Simultaneous Measurement of Two Parameters by Double Current Supplied Bridge

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Abstract:
A four-terminal (4T) bridge-circuit, with two voltage outputs is presented. This circuit, named as double current bridge is supplied by two equal current sources connected in parallel to opposite arms (2J) or by one such source switched between those arms (2x1J). Two output voltages from bridge diagonals as functions of arm resistance increments in absolute and in relative units are given. Also the example of this bridge application is proposed. Signal conditioning formulas of two-parameter measurement on the example of strain and temperature are discussed in detail. Some results obtained with the use of this bridge-circuit are briefly described.

Keywords: *multivariable measurement circuits, bridge circuit, strain measurement*

1. Introduction

In the most applications the newest analog-to-digital (ADC) converters and digital parts of measurement systems assure satisfying resolution, speed and universality due to programming facilities. At present, an improvement of strain, pressure, force, torque or other measurements depends mainly on metrological properties of the input analog part of these systems.

The sensor's thermal error (drift of sensor's offset and span) is compensated in the digital part of a conditioner by proper correction algorithms. For pressure measurement a piezoresistive sensor can be powered by an adjustable current source combined with a programmable-gain amplifier and external trimmable resistors (e.g. MAX1450) [1], or two amplifiers and two digitally controlled potentiometers [2], or four digital-to-analog converters (DAC) resulting in a temperature-depended bridge voltage (e.g. MAX1452) [3].

In a mass production of silicon piezoresistive-bridge pressure sensors, sensor-error correction is often affected by use of a laser or abrasive trimming machine, which trims resistors and thermistors in the signal conditioning circuit to the values required for offset and sensitivity compensation (e.g. in X-ducer piezoresistive pressure bridge-sensors [4], or NPC series of GE Novasensor pressure sensors [5]).

Apart from well-known instrumentation for the measurement of single variables, the development of methods of continuous indirect multivariable measurement is urgently needed. High accuracy measurement of increments of input immittances of multi-terminal circuit and of some quantities affecting them is an example.

Relevant problems have been considered on the example of two-parameter simultaneous measurement of resistance increments of the four-terminal (4T) circuit [6]. Since 1998 Warsza has been proposing two types of structures for such measurement and for the primary signal conditioning on the input analogue part of instrumentation channels. One is the circuit of two four-arm classic bridges connected in cascade [7]. The other one has an unconventional supplying: the 4T circuit is supplied by two equal current sources in parallel to opposite arms – **2J** or in practice by switching over two unequal sources between these arms – **2x2J** or even only one – **2x1J**. For all of these circuits Warsza proposed a common name: **double current bridges**. The circuits were described in [8], [9] and more extensively in [10].

To illustrate this concept of simultaneous two-parameter measurement, either one-axis strain and temperature or two-axis strain using strain gauges plugged in a double current bridge, an experimental bridge-circuit was built. It can be competitive to the other solutions [1]-[3] and it has following advantages:

- there are two different output voltages depending on two measured quantities, i.e. strain and temperature,
- the temperature reading and compensation in whole measuring span is realized without any additional sensor such as thermistor or thermistor-resistor parallel networks [4], [5].

Two output signals (representing temperature and strain) are interfaced to a microcontroller by ADCs.

The 2J bridge circuits and the cascade bridge circuit are applicable for the GMR (*Giant Magneto-Resistive*) [12], [13] and other impedance sensors. An alternative idea than 2J bridges is the method of Pallas-Areny and collaborators [14], based on detecting changes in resistance by measuring the time needed to discharge a given capacitor.

2. Unbalanced double current bridge with 4 variable arms

This section describes the difference between double current bridges (2J) introduced by Warsza [6] and Wheatstone bridge.

Both types are shown in Fig1.

