www.czasopisma.pan.pl PAN www.journals.pan.pl

INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2014, VOL. 60, NO. 4, PP. 327–330
Manuscript received September 14, 2014; revised December 2014. DOI: 10.2478/eletel-2014-0043

The Parameters of Unconventional Double-Current Circuit, their Accuracy Measures and Measurement of Strain and Temperature

Zygmunt Warsza, Adam Idzkowski, and Wojciech Walendziuk

***Abstract*—The two-voltage-output circuit called a double-current bridge is presented. A single DC current source is switched over and connected in turns to opposite arms of the four-element bridge circuit. The output voltages are dependent on the arm resistance increments and their values are given in absolute and relative units. The simplified signal conditioning formulas of strain and temperature simultaneous measurement of a cantilever beam are featured. The results achieved with the use of the circuit are also published.The accuracy measures (actual errors, limited errors and standard uncertainties) of the bridgetransfer functions are described.**

***Keywords*—electronics, measurement circuits**

I. Introduction

ONE of basic and well known measurement toolis Wheatstone bridge. This circuit, connected to additional integrated circuits such as analog-to-digital converter (ADC) or microprocessor systems provides great accuracy and speed of conducted measurement [3], [5]. Majority of DAQ systems are based on measuring one quantity. There is also a group of measurement methods which are used to measure several quantities at the same time [1], [4], [8], [9]. As an example it can bea system based on simultaneous measurement of two parameters of resistance increments in a four-terminal (4T) network [2], [7], [8]. Two types of circuits which realize such conditioning and analog signal measurement are presented in literature [9]. One of them is a circuit made up two four-arm classical (Wheatstone) bridges connected in cascade.

The authors of the article have not come across a work describing an accuracy analysis for two simultaneously measured parameters (2D). A description of the measurement accuracy with the use of the classical bridge circuit for one measured parameter (1D)was partly presented in previous work [10].There were shown two methods of describing measurement accuracy of the transfer coefficients of an unbalanced bridges. The general description of accuracy measures(actual errors, limited errors and standard uncertainties)may be useful for measurement systems constructors who use sensors of two different physical quantities (for example strain and temperature RTD sensors).

Z. Warsza is with Research Institute of Automation and Measurements PIAP, Al. Jerozolimskie 202, 02-486 Warszawa, Poland, (e-mail: zlw@op.pl).

A. Idzkowski and W. Walendziuk are with Bialystok University of Technology, Department of Electrical Engineering, Wiejska 45D str., 15-351 Bialystok, Poland, (e-mail: {a.idzkowski, w.walendziuk}@pb.edu.pl).

II. Unconventional Double-Current Circuit and the Parameters

The parameters of a double-current bridge are featured.

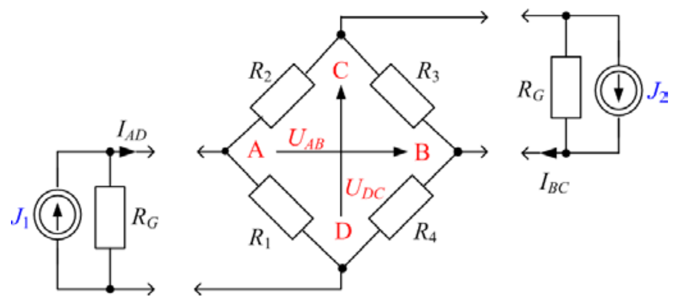


Fig. 1. Double-current bridge (2J) – idea of circuit

As shown in Fig. 1, power is deliveredby two equal current sources J=J_1=J_2 (R_G=∞). The output voltages of the bridge are:

$$U_{AB} = J\frac{R_1R_4 - R_2R_3}{\sum R_i} \equiv J\ r_{AB}(\varepsilon_i) \tag{1}$$

$$U_{DC} = J\frac{R_1R_2 - R_3R_4}{\sum R_i} \equiv J\ r_{DC}(\varepsilon_i) \tag{2}$$

where: $\sum R_i = R_1 + R_2 + R_3 + R_4, r_{DC}, r_{AB}$ - open-circuit voltage to current parameters of D-C and A-B outputs.Additionally, it is assumed that resistances R_i in the bridge are variables and are represented by equation [6]:

$$R_i = R_{i0}(1+\varepsilon_i) \tag{3}$$

where R_{i0} - initial (nominal) resistances, ε_i - relative increments of resistances (i=1, 2, 3, 4).

