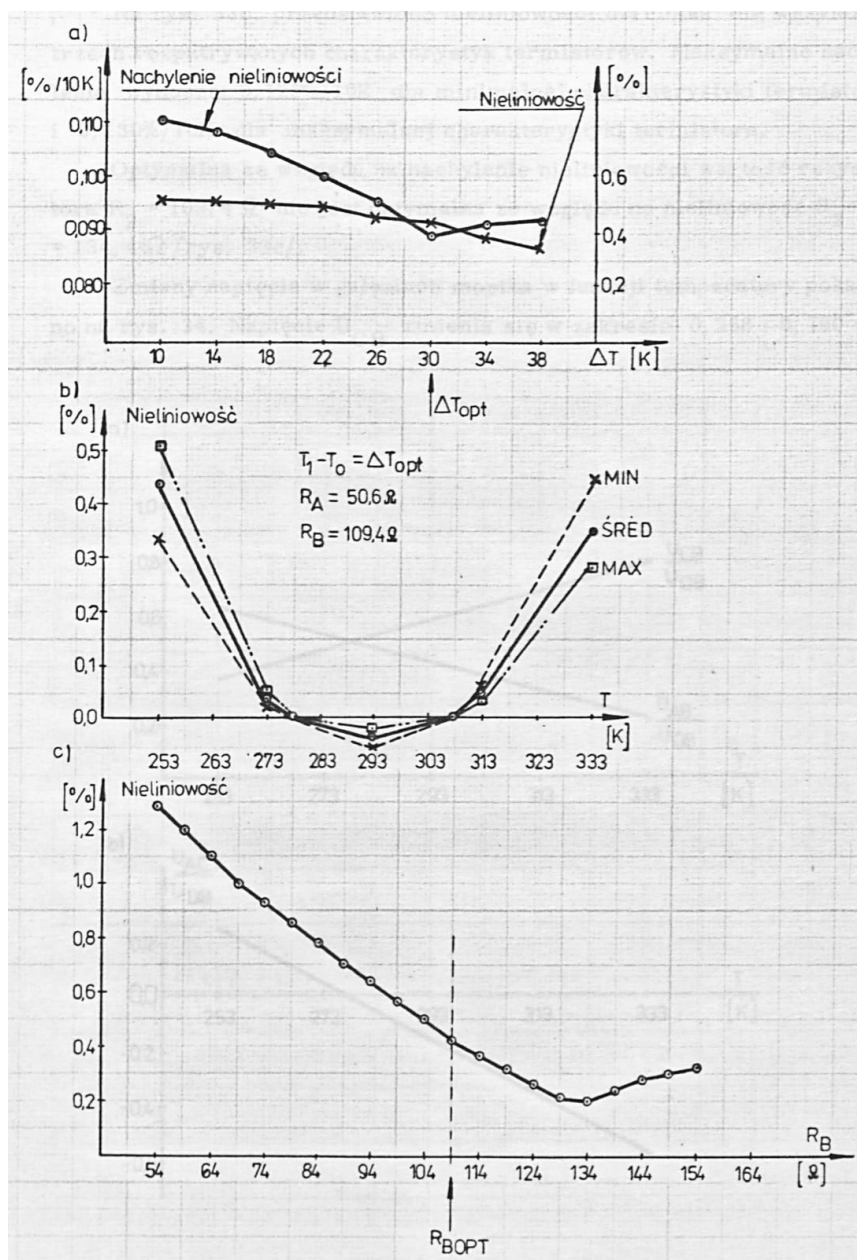


Fig. 33. Characteristics of the bridge compensating the zero drift

Labels: *Nachylenie nieliniowości* = slope of the nonlinearity; *Nieliniowość* = nonlinearity; *ŚRED* = mean (abbreviation of *średnia*)

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Fig. 33b shows the nonlinearities of the divider for all three thermistor characteristics considered. The maximum slopes are: 0.125 %/10 K for the minimum thermistor characteristic and 0.130 %/10 K for the maximum thermistor characteristic.

The value of the resistor $R_2 = 109.4 \Omega$ that is optimum with respect to the slope of the nonlinearity is not optimum with respect to the nonlinearity, $R_2 = 134.4 \Omega$ (Fig. 33c).

The changes of voltage in the bridge arms as a function of temperature are shown in Fig. 34. The voltage U_{CB} varies in the range 0.368 to 0.790 of the

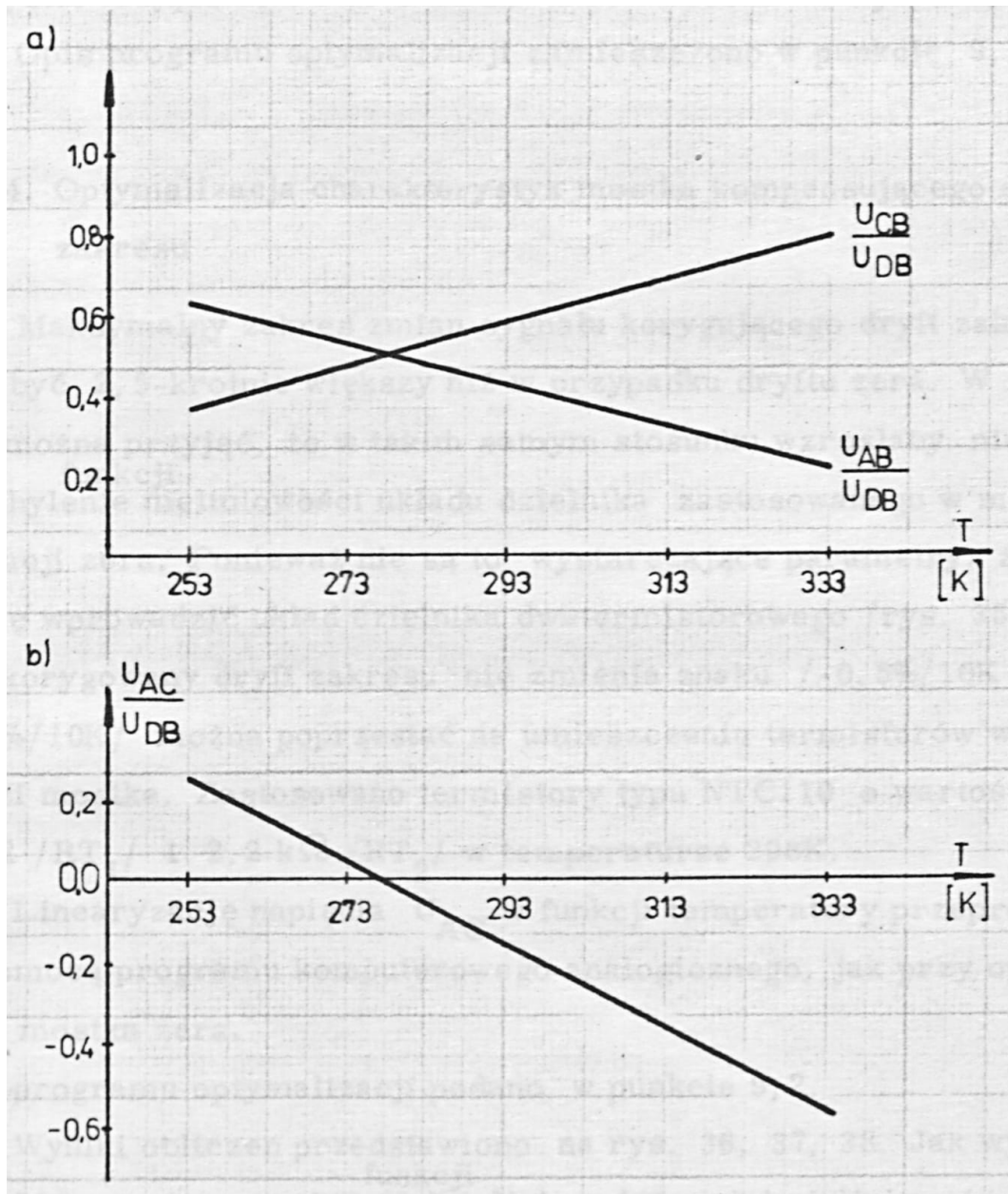


Fig. 34. Changes of voltage in the arms of the zero-drift compensation bridge

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value of the voltage U_{DB} supplying the bridge, whereas the voltage U_{AB} varies in the range 0.532 to 0.210 of the value of the voltage U_{DB} (Fig. 34a). The voltage U_{AC} occurring on the potentiometer varies in the range from +0.264 to -0.580 of the value of the voltage U_{DB} (Fig. 34b).