As it is shown in Fig. 1a,b the four resistance (4R) bridge is unconventionally powered by two equal current sources J connected in parallel to opposite bridge arms. Commonly known Wheatstone bridge is additionally given in Fig. 1c for comparison. The output voltages of bridges in Fig. 1 are:

$$U_{DC} = J\frac{R_1R_2 - R_3R_4}{\sum R_i} \equiv J \cdot t_{DC}(\varepsilon_i) \qquad (1)$$

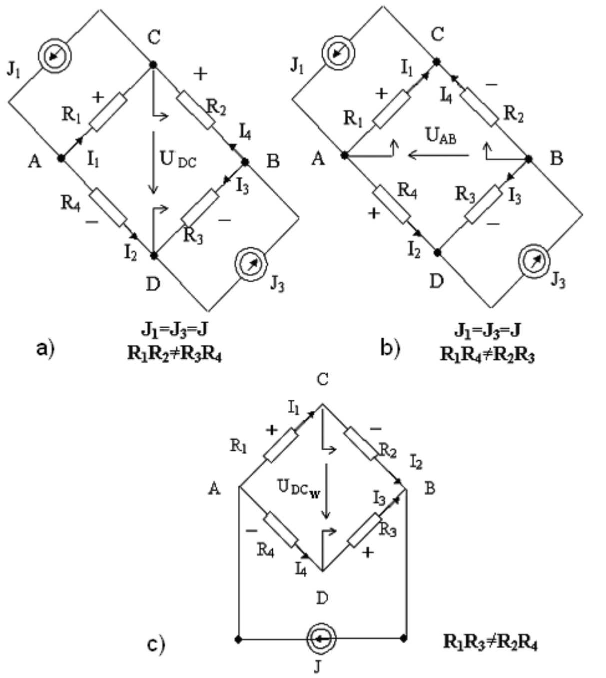

Fig. 1. a) and b) – illustration of work in unbalance conditions: $R_1R_2 \neq R_3R_4$ and $R_1R_4 \neq R_2R_3$ of two outputs DC and AB of the four resistance bridge circuit unconventionally supplied by two equal current sources J, introduced in [6]; and for comparison: c) well known Wheatstone bridge supplied by current source J, unbalanced for: $R_1R_3 \neq R_2R_4$

$$U_{AB} = J\frac{R_1R_4 - R_2R_3}{\sum R_i} \equiv J \cdot t_{AB}(\varepsilon_i) \qquad (2)$$

$$U_{DC_W} = J\frac{R_1R_3 - R_2R_4}{\sum R_i} = J \cdot t(\varepsilon_i) \qquad (3)$$

Where: $R_i = R_{i0}(1+\varepsilon_i)$, $\sum R_i = R_1 + R_2 + R_3 + R_4$; R_{i0} – the initial nominal resistance, ε_i – the relative change in resistance, t, t_{DC}, t_{AB} – open-circuit voltage to current transmittances of DC and AB outputs.

Forms (1), (2) of output voltages U_{DC}, U_{AB} of the 2 J bridge are similar to (3) for U_{DCW} of unbalanced Wheatstone bridge supplied from current source, but the outputs DC or AB of the 2J circuit are balanced for the equal products of resistances in the neighboring bridge arms. After separation of resistance changes, the formulas mentioned above are

$$U_{DC} = J\frac{R_{10}R_{20}}{\sum R_{i0}}\frac{(\varepsilon_1 + \varepsilon_2 - \varepsilon_3 - \varepsilon_4 + \varepsilon_1\varepsilon_2 - \varepsilon_3\varepsilon_4)}{1+\frac{\sum R_{i0}\varepsilon_i}{\sum R_{i0}}} \equiv T_{0DC} \cdot f_{DC}(\varepsilon_i) \qquad (4)$$

if $R_{10}R_{20} = R_{30}R_{40}$ and

$$U_{AB} = J\frac{R_{10}R_{20}}{\sum R_{i0}}\frac{(\varepsilon_1 - \varepsilon_2 - \varepsilon_3 + \varepsilon_4 + \varepsilon_1\varepsilon_4 - \varepsilon_2\varepsilon_3)}{1+\frac{\sum R_{i0}\varepsilon_i}{\sum R_{i0}}} \equiv T_{0AB} \cdot f_{AB}(\varepsilon_i) \qquad (5)$$