Bridge transfer functions (1), (2) can be simplified to products of their initial sensitivities t_0', t_0" in the balance and normalized unbalance functions $f'(\varepsilon_i)$, $f''(\varepsilon_i)$. Their formulas can be expressed by initial values R_{i0} and increments of all resistances, i.e.R_i=$R_{i0}(1+\varepsilon_i)$ and R_{i0} referencing to one of the first arm, i.e.: $R_{20} \equiv mR_{10}$, $R_{40} \equiv nR_{10}$ and $R_{30}' = (m/n)R_{10}$ or $R_{30}'' = (n/m)R_{10}$, as is shown in Table 1. It results from two balance states of this bridge-circuit.

If the sensors are situated in all arms of the bridge circuit and their resistances $R_{i0}$are equal and their resistance changes are small (thus $\varepsilon_i\varepsilon_j << \varepsilon_i + \varepsilon_j$ and $\Sigma R_{i0}\varepsilon_i << \Sigma R_{i0}$), the simplified version of the equations can be provided as follows:

$$U_{DC} = t_0''(\varepsilon_1 + \varepsilon_2 - \varepsilon_3 - \varepsilon_4) \tag{4}$$

$$U_{AB} = t_0'(\varepsilon_1 - \varepsilon_2 - \varepsilon_3 + \varepsilon_4) \tag{5}$$

TABLE 1
OPEN-CIRCUIT VOLTAGE TO CURRENT PARAMETERS IN FUNCTION OF RELATIVE INCREMENTS OF RESISTANCE

Circuit with arbitrary R_i	Open-circuit voltage to current parameters of A-B and D-C outputs (r_{AB}, r_{CD})	
In balance: $r_{AB0} = 0$ $R_{10} \cdot R_{40} = R_{20} \cdot R_{30}$ $R_{20}=mR_{10}, R_{40}=nR_{10}$ $R_{30}'=(m/n)R_{10}$ **or** $r_{CD0} = 0$ $R_{10} \cdot R_{20} = R_{30} \cdot R_{40}$ $R_{20}=mR_{10}, R_{40}=nR_{10}$ $R_{30}''=(n/m)R_{10}$	$r_{AB} \equiv \frac{U_{AB}}{J} = \frac{R_1R_4 - R_2R_3}{\sum R_i} \equiv t_0' f'(\varepsilon_i)$ (6) where: $t_0' \equiv \frac{m\,n R_{10}}{(m+n)(1+m)}$ $f'(\boldsymbol{\varepsilon}_i) = \frac{\Delta L'(\boldsymbol{\varepsilon}_i)}{1+\varepsilon'_{\Sigma R}}$ $\varepsilon'_{\Sigma R} = \frac{m(m\varepsilon_2+\varepsilon_1)+n(m\varepsilon_4+\varepsilon_3)}{(m+n)(1+m)}$ $\Delta L'(\varepsilon_i) = \varepsilon_1 - \varepsilon_2 - \varepsilon_3 + \varepsilon_4 + \varepsilon_1\varepsilon_4 - \varepsilon_2\varepsilon_3$	$r_{CD} \equiv \frac{U_{CD}}{J} = \frac{R_1R_2 - R_3R_4}{\sum R_i} \equiv t_0'' f''(\varepsilon_i)$ (7) where: $t_0'' \equiv \frac{m\,n R_{10}}{(m+n)(1+n)}$ $f''(\boldsymbol{\varepsilon}_i) = \frac{\Delta L''(\boldsymbol{\varepsilon}_i)}{1+\varepsilon''_{\Sigma R}}$ $\varepsilon''_{\Sigma R} = \frac{m(n\varepsilon_2+\varepsilon_3)+n(n\varepsilon_4+\varepsilon_1)}{(m+n)(1+n)}$ $\Delta L''(\varepsilon_i) = \varepsilon_1 + \varepsilon_2 - \varepsilon_3 - \varepsilon_4 + \varepsilon_1\varepsilon_2 - \varepsilon_3\varepsilon_4$