From the results presented in Fig. 33b it follows that the maximum slope of the nonlinearity function is caused by the large nonlinearity occurring at the extreme temperatures. In the temperature range 273 K to 313 K the value of this slope is more than two times smaller.⁶

In view of the fact that the maximum zero drift of the sensors (1 %/10 K) is two times greater than the mean drift, the results obtained were considered sufficiently good for use in the zero compensation bridge.

A description of the optimization program is given in Section 9.1.⁷

6.4.4. Optimization of the characteristics of the bridge compensating the span drift

The maximum range of variation of the signal correcting the span drift should be 2.5 times greater than in the case of the zero drift. In connection with this it may be assumed that the nonlinearity and the slope of the nonlinearity function of the divider circuit used in the zero compensation bridge would increase in the same ratio. Since these are not sufficient parameters, it was decided to

introduce a two-thermistor divider circuit (Fig. 35). Since the span drift being corrected does not change sign (-0.5 %/10 K to -2.5 %/10 K), it is enough to place the thermistors in one arm of the bridge. Thermistors of type NTC110 with values of $680\ \Omega$ (RT_1) and $2.2\ \text{k}\Omega$ (RT_2) at a temperature of 298 K were used.

The linearization of the voltage U_{AC} as a function of temperature was carried out by means of a computer program analogous to that used in the optimization of the zero bridge. A description of the optimization program is given in Section 9.2.

The results of the calculations are presented in Figs. 36, 37, 38. As follows from Fig. 36a, both the slope of the nonlinearity function and the nonlinearity are (after allowing for the increased range of variation of the division ratio) an order of magnitude smaller than in the single-thermistor circuit.

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Both of these parameters are the smaller, the greater the difference between the reference and compensation temperatures. Sufficiently good results are obtained for the pair of temperatures $T_0 = 278\ \text{K}$, $T_1 = 308\ \text{K}$, at which the minimum of the slope of the nonlinearity function in the zero compensation bridge occurs.

The nonlinearity as a function of temperature for this pair of temperatures is shown in Fig. 36b. The maximum slope of the nonlinearity function is 0.038 %/10 K for the mean thermistor characteristic, and 0.050 %/10 K for the minimum characteristic and 0.063 %/10 K for the maximum characteristic. Considering that the mean value of the span drift is almost two times smaller than the maximum value, the results obtained must be regarded as entirely satisfactory.

The sensitivity of the circuit to changes in the values of the resistors R_3 and R_5 is shown in Fig. 37 a and b. One may note the occurrence of a minimum nonlinearity for a value of resistor R_3 4 % greater, and for a value of resistor R_5 3 % smaller, than the respective values guaranteeing the minimum value of the slope of the nonlinearity function.

The temperature characteristic of the bridge is given in Fig. 37a, and the voltage on potentiometer P_1 in Fig. 36b.⁸

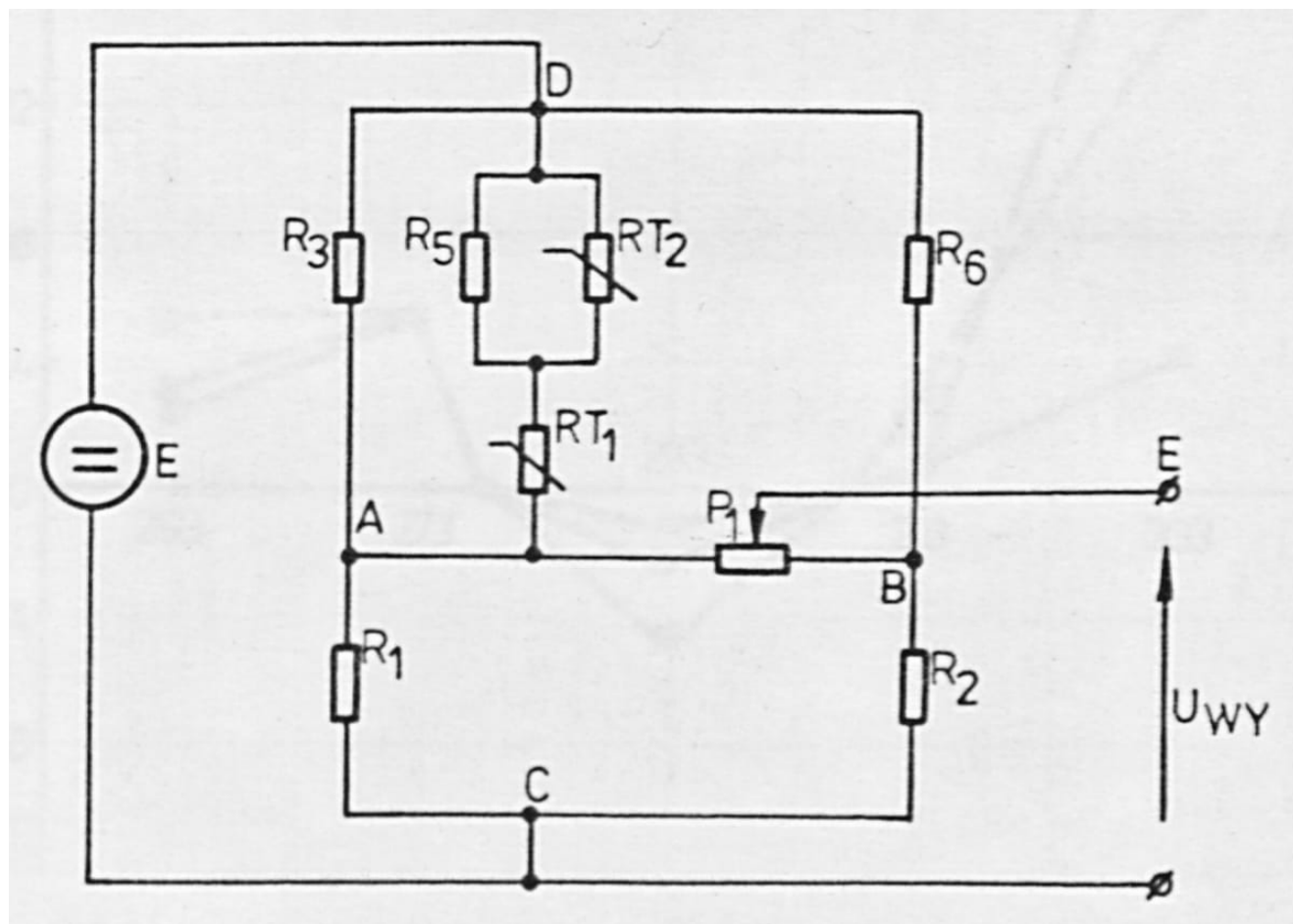


Fig. 35. Circuit of the span compensation bridge

Labels: U_{WY} (WY = wyjście) = U_{out} (output voltage)

