Experimental verification of the double-current supplied bridge circuit in 2D measurements of strain and temperature

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Abstract- *A four-terminal (4T) bridge circuit unconventionally supplied by two current sources connected in parallel to opposite arms, named double current bridge (2J) is presented. It has two different outputs from both diagonals. Their output voltages are described as functions of arm resistances and their increments from the bridge balance in relative units are given. Example of its application in two-parameter simultaneous (2D) measurements of the strain and temperature is presented. Formulas of their signals and details of the designed conditioning circuit are given. Some results of experimental verification of this instrumentation are shortly mentioned.*

I. Introduction

The majority of glue strain gauges used today is mainly resistive foil types. They are available in a wide choice of shapes and sizes to suit a variety of applications. As they are resistive elements, the sensitivity to temperature changes should be taken into consideration. This is a source of error that is compensated by special mounting the gauges upon a measuring beam [1]. Another method of temperature compensation is provided by simultaneously measuring both the temperature of the bridge and the primary output of the bridge transducer [2]. In X-ducer piezoresistive pressure bridge-sensors of Motorola [3] the compensation is effected by connecting a series or parallel resistor or thermistor-so called resistor parallel networks. Alternative bridge circuits for simultaneous measurements of two or more variables have been developed by the first author (presentations since 1998). The original leading idea is based on unconventional supply of four-arm bridge circuit by two current sources [4-6]. The common name for all of them **double current bridges**[1] was proposed with relevant symbols **2J, 2x2J** and **2x1J**. This paper deals with the application of the double current bridge 2x1J to simultaneous strain and temperature measurements by a single sensor set and also describes its advantages. The experimental test and numerical simulations of the circuit [7] was done in Białystok Technical University. In the next section, the concept of measurements and temperature compensation using two strain gauges plugged in Warsza double current bridge is described. Also, an errors analysis after sensor set replacing is mentioned.

II. Theoretical backgrounds

As stated above, double current bridge (Fig.1) differs from the Wheatstone bridge by using a different way of circuit supply which is quite easy to arrange [4]. Two equal current supply sources *J* are connected parallel to opposite arms (R_1, R_3). The bridge has two outputs: A-B and D-C. It may also be supplied by current source *J* (Fig. 2) switched over to the same arms just as in the previous circuit. The output voltages are measured and summed up in two cycles (the superposition theorem).

$$U_{AB} = U_{AB_1} + U_{AB_2} \tag{1}$$

$$U_{DC} = U_{DC_1} + U_{DC_2} \tag{2}$$

This way of supply causes compensation of thermoelectric voltages (of equal values) and independence of the direction of current *J*. Both circuit-bridges produce two output voltages (U_{DC} and U_{AB}) presented by (3) and (4).

[1] co-authors prefer to use the shorter, already common name - **Warsza bridges**

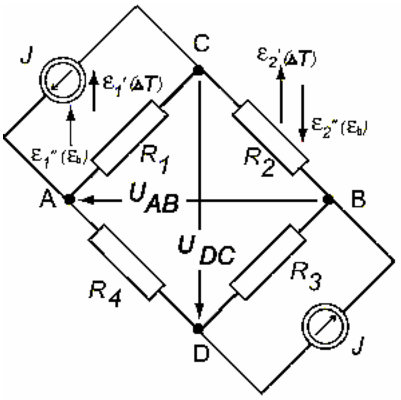

Fig. 1. Double current bridge circuit for temperature ΔT and bending strain ε_b measurements.

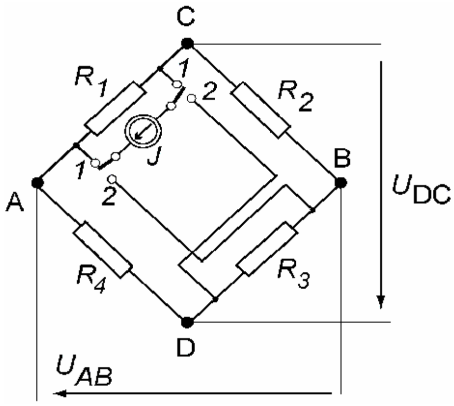

Fig. 2. Bridge circuit from Fig. 1 with the current source switched over [6].