III. ACCURACY MEASURES

Assume that open-circuit voltage to current parameters r_{AB}, r_{CD}consist of two components. The parameters r_{AB0}, r_{DC0} are initial values and Δ_{rAB}, Δ_{rCD} are the increments of r_{AB}, r_{CD}:

$$r_{AB} = r_{AB0} + \Delta_{r\,AB} \tag{8}$$

$$r_{CD} = r_{CD0} + \Delta_{r\,CD} \tag{9}$$

Then one can modify equations (1) and (2) as follows:

$$U_{AB} = J(r_{AB0} + \Delta_{r\,AB}) \equiv U_{AB0} + J\,t_0'\,f'(\varepsilon_i) \tag{10}$$

$$U_{CD} = J(r_{CD0} + \Delta_{r\,CD}) \equiv U_{CD0} + J\,t_0''\,f''(\varepsilon_i) \tag{11}$$

Actual (absolute) errors of parameters r_{AB0} and r_{DC0} are related to initial sensitivities t_0', t_0". The relative errors δ_{rAB0}, δ_{rCD0} are the functions of algebraic sum of the initial (zero) errors of all the resistances [10]:

$$\delta_{rAB0} \equiv \frac{\Delta_{rAB0}}{t_0'} = \delta_{10} - \delta_{20} - \delta_{30} + \delta_{40} \tag{12}$$

$$\delta_{rCD0} \equiv \frac{\Delta_{rCD0}}{t_0''} = \delta_{10} + \delta_{20} - \delta_{30} - \delta_{40} \tag{13}$$

Actual relative errors δ_{Ri} of resistances can beexpressed by initial errors δ_{i0} and errors$\delta_{\varepsilon i}$ of their increments

$$\delta_i \equiv \frac{\Delta_i}{R_{i0}} = \delta_{i0}(1+\varepsilon_i) + \Delta_{\varepsilon i} = \delta_{i0}(1+\varepsilon_i) + \varepsilon_i\delta_{\varepsilon i} \tag{14}$$

$$\delta_{Ri} \equiv \frac{\Delta_i}{R_i} = \delta_{i0} + \frac{\Delta_{\varepsilon i}}{1+\varepsilon_i} = \delta_{i0} + \frac{\varepsilon_i}{1+\varepsilon_i}\delta_{\varepsilon i} \tag{15}$$

Actual (absolute) errors of parameters r_{AB} and r_{DC} are also related to initial sensitivities t_0', t_0":

$$\delta_{rAB} \equiv \frac{\Delta_{rAB}}{t_0'} \tag{16}$$

$$\delta_{rCD} \equiv \frac{\Delta_{rCD}}{t_0''} \tag{17}$$

Their equations are more complicated. Actual values of measurement errors of bridge transfer functionsr_{AB} and r_{CD}result from the total differential of analytical equations (6) and (7) from Table 1. After ordering all components of actual errors δ_{Ri} of resistances R_i one can estimateabsolute errors Δr_{AB}(20a) andΔr_{CD} (20b). Then with (14- 17) the following accuracy measures can be expressed:

- relative actual errors (21a) and (21b),
- relative limited errors (22a) and (22b),
- random (mean square) measures (23a) and (23b).

All the accuracy measures are ordered in Table 2.Additionally, actual errors of increments r_{AB}-r_{AB0} and r_{CD}-r_{CD0} are defined. They were related to r_{AB} and r_{CD}parameters as follows:

$$\delta_{rAB\,r} \equiv \frac{\Delta_{rAB} - \Delta_{rAB\,0}}{r_{AB}} = \frac{t_0'\delta_{rAB} - t_0'(\delta_{10} - \delta_{20} - \delta_{30} + \delta_{40})}{t_0' f'(\boldsymbol{\varepsilon}_i)} = \frac{\delta_{rAB} - (\delta_{10} - \delta_{20} - \delta_{30} + \delta_{40})}{f'(\boldsymbol{\varepsilon}_i)} \tag{18}$$

$$\delta_{rCD\,r} \equiv \frac{\Delta_{rCD} - \Delta_{rCD\,0}}{r_{CD}} = \frac{\delta_{rCD} - (\delta_{10} + \delta_{20} - \delta_{30} - \delta_{40})}{f''(\boldsymbol{\varepsilon}_i)} \tag{19}$$

Actual (26a, 26b, 28a, 28b) and limited (27a, 27b, 29a, 29b) relative errors for the circuit with two sensors (with two resistances R_1 and R_2 variable) is shown in Table 3. All of errors depend on the two increments ε_A and ε_B (what represent two measured quantities A and B). They are also the functions of δ_{i0} (zero errors) and $\delta_{\varepsilon i}$ (gain errors) of resistors and sensors. This is a novelty in presenting of the accuracy measures in two parameter (2D) measurement.