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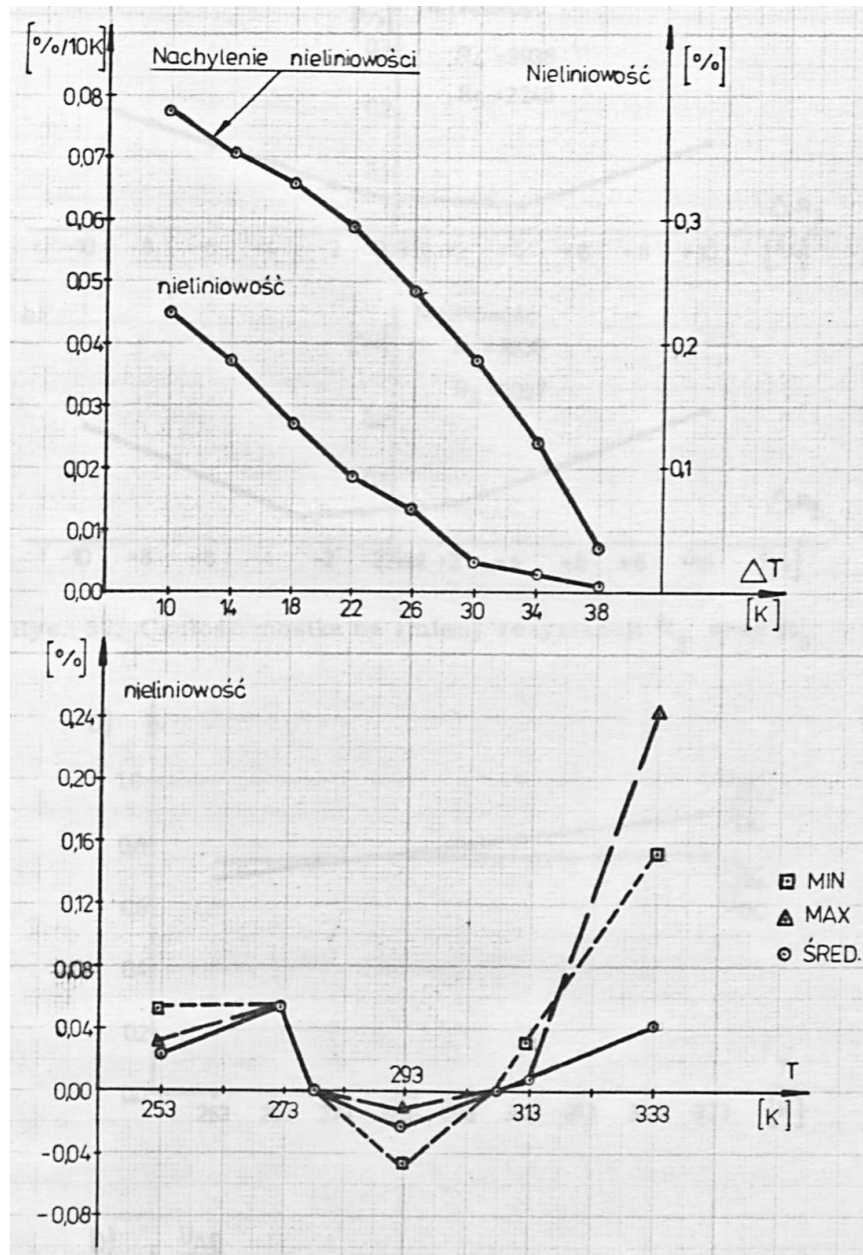


Fig. 36. Results of the calculations for the bridge correcting the span drift
 Labels: *Nachylenie nieliniowości* = slope of the nonlinearity; *Nieliniowość* = nonlinearity; *ŚRED.* = mean