if $R_{10}R_{40} = R_{20}R_{30}$, and

$$U_{DC_W} = J\frac{R_{10}R_{30}}{\sum R_{i0}}\frac{(\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4 + \varepsilon_1\varepsilon_3 - \varepsilon_2\varepsilon_4)}{1+\frac{\sum R_{i0}\varepsilon_i}{\sum R_{i0}}} \equiv T_0 \cdot f(\varepsilon_i) \qquad (6)$$

if $R_{20}R_{40} = R_{30}R_{10}$,

Where: T_{0AB}, T_{0DC}, T_0 – initial voltage sensitivities of circuits a- c; $f_{DC}(\varepsilon_i), f_{AB}(\varepsilon_i), f(\varepsilon_i)$ – their unbalance functions.

The above conditions for nominal initial values of resistances are fulfilled together if $R_{10} = R_{20} = R_{30} = R_{40} = R_0$. Assume that sensors are in all arms of the bridge and their resistance varies and that the sum of all relative resistance increments is equal zero, i.e. $\sum_{i=1}^{4}\varepsilon_i = 0$. In equations (4) and (5) one can notice that one pair of relative changes in resistance of the same index has the same sign and the other - opposite sign. Additionally, these changes are small when using pairs of strain gauges, then $\varepsilon_i\varepsilon_j < \varepsilon_i + \varepsilon_j$. Thus the equations can be simplified as follows.

$$U_{DC} = \frac{JR_0}{4}\frac{(\varepsilon_1 + \varepsilon_2 - \varepsilon_3 - \varepsilon_4 + \varepsilon_1\varepsilon_2 - \varepsilon_3\varepsilon_4)}{1+\frac{1}{4}\sum\varepsilon_i} \approx \frac{JR_0}{4}(\varepsilon_1 + \varepsilon_2 - \varepsilon_3 - \varepsilon_4) \qquad (7)$$

$$U_{AB} = \frac{JR_0}{4}\frac{(\varepsilon_1 - \varepsilon_2 - \varepsilon_3 + \varepsilon_4 + \varepsilon_1\varepsilon_4 - \varepsilon_2\varepsilon_3)}{1+\frac{1}{4}\sum\varepsilon_i} \approx \frac{JR_0}{4}(\varepsilon_1 - \varepsilon_2 - \varepsilon_3 + \varepsilon_4) \qquad (8)$$

More detailed information about this unconventional type of the bridge is given in [8]-[11].

In [6], [7] and [9] another methods to measure all separate arm increments of 4R bridge is also given. For example four measurements in sequence should be provided, i.e.: both voltages U_{DC}, U_{AB} when the bridge is supplied like in Fig. 1a and Fig. 1b, voltage U_{DCW} for classic diagonal current supply of AB terminals (Fig. 1c) and increment in input open-circuit resistance R_{AB}.

Examples of 2J bridge-circuit application for 2-parameter measurements are presented in the next sections of this paper.

3. 2J Bridge with 2 active arms

The 2J bridge differs from the Wheatstone bridge in the way of supplying. It is quite easy to arrange it for simul-

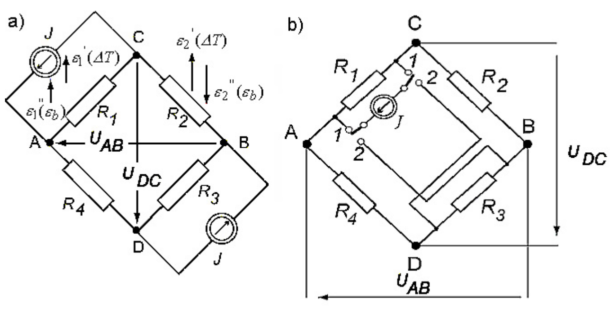

Fig. 2. Double current bridge circuits for temperature ΔT and bending strain ε measurements

tanous two variable measurements (Fig. 2). The bridge has two outputs: A-B and D-C.