IV. TWO-PARAMETER MEASUREMENT OF STRAIN AND TEMPERATURE CHANGE

A prototype version was worked out in order to explain the concept of operation of a system measuring two parameters at the same time. The system shown in Fig. 2 can be applied to measure strain in one axis (e.g. x-axis by strain gauge R_1) and temperature (strain gauge or resistance thermometer R_2). This type of measurement system can be also applied to examine other quantities which can be measured with the use of resistance sensors(parametric).

Great advantage of thiscircuitis possibility of compensation of temperature influence on a measurement strain gauge resistance (without using additional temperature sensors). An indirect method, examining appropriate voltage on the diagonals of a double-current bridge makes possible tomeasure temperature and resistance of a strain gauge simultaneously.

TABLE 2

ACCURACY MEASURES OF THE VOLTAGE TO CURRENT PARAMETERS OF 2J BRIDGE IN GENERAL CASE

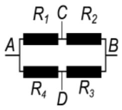
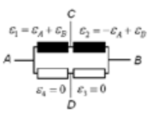
Parameters of circuit	Measure	Accuracy measures δ_{rAB}, $\lvert\delta_{rAB}\rvert$, $\bar{\delta}_{rAB}$ of r_{AB}	Accuracy measures δ_{rCD}, $\lvert\delta_{rCD}\rvert$, $\bar{\delta}_{rCD}$ of r_{CD}
General case	Actual errors: absolute and relative	$\Delta_{rAB}=R_1\frac{R_4-r_{AB}}{\Sigma R_i}\delta_{R1}-R_2\frac{R_3+r_{AB}}{\Sigma R_i}\delta_{R2}-R_3\frac{R_2+r_{AB}}{\Sigma R_i}\delta_{R3}+R_4\frac{R_1-r_{AB}}{\Sigma R_i}\delta_{R4}$ (20a)	$\Delta_{rCD}=R_1\frac{R_2-r_{CD}}{\Sigma R_i}\delta_{R1}+R_2\frac{R_1-r_{CD}}{\Sigma R_i}\delta_{R2}-R_3\frac{R_4+r_{CD}}{\Sigma R_i}\delta_{R3}-R_4\frac{R_3+r_{CD}}{\Sigma R_i}\delta_{R4}$ (20b)
		$\delta_{rAB}\equiv\frac{\Delta_{rAB}}{t_0'}=\sum_{i=1}^{4}w_{Ri}'\delta_{Ri}=\sum_{i=1}^{4}w_{Ri}'(\delta_{i0}+\frac{\varepsilon_i}{1+\varepsilon_i}\delta_{\varepsilon i})$ (21a) where: $w_{R1}'=\frac{1+\varepsilon_1}{1+\varepsilon'_{\Sigma R}}\left[(1+\varepsilon_4)-\frac{r_{AB}}{R_{40}}\right]$ $w_{R2}'=-\frac{1+\varepsilon_2}{1+\varepsilon'_{\Sigma R}}\left[(1+\varepsilon_3)+\frac{r_{AB}}{R_{30}}\right]$ $w_{R3}'=-\frac{1+\varepsilon_3}{1+\varepsilon'_{\Sigma R}}\left[(1+\varepsilon_2)+\frac{r_{AB}}{R_{20}}\right]$ $w_{R4}'=\frac{1+\varepsilon_4}{1+\varepsilon'_{\Sigma R}}\left[(1+\varepsilon_1)-\frac{r_{AB}}{R_{10}}\right]$	$\delta_{rCD}\equiv\frac{\Delta_{rCD}}{t_0''}=\sum_{i=1}^{4}w_{Ri}''\delta_{Ri}=\sum_{i=1}^{4}w_{Ri}''(\delta_{i0}+\frac{\varepsilon_i}{1+\varepsilon_i}\delta_{\varepsilon