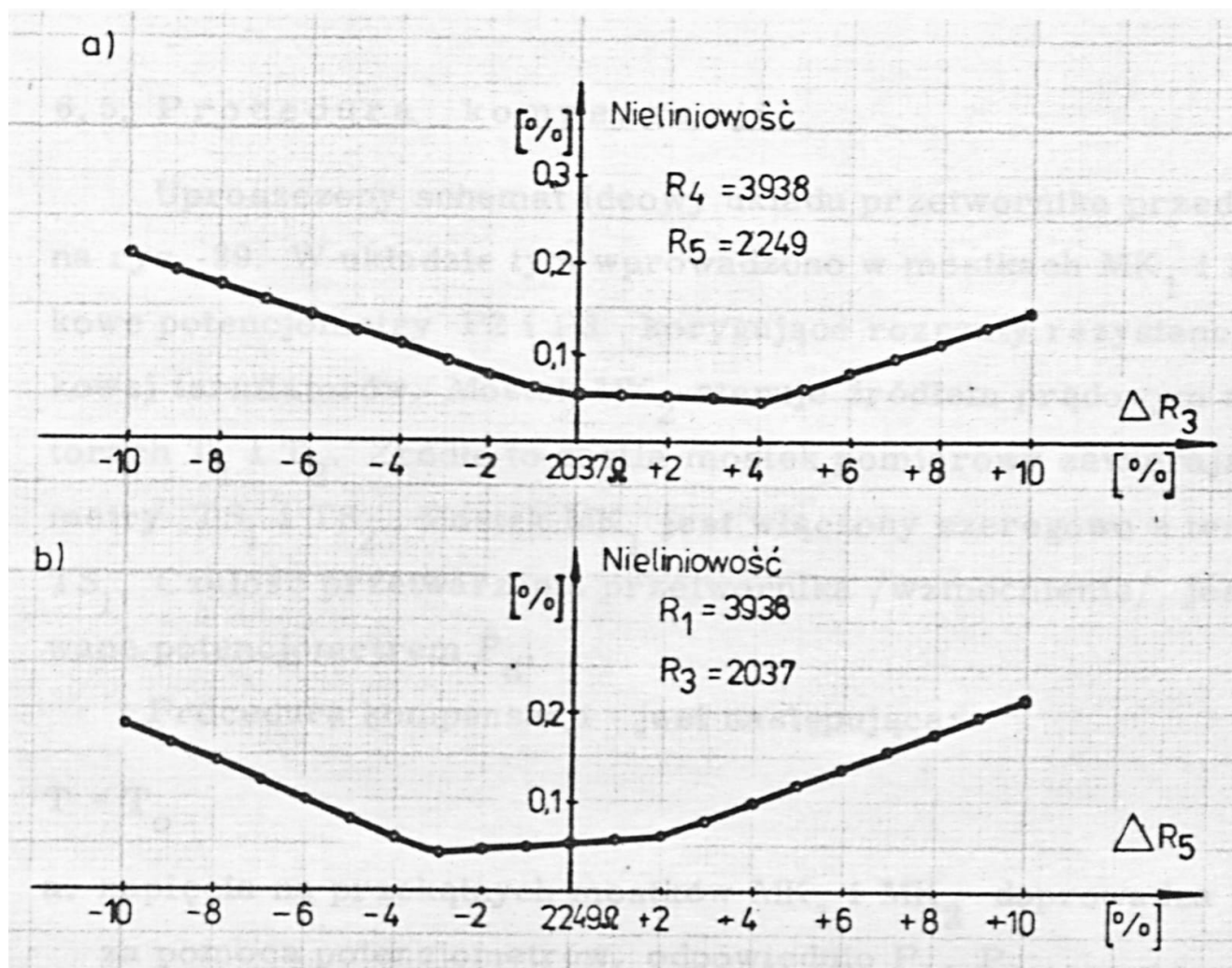


Fig. 37. Sensitivity of the bridge to changes of the resistances R_3 and R_5

Labels: Nieliniowość = nonlinearity

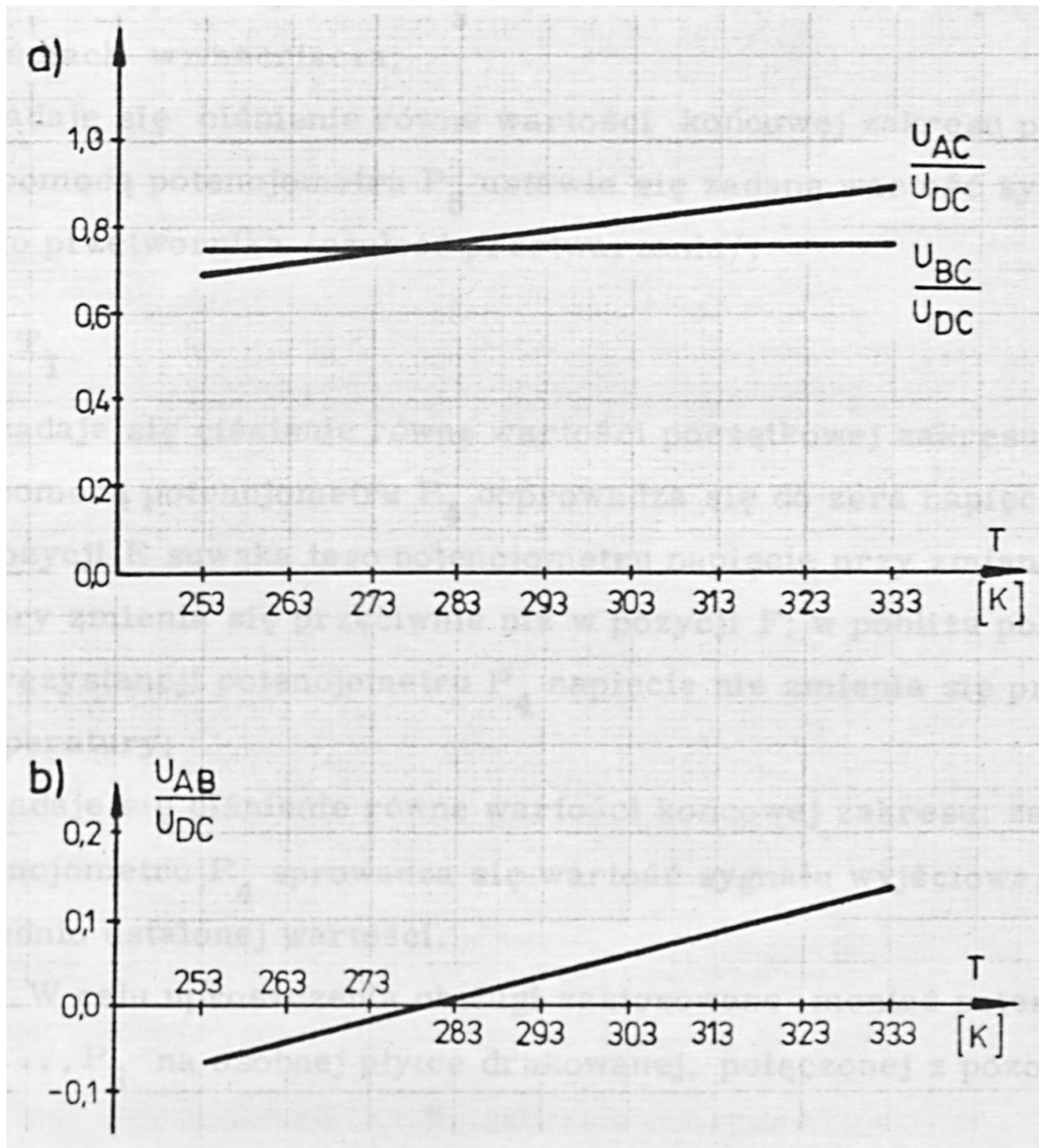


Fig. 38. Changes of voltage in the arms of the span-drift compensation bridge

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6.5. Compensation procedure

A simplified circuit diagram of the transducer circuit is shown in Fig. 39. In this circuit additional potentiometers P_2 and P_3 , correcting the spread of the initial resistance of the thermistors, have been introduced into the bridges MK_1 and MK_2 . The bridge MK_2 controls the current source on the transistors T_1 and T_2 . This source supplies the measuring bridge containing the strain gauges TS_1 and TS_2 . The bridge MK_1 is connected in series with the strain gauge TS_1 . The sensitivity of the transducer (gain) is adjusted by potentiometer P_6 .^{9 10}

The compensation procedure is as follows:

$$T = T_o$$

- the voltages on the diagonals of the bridges MK_1 and MK_2 are brought to zero by means of potentiometers P_3 , P_2 respectively;
- a pressure equal to the lower range value is applied; by means of potentiometer P_5 the voltage U_{GH} at the amplifier inputs is brought to zero; c. a pressure equal to the upper range value is applied; by means of potentiometer P_6 the required value of the transducer output signal (sensitivity) is set;

$$T = T_1$$

a. a pressure equal to the lower range value is applied; by means of potentiometer P_4 the voltage U_{GH} is brought to zero; in position E of the wiper of this potentiometer the voltage changes with changes of temperature in the opposite sense to that in position F; near the middle of the resistance value of potentiometer P_4 the voltage does not change with a change of temperature; b. a pressure equal to the upper range value is applied; by means of potentiometer P_1 the value of the output signal is brought to the value established previously.¹¹

In order to simplify handling, the potentiometers $P_1, \dots, P_6$ are mounted on a separate printed-circuit board, connected to the rest of the

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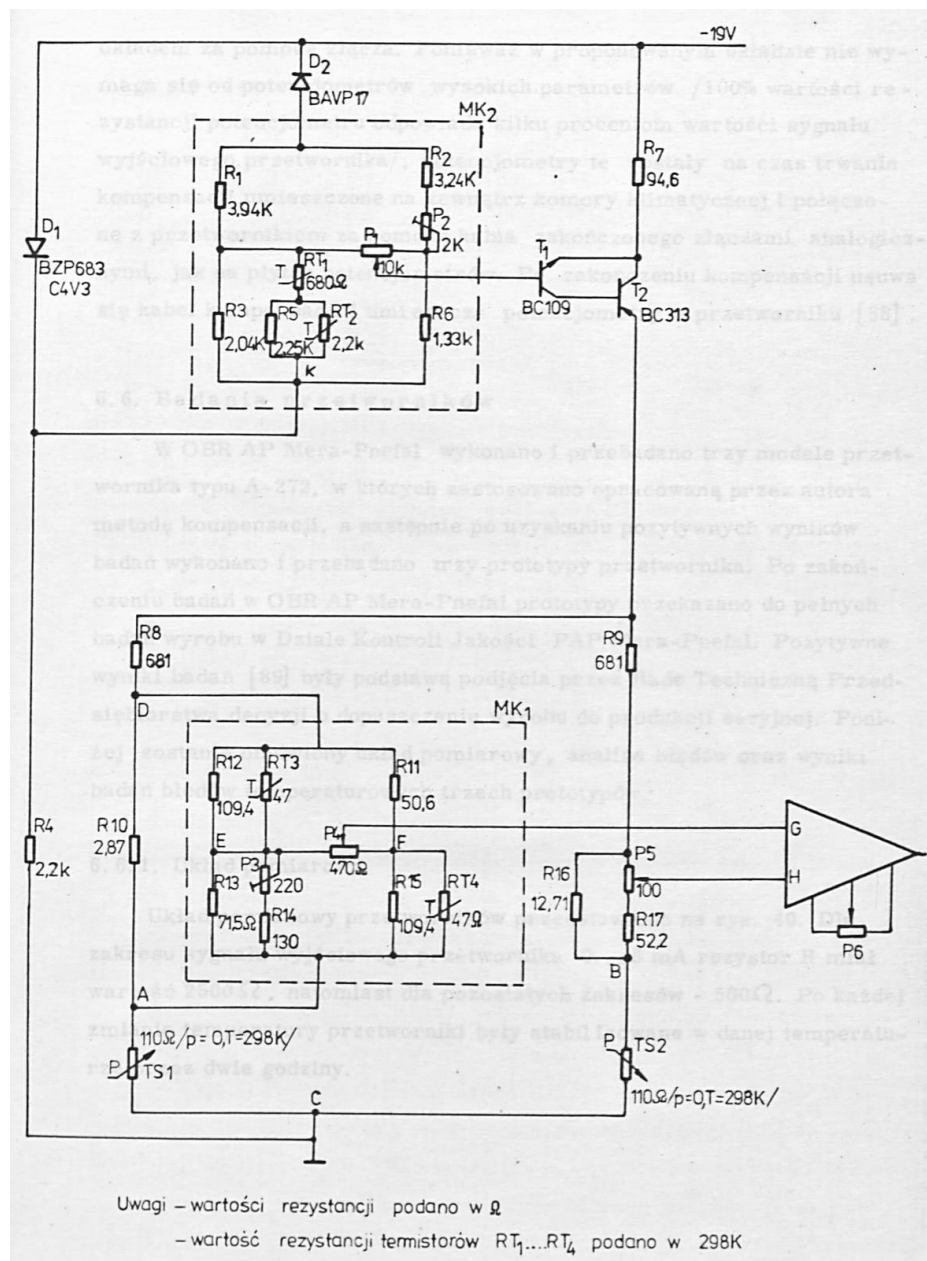


Fig. 39. Simplified circuit diagram of the transducer

Labels: Uwagi = notes; wartości rezystancji podano w Ω = resistance values are given in Ω ; wartość rezystancji termistorów $RT_1 \dots RT_4$ podano w 298K = the resistance of thermistors $RT_1 \dots RT_4$ is given at 298 K

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circuit by means of a connector. Since in the proposed circuit high performance is not required of the potentiometers (100 % of the resistance value of the potentiometer corresponds to a few per cent of the value of the transducer output signal), these potentiometers were placed, for the duration of the compensation, outside the climatic chamber and connected to the transducer by

means of a cable terminated with connectors analogous to those on the potentiometer board. After completion of the compensation the compensation cable is removed and the potentiometers are placed in the transducer [88].