Two equal current supply sources J are connected in parallel to opposite arms (R_1, R_3) of the bridge – circuit a). However it is difficult in practice to implement. If the excitations are not equal, equations (1) and (2) have additional components which are dependent on the difference ΔJ [6], [10].

The bridge can also be supplied by single current source J switched over to the same arms – circuit b). Then each of the output voltages is held, averaged in two cycles and measured, i.e.:

$$U_{DC} = 0,5\left(U_{DC\,1} + U_{DC\,2}\right) \tag{9}$$

$$U_{AB} = 0,5\left(U_{AB\,1} + U_{AB\,2}\right) \tag{10}$$

Such a supply does not cause the aforesaid problem of the different excitation currents. It ensures a compensation of thermoelectric voltages (of equal opposite values between output terminals) and the independence of the current J direction.

Both circuit-bridges in Fig. 2. produce two output voltages (U_{DC} and U_{AB}) presented by (1) and (2) or (7) and (8).

Assuming that: $R_3 = R_{30}$, $R_4 = R_{40}$ (which is tantamount to $\varepsilon_3 = \varepsilon_4 = 0$) the output voltages are

$$U_{DC} = T_0 \frac{\varepsilon_1 + \varepsilon_2 + \varepsilon_1\varepsilon_2}{1 + \frac{\varepsilon_1 + \varepsilon_2}{4}} \tag{11}$$

$$U_{AB} = T_0 \frac{\varepsilon_1 - \varepsilon_2}{1 + \frac{\varepsilon_1 + \varepsilon_2}{4}} \tag{12}$$

If modules of the values $|\varepsilon_1|$, $|\varepsilon_2|$ are small enough, i.e. $|\varepsilon_1 \cdot \varepsilon_2| << |\varepsilon_1 + \varepsilon_2|$ and $|\varepsilon_1 + \varepsilon_2| << 4$ (for absolute changes it is $|\Delta R_1 + \Delta R_2| << 2(R_{10} + R_{20})$, formulas (11), (12) are simplified to:

$$U_{DC} = T_0(\varepsilon_1 + \varepsilon_2) \tag{13}$$

$$U_{AB} = T_0(\varepsilon_1 - \varepsilon_2) \tag{14}$$

where: $T_0 = \frac{JR_0}{8}$ – the initial voltage sensitivity is equal for both outputs.

The first output voltage is proportional to the sum and the other one to the difference of increments. Also (13) and (14) become simpler, because U_{AB} disappears in the denominators.

4. Example of application for strain and temperature measurements

Taking the 4T structure of the 2J bridge circuit into consideration, it can be applied to strain gauges. Two ways of placing the strain gauges on the beam are shown in Fig. 3. The first example is one-axis strain and temperature measurement by using two strain gauges A and B. The second example is 2-axis strain measurement when two forces (moments) are applied in two directions (it will be the purpose of future investigations).

The increments in resistance of strain gauges consist of

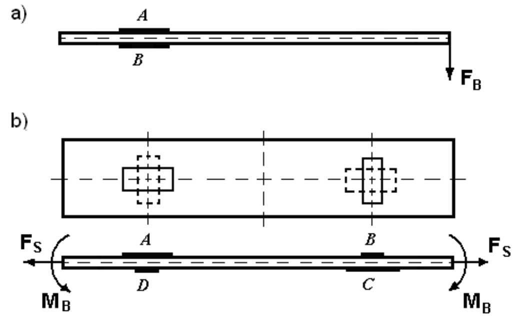

Fig. 3. One-axis (a) and two-axis (b) strain measurement, A, B, C, D – strain gauges, F_B – bending force, F_S – stretching force, M_B – bending moment

two parts ($\varepsilon_1 = \varepsilon' + \varepsilon''$, $\varepsilon_2 = \varepsilon' - \varepsilon''$, respectively). One part is increment due to temperature (15), the other one is the increment (or decrement) due to mechanical stress (16). If there are two strain gauges of the same type, the relative increments in temperature are of the same value and of the same sign. If strain gauges are glued to a beam such that the first gauge is stretched and the other compressed (Fig. 3a) then the increments due to mechanical stress are of the opposite signs.