i})$ (21b) where: $w_{R1}''=\frac{1+\varepsilon_1}{1+\varepsilon''_{\Sigma R}}\left[(1+\varepsilon_2)-\frac{r_{CD}}{R_{40}}\right]$ $w_{R2}''=\frac{1+\varepsilon_2}{1+\varepsilon''_{\Sigma R}}\left[(1+\varepsilon_1)-\frac{r_{CD}}{R_{30}}\right]$ $w_{R3}''=-\frac{1+\varepsilon_3}{1+\varepsilon''_{\Sigma R}}\left[(1+\varepsilon_4)+\frac{r_{CD}}{R_{20}}\right]$ $w_{R4}''=-\frac{1+\varepsilon_4}{1+\varepsilon''_{\Sigma R}}\left[(1+\varepsilon_3)+\frac{r_{CD}}{R_{10}}\right]$
 $R_1=R_{10}(1+\varepsilon_1)R_2=R_{20}(1+\varepsilon_2)$ $R_3=R_{30}(1+\varepsilon_3)$ $R_4=R_{40}(1+\varepsilon_4)$ $\varepsilon_i\geq -1$	Limited errors	$\lvert\delta_{rAB}\rvert=\sum_{i=1}^{4}\lvert w_{Ri}'\rvert\ \lvert\delta_{Ri}\rvert=\sum_{i=1}^{4}\lvert w_{Ri}'\rvert\left(\lvert\delta_{i0}\rvert+\frac{\lvert\varepsilon_i\rvert}{1+\varepsilon_i}\lvert\delta_{\varepsilon i}\rvert\right)$ (22a)	$\lvert\delta_{rCD}\rvert=\sum_{i=1}^{4}\lvert w_{Ri}''\rvert\ \lvert\delta_{Ri}\rvert=\sum_{i=1}^{4}\lvert w_{Ri}''\rvert\left(\lvert\delta_{i0}\rvert+\frac{\lvert\varepsilon_i\rvert}{1+\varepsilon_i}\lvert\delta_{\varepsilon i}\rvert\right)$ (22b)
	Random measures	$\bar{\delta}_{rAB}=\sqrt{\sum_{i=1}^{4}w_{Ri}'^2\,\bar{\delta}_{Ri}^2}=\sqrt{\sum_{i=1}^{4}w_{Ri}'^2\left(\bar{\delta}_{i0}^2+\frac{\varepsilon_i^2}{(1+\varepsilon_i)^2}\bar{\delta}_{\varepsilon i}^2\right)}$ (23a) correlation coefficient $k_{ij}=0$	$\bar{\delta}_{rCD}=\sqrt{\sum_{i=1}^{4}w_{Ri}''^2\,\bar{\delta}_{Ri}^2}=\sqrt{\sum_{i=1}^{4}w_{Ri}''^2\left(\bar{\delta}_{i0}^2+\frac{\varepsilon_i^2}{(1+\varepsilon_i)^2}\bar{\delta}_{\varepsilon i}^2\right)}$ (23b) correlation coefficient $k_{ij}=0$
Measures for $r_{AB0}=0$	Actual errors	$\delta_{rAB0}=\delta_{10}-\delta_{20}-\delta_{30}+\delta_{40}$	Limited errors: $\lvert\delta_{rAB0}\rvert_m=\sum\lvert\delta_{i0}\rvert$ (24a); Mean square measures $k_{ij}=0$: $\bar{\delta}_{rAB0}=\sqrt{\sum\bar{\delta}_{i0}^2}$ (25a)
Measures for $r_{CD0}=0$	Actual errors	$\delta_{rCD0}=\delta_{10}+\delta_{20}-\delta_{30}-\delta_{40}$	Limited errors: $\lvert\delta_{rCD0}\rvert_m=\sum\lvert\delta_{i0}\rvert$ (24b); Mean square measures $k_{ij}=0$: $\bar{\delta}_{rCD0}=\sqrt{\sum\bar{\delta}_{i0}^2}$ (25b)

TABLE 3

ACCURACY MEASURES OF THE VOLTAGE TO CURRENT PARAMETERS OF 2J BRIDGE IF ALL ARM INITIAL RESISTANCES ARE EQUAL AND TWO INCREMENTS OF RESISTANCE VARIABLE