$$U_{DC} = J\frac{R_1R_2 - R_3R_4}{\sum R_i} \equiv J\, t_{DC} \qquad (3)$$

$$U_{AB} = J\frac{R_1R_4 - R_2R_3}{\sum R_i} \equiv J\, t_{AB} \qquad (4)$$

where: t_{DC}, t_{AB} – open-circuit voltage to current transmittances of DC and AB outputs: $\Sigma R_i = R_1 + R_2 + R_3 + R_4$.
Assuming that:

$$R_1 = R_{10}\,(1+\varepsilon_1)\,,\ R_2 = m\,R_{20}\,(1+\varepsilon_2)\,,\ R_3 = R_{30}\,,\ R_4 = m\,R_{40}\,,$$

where: R_{i0} – nominal (initial) resistances (in this application $R_{10}=R_{20}=R_{30}=R_{40}$) and ε_i – relative increments of resistances,

If absolute incremental values $|\varepsilon_1|$, $|\varepsilon_2|$, are small enough, i.e. $|\varepsilon_1\varepsilon_2| << |\varepsilon_1+\varepsilon_2|$ and $|\varepsilon_1 + m\varepsilon_2| << 2(1+m)$, or $|\Delta R_1 + \Delta R_2| << 2(R_{10} + R_{20})$, the formulas are simplified to:

$$U_{DC} = J\frac{mR_{10}}{2(1+m)}(\varepsilon_1+\varepsilon_2) = T_0\,(\varepsilon_1+\varepsilon_2)\,, \qquad (5)$$

$$U_{AB} = J\frac{mR_{10}}{2(1+m)} = T_0\,(\varepsilon_1-\varepsilon_2)\,. \qquad (6)$$

where:

$T_0 = J\dfrac{mR_{10}}{2\,(1+m)}$ - the initial voltage sensitivity (equal for both outputs $T_0 = 0.25J\ R$ for $m = 1$).

The output voltage U_{DC} is proportional to the sum and the other one U_{AB} to the difference of increments. Hence the increments can be a function of two output voltages:

$$\varepsilon_1 = \frac{m+1}{m}\ \frac{U_{DC}+U_{AB}}{JR_{10}}\,, \qquad (7)$$

$$\varepsilon_2 = \frac{m+1}{m}\ \frac{U_{DC}-U_{AB}}{JR_{10}}\,. \qquad (8)$$

This circuit can be applied for measuring techniques of strain gauges. The resistance increments of strain gauges consist of two components ($\varepsilon_1 = \varepsilon' + \varepsilon''$, $\varepsilon_2 = \varepsilon' - \varepsilon''$, respectively). The first one is the temperature increment (9), the second one is due to mechanical stress (10). If there are two identical strain gauges, the temperature increments are of the same value and of the same sign. Additionally, if strain gauges are glued to a beam such that the first gauge is stretched and the other compressed then the increments due to mechanical stress are of the opposite signs.

$$\varepsilon_1'(\Delta T) = \varepsilon_2'(\Delta T) = \varepsilon' \qquad (9)$$

$$\varepsilon_1''(\varepsilon_b) = -\,\varepsilon_2''(\varepsilon_b) = \varepsilon'' \qquad (10)$$

The increments are linear for both measured quantities, i.e. $\varepsilon'(\Delta T) = \alpha\ \Delta T;\ \varepsilon''(\varepsilon_b) = k\ \varepsilon_b$ (where: α_T – temperature coefficient of resistance, ΔT – change of temperature, k – strain gauge factor, ε_b – bending strain).
The both measuring quantities depend on (13, 14) voltages U_{AB} and U_{CD}, supplying current J and the parameters of the gauges (R_{10} - nominal resistance, $k_0 = k\,/\,(1+\alpha_K\ \Delta T)$ – nominal gauge factor, α_K - temperature variation of gauge factor).

$$\Delta T = \frac{(1+m)U_{DC}}{m\,J\,R_{10}\,\alpha_T} \qquad (13) \qquad \varepsilon_b = \frac{(1+m)U_{AB}\,\alpha_T}{m\,J\,R_{10}\,k_0\,\alpha_T + (1+m)U_{DC}\,\alpha_K} \qquad (14)$$

This feature is an advantage of the circuit and it cannot be achieved in classic bridges [8,9].