6.6. Transducer tests

At the Mera-Pnefal Industrial Automation Research and Development Centre (OBR AP) three engineering models of the transducer type A-272 were made and tested, in which the compensation method developed by the author was applied, and then, after positive test results had been obtained, three prototypes of the transducer were made and tested. After completion of the tests at OBR AP Mera-Pnefal the prototypes were handed over for full product tests at the Quality Control Department of the Mera-Pnefal Industrial Automation Enterprise (PAP). The positive test results [89] were the basis for the decision of the Technical Council of the enterprise to release the product for series production. Below are discussed the measuring setup, the error analysis and the results of the tests of the temperature errors of the three prototypes.

6.6.1. Measuring setup

The measuring setup for the transducers is shown in Fig. 40. For the transducer output signal range 0 to 5 mA the resistor R had a value of 2500 Ω , and for the remaining ranges 500 Ω . After each change of temperature the transducers were allowed to stabilize at the given temperature for two hours.

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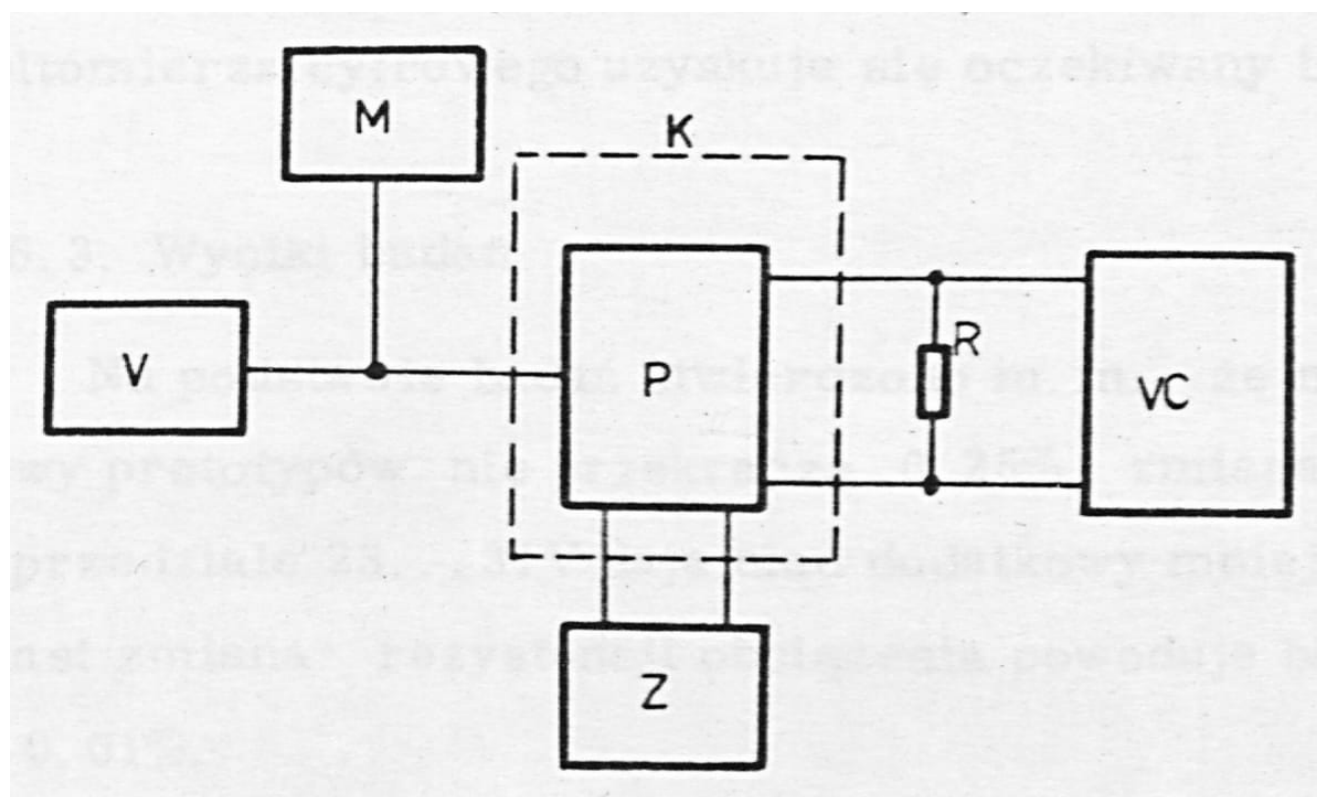


Fig. 40. Measuring setup for the transducers

- P - transducer under test
- R - standard resistor 500 Ω or 2500 Ω , accuracy $\pm 0.02\%$
- VC - digital voltmeter type 3490A, Hewlett Packard
- Z - power supply V-316, Meratronik
- M - digital pressure gauge, Ashcroft, type 7781
- V - precision pressure setter
- K - variable-temperature chamber

6.6.2. Error analysis

The digital pressure gauge used for measuring the input pressure is characterized by a measuring range of 200 kPa and an accuracy of $\pm 0.05\%$ of the measuring range. Transferring this accuracy to the measuring range of the transducer, 20 to 100 kPa, one obtains an accuracy of 0.125 % of the measuring range of the transducer (80 kPa).

The transducers tested had the following output signal values: 0 to 5 mA, 0 to 20 mA and 4 to 20 mA. The output signal was measured by measuring the voltage on the standard resistor, $500\ \Omega$ or $2500\ \Omega \pm 0.02\ \%$, by means of a digital voltmeter with a 120 000-count display. In all cases a measured output voltage range of 10 V was obtained. The accuracy of the measurement made with the digital voltmeter was better than 0.01 % of the measured range

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Taking into account the errors of the pressure gauge, of the manufacture of the resistors R and of the digital voltmeter, one obtains an expected measurement error $d = 0.073\ \%$

6.6.3. Test results

On the basis of the tests it was found, among other things, that the maximum intrinsic error of the prototypes does not exceed 0.25 %, a change of the supply voltage in the interval 23 to 31 V gives an additional error smaller than 0.04 %, whereas a change of the load resistance causes an additional error smaller than 0.01 %.¹²

The temperature error was determined in the test report [89] with the intrinsic error included. As the temperature error of the transducer was taken the greatest slope of the changes of the transducer output signal at 20 kPa or 100 kPa with respect to the temperature 293 K. With this interpretation the following maximum temperature errors were obtained:

- for the transducer with the 0 to 5 mA range - 0.193 %/10 K
- for the transducer with the 0 to 20 mA range - 0.128 %/10 K
- for the transducer with the 4 to 20 mA range - 0.050 %/10 K

In the tests carried out at OBR AP Mera-Pnefal, in determining the temperature error the intrinsic error was disregarded, and only the change of the output signal for the zero (20 kPa) and for the span (80 kPa) caused by the change of temperature was taken into account. The tests were carried out at seven temperatures in the range from 253 K to 333 K. The test results are presented in Figs. 41, 42, 43. The dashed line shows the temperature error limit. It amounts to

- for the transducer with the 0 to 5 mA range - limiting zero drift 0.02 %/10 K, limiting span drift 0.14 %/10 K
- for the transducer with the 0 to 20 mA range - limiting zero drift 0.07 %/10 K, limiting span drift 0.11 %/10 K
- for the transducer with the 4 to 20 mA range - limiting zero drift 0.06 %/10 K, limiting span drift 0.09 %/10 K