Parameters of circuit	Measures R_i	Related accuracy measures of bridge of r_{AB}, r_{CD}	
		related to initial sensitivities t_0' or t_0''	of increments r_{AB}-r_{AB0} and r_{CD}-r_{CD0}
ΔR_1 and ΔR_2 variable $\varepsilon_1=\varepsilon_A+\varepsilon_B$, $\varepsilon_2=-\varepsilon_A+\varepsilon_B$,	arbitrary	$\delta_{r\,AB}=\frac{4-2\varepsilon_A+6\varepsilon_B}{4(1+\varepsilon_B)}(\delta_{10}-\delta_{20}-\delta_{30})+\frac{4+2\varepsilon_A+6\varepsilon_B}{4(1+\varepsilon_B)}\delta_{40}+\frac{\varepsilon_A+\varepsilon_B}{1+\varepsilon_B}\delta_{\varepsilon1}+\frac{\varepsilon_A-\varepsilon_B}{1+\varepsilon_B}\delta_{\varepsilon2}$ (26a)	$\delta_{r\,ABr}=\frac{2+\varepsilon_B}{4\varepsilon_A}\left[\frac{3-2\varepsilon_A+6\varepsilon_B}{4(1+\varepsilon_B)}(\delta_{10}-\delta_{20}-\delta_{30})+\frac{3+2\varepsilon_A+6\varepsilon_B}{4(1+\varepsilon_B)}\delta_{40}+\frac{\varepsilon_A+\varepsilon_B}{1+\varepsilon_B}\delta_{\varepsilon1}+\frac{\varepsilon_A-\varepsilon_B}{1+\varepsilon_B}\delta_{\varepsilon2}\right]$ (26b)
$\varepsilon_3=0,\ \varepsilon_4=0,$ $\varepsilon_A{}^2\approx0,\ \varepsilon_B{}^2\approx0,$ $\varepsilon_A\,\varepsilon_B\approx0.$	if $\lvert\delta_{i0}\rvert=\lvert\delta_0\rvert$ $\lvert\delta_{\varepsilon1}\rvert=\lvert\delta_{\varepsilon2}\rvert\equiv\lvert\delta_\varepsilon\rvert$	$\lvert\delta_{r\,AB}\rvert=\frac{4+2\lvert\varepsilon_A\rvert+6\lvert\varepsilon_B\rvert}{1+\lvert\varepsilon_B\rvert}\lvert\delta_0\rvert+\frac{2(\lvert\varepsilon_A\rvert+\lvert\varepsilon_B\rvert)}{1+\lvert\varepsilon_B\rvert}\lvert\delta_\varepsilon\rvert$ (27a)	$\lvert\delta_{r\,ABr}\rvert=\frac{2+\lvert\varepsilon_B\rvert}{4\lvert\varepsilon_A\rvert}\left[\frac{3+2\lvert\varepsilon_A\rvert+6\lvert\varepsilon_B\rvert}{1+\lvert\varepsilon_B\rvert}\lvert\delta_0\rvert+\frac{2(\lvert\varepsilon_A\rvert+\lvert\varepsilon_B\rvert)}{1+\lvert\varepsilon_B\rvert}\lvert\delta_\varepsilon\rvert\right]$ (27b)
	arbitrary	$\delta_{rCD}=\frac{1+2\varepsilon_B}{1+\varepsilon_B}(\delta_{10}+\delta_{20})-(\delta_{30}+\delta_{40})+\frac{\varepsilon_A+\varepsilon_B}{1+\varepsilon_B}\delta_{\varepsilon1}+\frac{\varepsilon_B-\varepsilon_A}{1+\varepsilon_B}\delta_{\varepsilon2}$ (28a)	$\delta_{r\,CDr}=\frac{(2+\varepsilon_B)(\delta_{10}+\delta_{20})}{2(1+\varepsilon_B)}+\frac{2+\varepsilon_B}{4\varepsilon_B}\left[\frac{\varepsilon_A+\varepsilon_B}{1+\varepsilon_B}\delta_{\varepsilon1}+\frac{\varepsilon_B-\varepsilon_A}{1+\varepsilon_B}\delta_{\varepsilon2}\right]$ (28b)
$r_{AB}=\frac{R_{10}\ \varepsilon_A}{2+\varepsilon_B}$ $r_{CD}=\frac{R_{10}(2\varepsilon_B-\varepsilon_A^2+\varepsilon_B^2)}{4+2\varepsilon_B}$	if $\lvert\delta_{i0}\rvert=\lvert\delta_0\rvert$ $\lvert\delta_{\varepsilon1}\rvert=\lvert\delta_{\varepsilon2}\rvert\equiv\lvert\delta_\varepsilon\rvert$	$\lvert\delta_{r\,CD}\rvert=\frac{4+6\lvert\varepsilon_B\rvert}{1+\lvert\varepsilon_B\rvert}\lvert\delta_0\rvert+\frac{2(\lvert\varepsilon_A\rvert+\lvert\varepsilon_B\rvert)}{1+\lvert\varepsilon_B\rvert}\lvert\delta_\varepsilon\rvert$ (29a)	$\lvert\delta_{r\,CDr}\rvert=\frac{2+\lvert\varepsilon_B\rvert}{1+\lvert\varepsilon_B\rvert}\left[\lvert\delta_0\rvert+\frac{(\lvert\varepsilon_A\rvert+\lvert\varepsilon_B\rvert)}{2\lvert\varepsilon_B\rvert}\lvert\delta_\varepsilon\rvert\right]$ (29b)