III. Experimental verification

The theoretical considerations have been verified by experiment. The switched current source has been realised with the use of four MOSFET transistor keys (STP20NE06L) which are characterised by low on-resistance R_{ON}=0.06Ω. The transistors work in pairs – two switched on and two switched off at the same time. Their state of work is controlled by port of Atmega16 microcontroller. The voltages U_{AB} and U_{DC} are connected to the inputs of post-conditioning module which consists of instrumentation amplifiers (AD620AN) and then to 24-bit sigma-delta A/D converter (AD7718). The data processing of the acquired voltages from the circuit outputs is effected by the microcontroller.

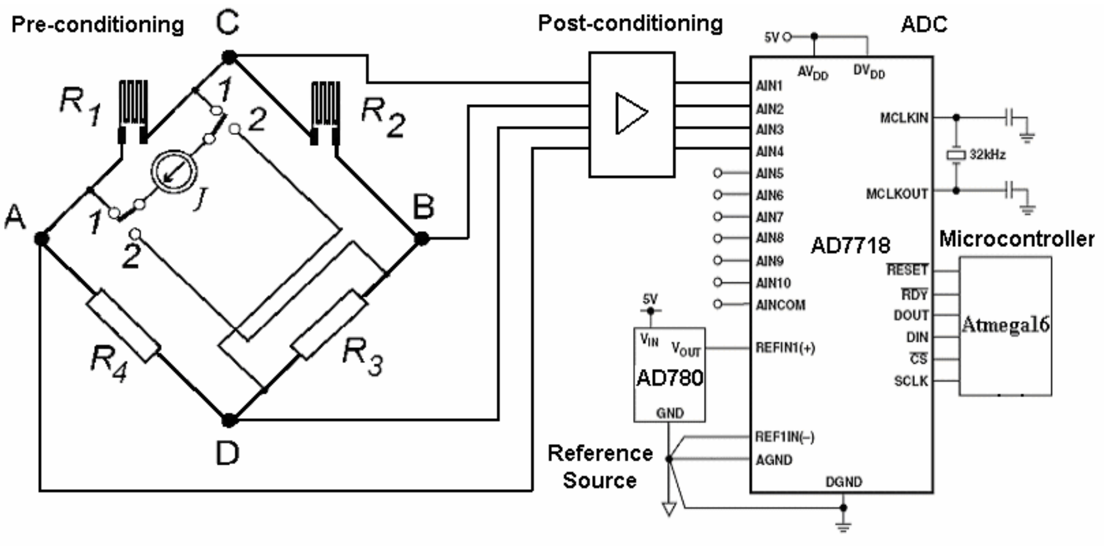

Fig. 3 General scheme (R_1, R_2 – strain gauges, J – current source (LM317))

Constantan foil strain gauges were placed on the beam as shown in Fig. 4. The measurements were taken for four temperatures of a cantilever beam (from 22°C until 62°C) while the beam was bent by a micrometer screw.

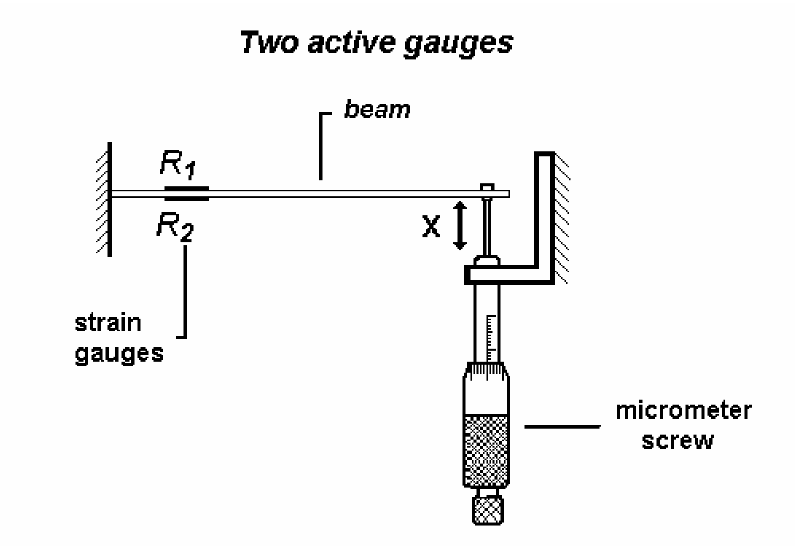

Fig. 4 Strain gauges glued to cantilever beam made of steel (rectangle cross-section, width 20 mm, height 0.8mm, length 200mm, the distance from place of fixing 20mm)