$$\varepsilon_1'(\Delta T) = \varepsilon_2'(\Delta T) = \varepsilon' \tag{15}$$

$$\varepsilon_1''(\varepsilon_b) = -\varepsilon_2''(\varepsilon_b) = \varepsilon'' \tag{16}$$

From (13) and (14)

$$U_{DC} = T_0(\varepsilon' + \varepsilon'), \qquad U_{AB} = T_0(\varepsilon'' + \varepsilon'') \tag{17}$$

Increments could be considered as linear for both measured quantities, i.e. $\varepsilon'(\Delta T) = \alpha_T \Delta T$; $\varepsilon''(\varepsilon_b) = k \cdot \varepsilon_b$ (where: α_T – the temperature coefficient of resistance, ΔT – change of temperature, $k = k_0(1 + \alpha_K \Delta T)$ – strain gauge factor, ε_b – bending strain).

After substitution, both functions are as follows:

$$\varepsilon' = \alpha_T \cdot \Delta T = \frac{U_{DC}}{2T_0} = \frac{4}{JR_0} U_{DC} \quad \Rightarrow \Delta T = \frac{4U_{DC}}{JR_0 \alpha_T} \tag{18}$$

$$\varepsilon'' = k \cdot \varepsilon_b = \frac{U_{AB}}{2T_0} = \frac{4}{JR_0} U_{AB} \quad \Rightarrow \varepsilon_b = \frac{4U_{AB}}{JR_0 k} \tag{19}$$

The both measured quantities depend linearly on the output voltages U_{AB} and U_{CD} (respectively), supplying current J and the parameters of the gauges. Such an advantage of the circuit is difficult to achieve in other DC bridges [15], [16].

5. Real circuit and the experiment

The theory has been verified in the experimental circuit of a transducer given in Fig 4. The switched current source was constructed with the use of LM317 and four MOSFET switches (STP20NE06L), which has very low on-resistance $R_{ON} = 0.06\ \Omega$. The current excitation can be manually adjustable from 9 mA to 38 mA. The transistors work in pairs – two switched on and two switched off at the

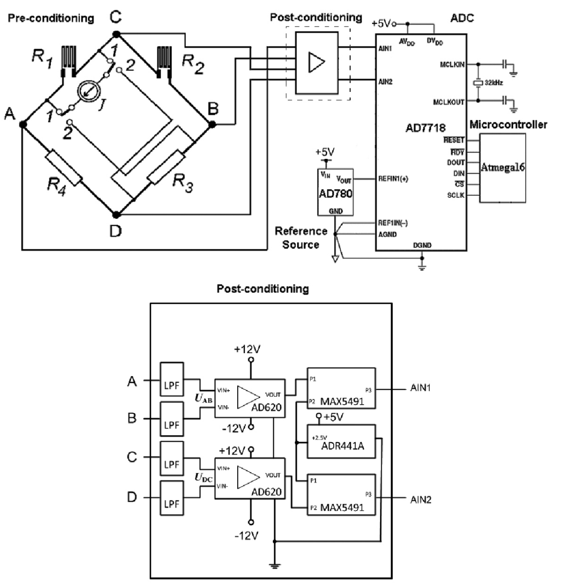

Fig. 4. Transducer system of double current bridge for measurement of strain and temperature

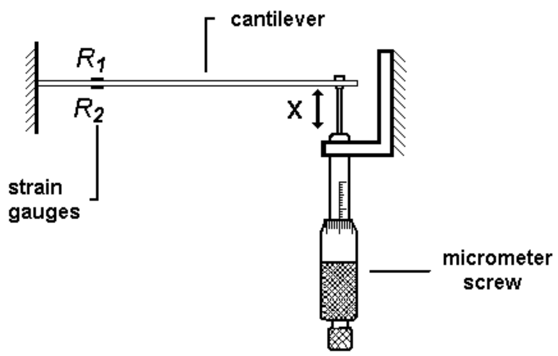

Fig. 5. Laboratory stand (the cantilever had rectangle cross-section, width b = 20 mm, height h = 0.8 mm, length L = 200 mm, the distance between strain gauges and the place where force is fixed l = 180 mm, Young's modulus $E = 2.1 \cdot 10^{11} N/m^2$)

same time. Their state of work is controlled by Atmega16 microcontroller port.