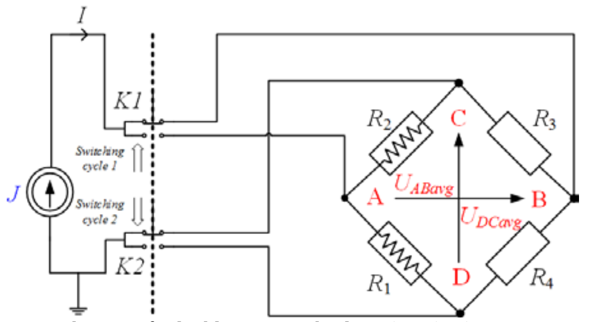


Fig. 2. Scheme of double-current bridge (2x1J) (J-current source, R_1, R_2 – sensors, R_3, R_4 – resistors, $K1$, $K2$ – electronic switches)

Itwas conductedan experimental test on the 2x1J circuit. The real change in temperature of strain gauges in the point of their placement and the mechanical stress (deflection of cantilever beam) wereexamined. The circuit was tested with two metal (foil) strain gauges. Both output voltages are the means of voltages measured in two cycles [2]:

$$U_{DCavg} = 0.5t_0''(\varepsilon_1 + \varepsilon_2) \tag{30}$$

$$U_{ABavg} = 0.5t_0'(\varepsilon_1 - \varepsilon_2) \tag{31}$$

In such a situation the resistance incrementsof strain gauges consists of two components: $\varepsilon_1 = \varepsilon_A + \varepsilon_B$, $\varepsilon_2 = -\varepsilon_A + \varepsilon_B$. The first one is resistance increment or decrement which is caused by bending force. The second one is the increment of temperature change ΔT.In a case of using two identical strain gauges in the circuit it will cause the same value and sign of the relative temperature increments.When one gauge is stretched (Fig. 3) and the other one iscompressed at the same time, the increments of the mechanical stress will have the opposite signs:

$$\varepsilon_1^{'}(\Delta T) = \varepsilon_2^{'}(\Delta T) = \varepsilon_B \tag{32}$$

$$\varepsilon_1^{''}(e_B) = -\varepsilon_2^{''}(e_B) = \varepsilon_A \tag{33}$$

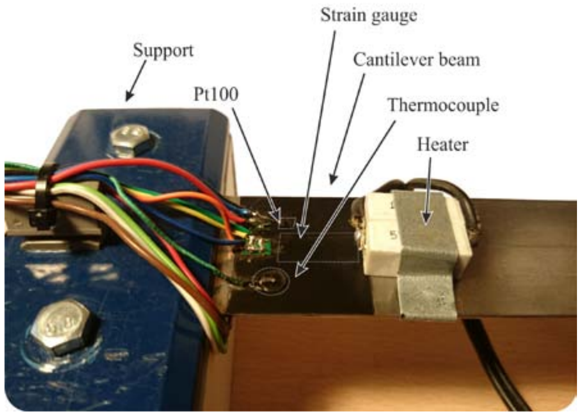


Fig. 3. Heater, strain gaugeand temperature sensorson cantilever beam.