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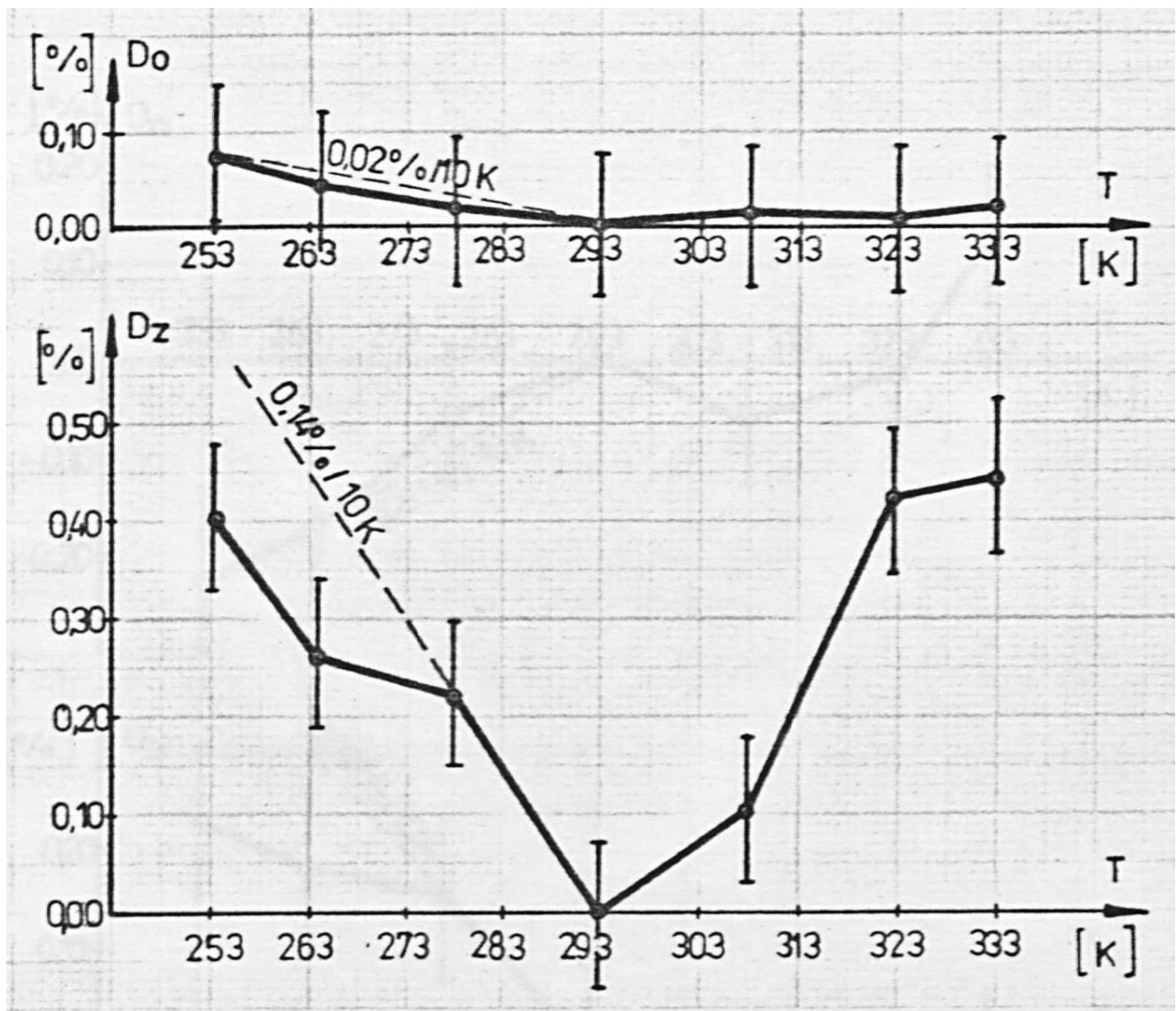


Fig. 41. Temperature drift of the zero D_0 and of the span D_z for the transducer with the 0 to 5 mA range

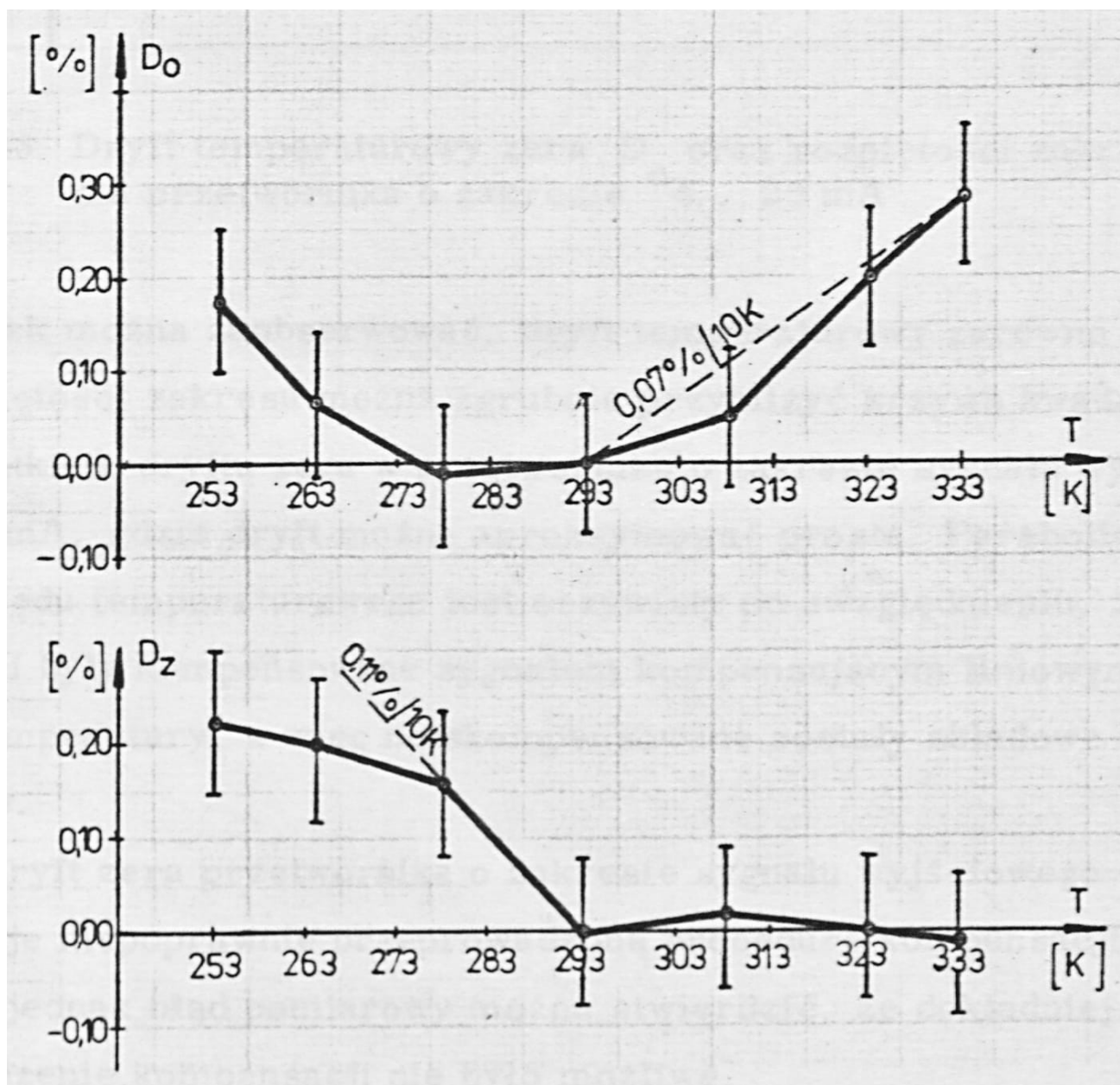


Fig. 42. Temperature drift of the zero D_0 and of the span D_z for the transducer with the 0 to 20 mA range