The output voltages U_{AB} and U_{DC} (two of them of positive sign and another two of negative sign) are connected to 24-bit sigma-delta ADC (AD7718) *via* post-conditioning module. It consists of instrumentation amplifiers (AD620AN) and ultra-precision voltage-dividers (MAX5491). The use of this module is necessary because AD7718 requires positive sign voltages of (0 – 2.56 V).

The acquired voltage data from the circuit outputs were processed by the microcontroller.

The measurements were taken for two temperatures of a cantilever beam (23 °C and 65 °C) while the beam was being bent by a micrometer screw (Fig. 5).

6. Experimental Results

The results of the experiment are shown in Fig. 6. It presents the diagrams of relative increments in resistance ε in response to the beam X deflection: $\varepsilon'(23)$, $\varepsilon'(65)$ – the increment in temperature calculated for 23°C and for 65°C

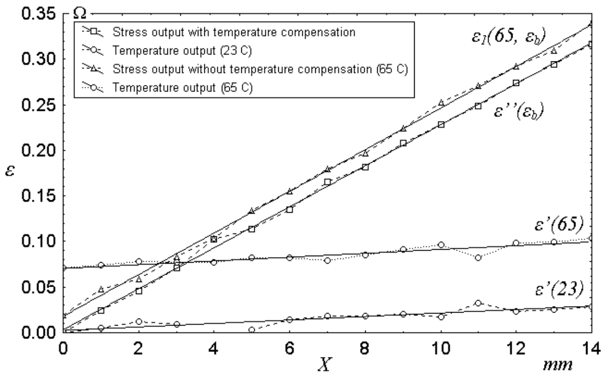

Fig. 6. Relative increments in resistance ε in response to the beam deflection X [11]

respectively, $\varepsilon_1(65, \varepsilon_b)$ – the increment due to mechanical stress in temperature 65°C, $\varepsilon''(\varepsilon_b)$ – the increment of mechanical stress after temperature compensation.

The best straight line fit to data points presented in Fig. 6 are defined by :

$$\varepsilon'(65) = 0.0022X + 0.0710 \tag{20}$$

$$\varepsilon_1(65, \varepsilon_b) = 0.0228X + 0.0196 \tag{21}$$

$$\varepsilon'(23) = 0.0021X \tag{22}$$

$$\varepsilon''(\varepsilon_b) = 0.0226X \tag{23}$$

The nonlinearity error with respect to mechanical stress was 1.8% FSR maximum and 0.6% FSR in average. For the measurement of temperature changes the nonlinearity error is a little bigger – 2.5% FSR (maximum) and 1.0% FSR (average).

7. Bias and precision uncertainties

We assumed that our experimental results were obtained as several independent measurements combined in a single quantity for both measuring channels.

K_1 and K_2 are the calibration factors to be determined. They are output quantities in the measurement models (24) and (25). The input quantities x_i are:

- voltages U_{AB} and U_{CD} - series of measurements reflect bias (offset) and precision (random) errors,
- current J (single measurement – only bias component)
  - temperature ΔT (single measurement – only bias component),
  - beam length L (single measurement – only bias component),
  - beam height h (single measurement – only bias component),
  - beam deflection X (single measurement – only bias component),
  - parameters of strain gauges - k, α_T, R_0 (only bias components).