For several (constant) temperatures of a cantilever beam (from 20°C until 60°C) the measurements were conducted.The reference temperature was 20°C and the beam was bentwith the use of micrometer screw in the range from 0 until 10 mm. As shown in Fig. 4there is a significant influence of rising temperature T on the $\varepsilon_i$intercept. The slope is almostidentical.

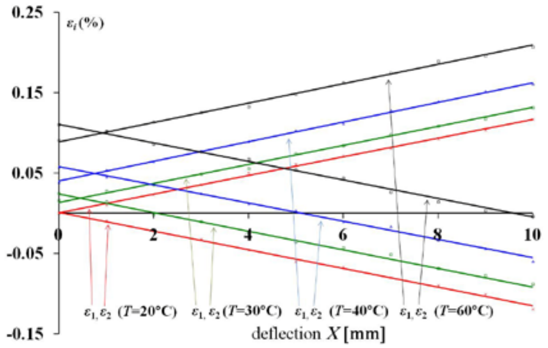


Fig. 4. The relative resistance increments ε_1, $\varepsilon_2$of strain gauges in the function of the beam deflection X,temperature Tisvariable.

V. Conclusions

The accuracy measures of parameters r_{AB} and r_{CD} are obtained after transformation of error propagation formulas. The two-component method [10] of the bridge transfer functionsgives accuracy representation separately for its initial value and for increment. It is similar like unified one used for digital instruments and sensor transducers (Table 2). The parameters r_{AB}, r_{CD} and their actual and limited errors as the functions of relative increments of resistance ε_i are shown for the bridge circuit with two sensorsR_1, R_2 (Table 3).The error formulas are presentedfor the measurement of two quantities (ε_1=ε_A+ε_B,ε_2=-ε_A+ε_B).

The application of this circuit in simultaneous measurement of strain and temperature change wasfeatured. The experiment confirmed that there was linear relationship between and deflection and relative resistance increments of strain gauges (Fig. 4).

References

[1] P. Cappa, F. Marinozzi, S.A. Sciuto, “A novel method for the simultaneous measurement of temperature and strain using a three-wire connection”, *Measurement Science and Technology*, vol. 12, no. 4, pp. 502-506, 2001.

[2] A. Idzkowski, J. Makal, Z. L. Warsza, “Simultaneous measurement of two parameters by double current supplied bridge”, *Journal of Automation, Mobile Robotics and Intelligent Systems*, vol. 6, no. 2, pp. 26-31, 2012.

[3] E. Sifuentes, O. Casas, F. Reverter, R. Pallas-Areny, “Direct interface circuit to linearise resistive sensor bridges”, *Sensors and Actuators A-physical*, vol. 147, pp. 210-215, 2008.

[4] A. R. Parker, “Simultaneous Measurement of Temperature and Strain Using Four Connecting Wires”, *NASA Technical Memorandum* 104271, 1993.

[5] P. H. Sydenham, R. Thorn, “Handbook of Measuring System Design”, John Wiley & Sons, Chapter 126: “Electrical Bridge Circuits – Basic Information” by Z. L. Warsza, New York, pp. 867–877, 2005.

[6] Z. L. Warsza, “Bridges Supplied by Two Current Sources–New Tool for Impedance Measurements and Signal Conditioning”, *Proc. of IMEKO-TC-7 Symposium*, pp. 231-236, 2002.

[7] Z. L. Warsza, “Four-Terminal (4-T) Immitance Circuits (4T) in Multivariable Measurements”, *Monograph of Industrial Institute of Control and Measurement PIAP*, Warsaw, 2004.

[8] Z. L. Warsza, “Two Parameter (2D) Measurements in Double – current Supply Four-terminal Resistance Circuits”, *Metrology and Measurement Systems, Polish Academy of Sciences*, vol. XIII, no. 1, pp. 49-65, 2006.

[9] Z. L. Warsza, “Backgrounds of two variable (2D) measurements of resistance increments by bridge cascade circuit”, *Proc. of SPIE*, vol. 6347, part 2, R63472, 2006.

[10] Z. L. Warsza, “New approach to the accuracy description of unbalanced bridge circuits with the example of pt sensor resistance bridges”, *Journal of Automation, Mobile Robotics and Intelligent Systems*, vol. 4, no. 2, pp. 8-15, 2010.