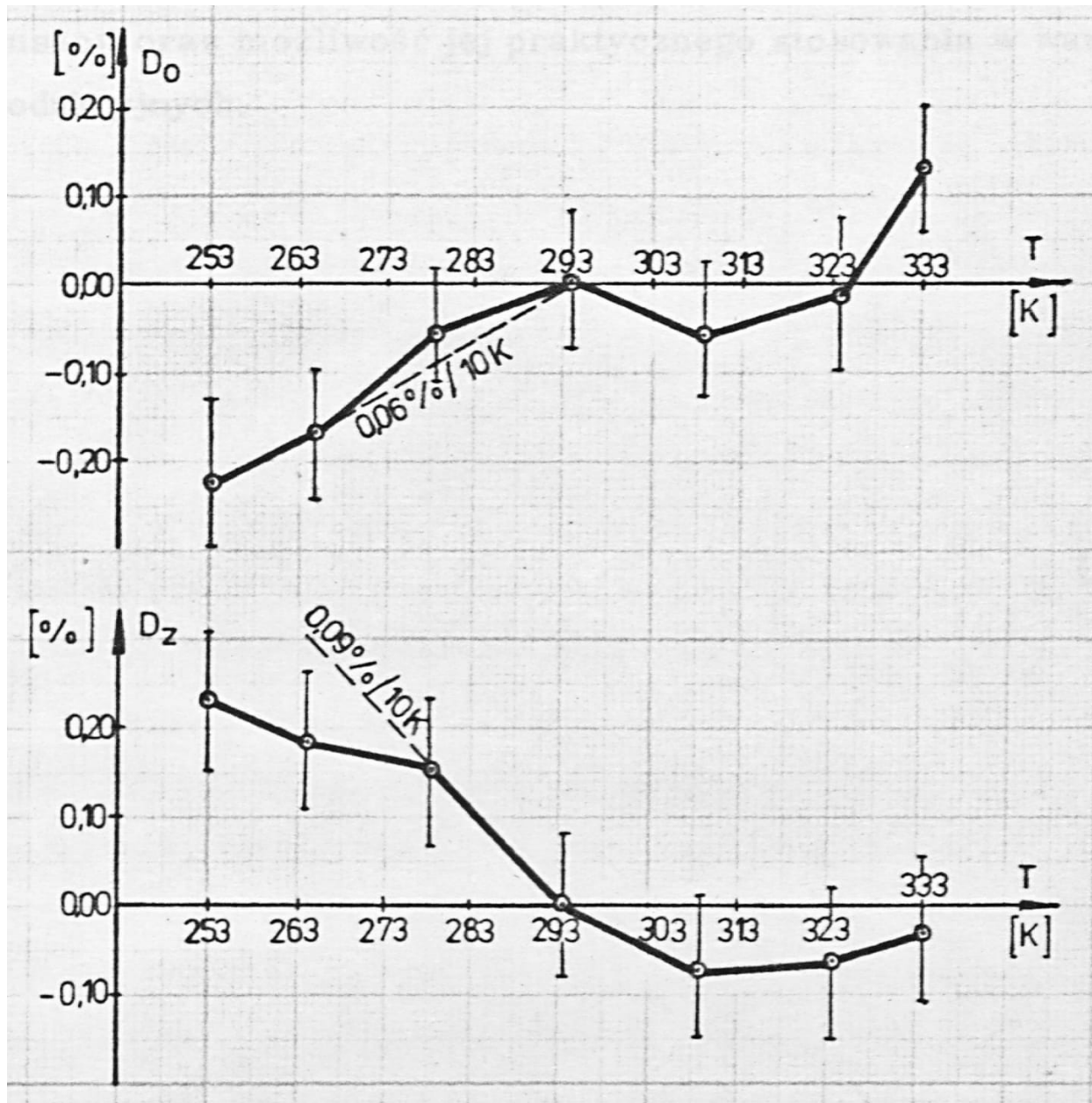


Fig. 43. Temperature drift of the zero D_0 and of the span D_z for the transducer with the 4 to 20 mA range

As may be observed, the temperature drift of both the zero and the span can be coarsely approximated by a quadratic curve, with the exception of the zero drift in the transducer with the 4 to 20 mA output signal range, where the drift can be approximated by a straight line. The parabolic course of the temperature error is obvious once it is taken into account that the transducers were compensated with a compensating signal linear in temperature, so that the higher-order components were left uncompensated. The zero drift of the transducer with the 4 to 20 mA output signal range suggests an incorrectly performed compensation procedure. Taking the measurement error into account, however, it can be stated that a more accurate performance of the compensation was not possible.

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The test results fully confirm the effectiveness of the new compensation method and the possibility of its practical application under production conditions.

Translator's notes

1. "inter-system converter" ("przetwornik międzysystemowy") is the Mera product class of the type A271: an instrument converting between the pneumatic standard signal (20 to 100 kPa) and the electric standard signal.
2. "intrinsic error" ("błąd podstawowy") is the error under reference conditions, i.e. at the reference temperature; the literal rendering of the Polish term is "basic error".

3. the typescript prints this table in four blocks of columns (sensors 1–5, 6–10, 11–15, 16) across the page width; it is set here as one table with a row per sensor.
4. "Table 1" refers to the table of X and Y values on the preceding page, which carries no number as printed; the next table is numbered Table 2.
5. the row headings read "P/X A/" and "P/Y A/" in the original, with no relational sign between the symbols; the evident intent, the probability that the drift is smaller than the threshold A, is rendered as $P(X < A)$, $P(Y < A)$. The last cell in the $P(Y < A)$ row reads "1" as printed.
6. the word "function" ("funkcji") is a handwritten insertion above the line in the typescript here and in two places in Section 6.4.4 ("slope of the nonlinearity function"); the insertions are read as part of the text.
7. the section references read "9,1" and "9,2" (comma) in the original; rendered as 9.1 and 9.2.
8. figure references as printed ("rys. 37a", "rys. 36b"); by their captions Fig. 37a shows the sensitivity to R_3 and Fig. 36b the nonlinearity versus temperature, whereas the voltages in the bridge arms are plotted in Fig. 38 (panel a: U_{AC} , U_{BC} ; panel b: U_{AB} , the voltage on potentiometer P_1). Kept as printed, since the intended panels are not stated.
9. original reads "termistorem TS_1 " ("the thermistor TS_1 "); in Fig. 39 and in the preceding sentence TS_1 is a strain gauge, and MK_1 is drawn in series with it. The evident intent is rendered.
10. T_1 and T_2 in this paragraph are the transistors of Fig. 39, not the compensation temperatures.
11. original reads "potencjometru P_4 " in step b; P_4 is the zero-compensation potentiometer just used in step a, and the span adjustment at T_1 is made by the potentiometer on the diagonal of MK_2 , which is P_1 in Figs. 31, 35 and 39. The evident intent is rendered.
12. "additional error" ("błąd dodatkowy") is the error caused by an influence quantity (here supply voltage, load, temperature) beyond the intrinsic error; IEC usage would call it a "variation".

7. CONCLUSIONS

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This work has presented a new method of compensation of temperature errors in semiconductor pressure transducers. The method consists in carrying out the nulling of the temperature error of the transducer at a certain number of discrete temperatures. This nulling brings the temperature error of the transducer identically to zero over the whole operating temperature range, independently of the choice of the values of the compensation temperatures, in the case of complete temperature compensation, and makes possible a considerable reduction of the value of the temperature error in the case of incomplete compensation.

The method is characterized by the use of only one element realizing the nulling of the temperature error for each selected compensation temperature and for each compensated parameter (zero, span) of the transfer characteristic of the transducer. What is required of such elements is the realization of the division of the compensating signal. The signals present on such elements are therefore equal to the temperature errors compensated by them, that is, small fractions of the measuring range, as a result of which the requirements on their absolute stability are lowered. This makes it possible, in the compensation process, to place these adjusting elements outside the temperature chamber, by which directness and ease of compensation are achieved.¹

The theoretical analysis carried out has shown the possibility of obtaining complete compensation in the case where the number of compensation temperatures is equal to the degree of the polynomial describing the temperature error of the sensor parameter under consideration. It has also been proved that complete compensation can also be obtained with a reduced number of temperatures if certain properties of the function approximating the temperature error of the sensor are known in advance.