$$K_1 = \frac{8L^2}{3hkX} \cdot \frac{U_{AB}}{JR_0} \tag{24}$$

$$K_2 = \frac{4}{\alpha_T \Delta T} \cdot \frac{U_{DC}}{JR_0} \tag{25}$$

For uncertainties $u(x_i)$ that are small compared to x_i statistical theorem states that combined standard measurement uncertainty (uncorrelated quantities) is:

$$u_c(y) = \left[\sum_{i=1}^{N} \left(\frac{\partial y}{\partial x_i} \cdot u(x_i) \right)^2 \right]^{1/2} \tag{26}$$

The uncertainties of K_1 and K_2 are:

$$\frac{u_c(K_1)}{K_1} = \left[\begin{array}{l} \left(\frac{2u(L)}{L}\right)^2 + \left(\frac{u(U_{AB})}{U_{AB}}\right)^2 + \left(\frac{2u(h)}{h}\right)^2 + \left(\frac{u(k)}{k}\right)^2 + \left(\frac{u(X)}{X}\right)^2 + \\ + \left(\frac{u(J)}{J}\right)^2 + \left(\frac{u(R_0)}{R_0}\right)^2 \end{array} \right]^{1/2} \tag{27}$$

$$\frac{u_c(K_2)}{K_2} = \left[\left(\frac{u(U_{CD})}{U_{CD}}\right)^2 + \left(\frac{u(\alpha_T)}{\alpha_T}\right)^2 + \left(\frac{u(\Delta T)}{\Delta T}\right)^2 + \left(\frac{u(J)}{J}\right)^2 + \left(\frac{u(R_0)}{R_0}\right)^2 \right]^{1/2} \tag{28}$$

Assume Assume the values of relative uncertainties in Tab. 1, total uncertainties of the calibration factors K_1 and K_2 are:

$$\frac{u_c(K_1)}{K_1} = \left[u_b(K_1)^2 + u_p(K_1)^2 \right]^{1/2} \tag{29}$$

$$\frac{u_c(K_2)}{K_2} = \left[u_b(K_2)^2 + u_p(K_2)^2 \right]^{1/2} \tag{30}$$

where $u_b(y)$ - combined bias uncertainty, $u_p(y)$ – combined precision uncertainty.

Table 1. Bias and precision uncertainties of input and output quantities

Quantity	Bias $u_b(x_i)/x_i$	Precision $u_p(x_i)/x_i$
U_{AB}	0.1%	0.3%
J	0.5%	0
R_0	0.2%	0
k	0.5%	0
L	0.05%	0
X	0.1%	0
h	1.25%	0
U_{DC}	0.1%	0.3%
ΔT	0.5%	0
α_T	0.5%	0
J	0.5%	0
R_0	0.2%	0
$u_C(K_1)/K_1$	$u_b(K_1)$	$u_p(K_1)$
1.5%	1.46%	0.3%
$u_C(K_2)/K_1$	$u_b(K_2)$	$u_p(K_2)^2$
1.0%	0.94%	0.3%

8. Conclusions

The 2J bridge which measures the real change in temperature of strain gauges in their localization and the mechanical stress is presented in this paper. The innovation of this method consists in a particular supplying of the circuit and in measuring the voltages on diagonals. The measured quantities depend on these values. The resistor bridge does not require an additional temperature sensor.

The maximum nonlinearity error with respect to mechanical stress is 1.8% FSR and for the measurement of changes in temperature is a little bigger – 2.5% FSR. Although it is acceptable for many industrial applications the additional experimental tests and some upgrading is still needed. Combined, relative uncertainties of calibration factors K1 and K2 in this experiment are 1.5% and 1.0% (Tab. 1).

Furthermore the method of 2-parameter measurement with the two current supply sources can be applied for semiconductor strain gauges. They have not only higher sensitivity than the metallic ones, but are more dependent on temperature. This kind of compensation could be replaced by 2-parameter measurement by the 2J-supply method with digital processing of their output signals.

The 2J supplied bridge circuits could be implemented to design different types of MEMS sensors. It will be the aim of further work by the author.

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