Incomplete compensation has been analysed for the cases most often encountered in practice, namely for the case of a quadratic and of a cubic function describing the temperature error of the compensated sensor parameter.

A general design of a circuit realizing the method has been proposed in

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the form of a multiple bridge. The triple bridge circuit has been considered in more detail. The problem of the interaction between the temperature compensation of the lower and upper range values of the measuring range has been discussed. A detailed design of a circuit realizing the method has been presented on the example of a piezoresistive pressure transducer. A design outline of the more interesting subassemblies of the transducer connected with the compensation circuit has been presented. A statistical analysis of the maximum errors of the sensor has been discussed with a view to the choice of the degree of the polynomial describing the compensating signal. Computer programs optimizing the characteristics of the single bridges compensating the zero drift and span drift of the transducer have been presented. On the basis of the results of these programs the optimum difference between the reference temperature and the compensation temperature has also been determined. The temperature compensation procedure of the transducer has been discussed. The results of tests of the prototypes, fully confirming the effectiveness of the new method, have been included.

A particular advantage of the new method is the unidirectional independence of the settings of the elements nulling the temperature error. This independence consists in the fact that adjustment at a given temperature does not make it necessary to change the settings of the elements adjusted at the preceding temperatures. This eliminates the need for iterative determination or calculation of the final settings of these elements. This property is particularly valuable under the conditions of industrial series production of transducers, since the adjustment can be carried out quickly by staff without high qualifications.

In the proposed circuit design of the method, independence is obtained between the conditions ensuring compensation of the lower range value and the conditions ensuring compensation of the upper range value of the measuring range.

The method presented in this work is at present being introduced into series production at the Mera-Pnefal Industrial Automation Enterprise, and in 1978 the manufacture of 1000 units of transducers using the method is planned. The introduction of the new method eliminates the time-consuming

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and laborious process of selecting the values of, and winding, the copper and manganin compensation resistors that was used in the old product, at the same time shortening by approx. 80 % the time needed to carry out the compensation. The new method is characterized by universality of application. It may be applied to the compensation of the temperature errors of any transducers for non-electrical quantities having a linear transfer characteristic and a temperature error additive to the value of the measured signal. In such cases only the detailed circuit design is subject to modification. The method may also find application in the compensation of the effect of temperature in measuring instruments other than transducers for non-electrical quantities, e.g. in instrumentation amplifiers, analog-to-digital converters, generators, etc. The method moreover makes possible the compensation of the effect of quantities other than temperature, for example giving the possibility of compensating the effect of pressure in a temperature transducer.

On the basis of the theoretical analysis carried out in this work and of the experimental results obtained, it appears that the thesis stated at the outset has been fully proved.

Translator's notes

1. original reads "wymagane jest realizowane dzielnikowania"; "realizowane" is a typist's slip for "realizowanie" (the realization of).

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9. APPENDIX

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The appendix discusses the computer programs used for the optimization of the temperature characteristics of the zero-drift and span-drift compensation bridges. The programs were written in Fortran and run on an ODRA 1305 computer.¹

9.1. Description of the program optimizing the characteristics of the zero-drift compensation bridge

The characteristics of the zero bridge were optimized with a view to minimizing the slope of the nonlinearity function of the resistor-thermistor divider (Fig. 32) present in each arm of the zero-drift compensation bridge. This divider has two degrees of freedom. One of them, the value of the resistor R_1 , was used to obtain a division ratio equal to 0.5 (zero voltage across potentiometer P) at the reference temperature T_3 . The second degree of freedom, in the form of the value of the resistor R_2 , was used to minimize the slope of the nonlinearity function.

All printed results for the nonlinearity function and the slope of the nonlinearity were referred to the span of the transducer. This normalization was carried out by assuming that the change of the division ratio between the temperatures 253 K and 333 K corresponds to 8 % of the span.

The input data to the program were the resistance values of the thermistors at the temperatures $T_1 = 253$ K, $T_2 = 273$ K, $T_4 = 293$ K, $T_6 = 313$ K, $T_7 = 333$ K for the thermistor of maximum and of minimum resistance in the batch under study, and the resistance values of a hypothetical thermistor whose resistance values are equal to the mean resistance of the thermistors at each temperature.²

The simplified computation procedure was as follows:

1. Assume $T_3 = 288$ K, $T_5 = 298$ K, $R_2 = 59$ Ω , for the mean thermistor characteristic

2. Compute R_1 such that the division ratio $WD = 0.5$ at the temperature $T = T_3$

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$$WD = \frac{U_{AB}}{U_{DB}}$$

3. For this R_1 compute WD at the remaining six temperatures

4. Compute, at all seven temperatures, the ordinates of the straight line having the same values as the ratio WD at the temperatures T_3 and T_5

5. Compute the differences D between the ratio WD and the ordinates of the straight line from step 4 at the seven temperatures

6. Compute the coefficients of the equations of the straight lines having values in common with the difference D at the temperature 293 K and at each of the remaining six temperatures

7. Find and store the maximum value M of the modulus of the slope of the six straight lines from step 6

8. Repeat the computations of steps 2 to 7 150 times, changing the value of R_2 by +1 % at each step

9. Compute the minimum value of M in the set of 150 values. For this value print the computed values of the resistors R_1 and R_2 .

10. For the values of R_1 and R_2 found, compute and print the difference D at the seven temperatures for all three thermistor characteristics, print the range of variation of the ratio WD between the temperatures 253 K and 333 K, and the value of the modulus M .

11. Compute and print the value of the maximum difference D for ten values of the resistor R_2 smaller than the optimum and for ten values of the resistor R_2 larger than the optimum, changing the resistor value by 5 Ω each time.

12. Repeat computations 2 to 11 for the remaining seven pairs of temperatures $T_o - T_1$.³

13. Print the maximum value of D from step 10 (the nonlinearity) as a function of the temperature pairs $T_3 - T_5$.

9.2. Description of the program optimizing the characteristics of the span-drift compensation bridge

The linearization of the voltage U_{AC1} (Fig. 35) as a function of temperature was carried out by a computer procedure analogous to that for the zero-drift compensation bridge. The differences lay in a different initial condition – select the resistor R_1 so that, for the assumed R_3 , R_5 , a relative change of the voltage U_{AC} referred to the temperature 293 K equal to 20 % is obtained – and in a different procedure for searching for the extremum. Since, after the value of R_1 had been fixed, two degrees of freedom still remained – the values of the resistors R_3 , R_5 – four search-density levels were introduced. At the first level the program searched for the minimum slope of the nonlinearity for eight values of each of the resistors, varied with a ratio of 1.64, starting from 200. At the second level, the search for the minimum slope began from the value preceding the optimum value found for each resistor, and was likewise carried out for a further eight values with a ratio of 1.16. At the third level the ratio was 1.04 and at the fourth, last level 1.01.⁴

As a result of the search, at each level the minimum was sought from a set of 84 values.⁵

For each of the pairs of temperatures $T_3 - T_5$ the computed optimum resistance values R_1 , R_3 , R_5 were printed, together with the nonlinearity as a function of temperature for these values for the three thermistor characteristics. In addition, the nonlinearity was printed for 10 values smaller and 10 values larger than the computed optimum values of the resistors R_3 and R_5 , as well as the maximum slope of the nonlinearity characteristic as a function of the temperature pairs $T_3 - T_5$.

The normalization of the results was carried out taking into account that the change of the division ratio between the temperatures 253 K and 333 K corresponds to 20 % of the measuring range.

Translator's notes

1. ODRA 1305 — a Polish mainframe built by Elwro, compatible with the ICL 1900 series.
2. in this appendix T_1 to T_7 denote the seven computation temperatures 253 K to 333 K, with T_3 and T_5 the reference and compensation temperatures; this differs from chapters 4 to 6, where T_1 to T_n are the compensation temperatures.
3. here the pair $T_o - T_1$ denotes the reference and compensation temperatures in the general sense of chapter 4, not the computation temperatures T_1 to T_7 of this appendix.
4. original reads "zaczynając od 200" followed by a blank space where the unit was expected; the unit (presumably Ω , as for the other resistor values in this appendix) is not printed in the typescript.
5. "84" as printed; eight values of each of the two resistors give 64 combinations.