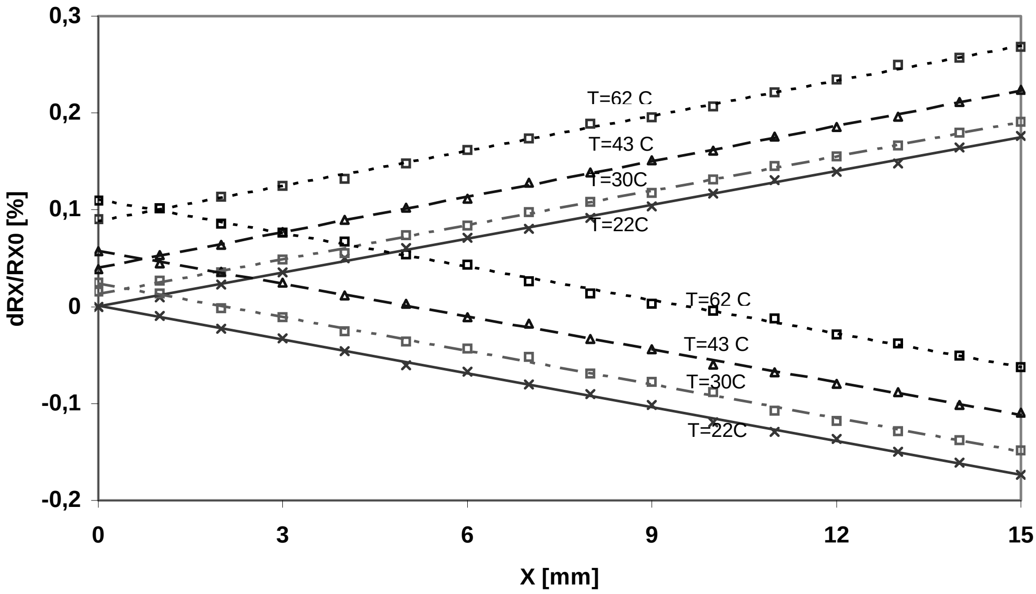

Fig. 5 Relative increments of resistance of both strain gauge*s* in function of beam deflection X in different temperatures

The results of the experiment are shown in Fig. 5. It presents the charts of relative resistance increments (strain) of both strain gauges in the function of deflection X of the beam. The temperature has a significant influence on the value of strains and causes an offset (approximately 0.1% for temperature change ΔT= 40˚C). If the value of this offset is known the temperature effect can be easily corrected by microprocessor software.
The regression lines presented above are defined by following equations:

$$\varepsilon_1(22)= 0.0016\,X + 0.0003 \tag{15}$$

$$\varepsilon_2(22)= -0.0016\,X + 0.0008 \tag{16}$$

$$\varepsilon_1(62)= 0.0121\,X + 0.0886 \tag{17}$$

$$\varepsilon_2(62)= -0.0115\,X + 0.1106 \tag{18}$$

For all lines the value of coefficient of determination R^2 is 0.998. The results of repeatability of resistance measurements (mean of 10 measurements which were taken every 1 minute) are presented in Table 1.

Table 1 Repeatability of measurements

	T=43°*C*, X=5 *mm*	
	R_1 [Ω]	R_2 [Ω]
Mean	121.7483	122.1548
Sample standard deviation	0.0041	0.0022

If sensors of the same type but different parameters are used in industrial measurements then it influences on measurement readings. So, it is necessary to perform error analysis of two transmittances (3) and (4). To present the impact of the parameter variety on reading values, the maximum transmittance errors have been calculated:

$$\left|\Delta t_{DC}\right| = \frac{R_{10}}{2(1+\varepsilon'')}\left[\sum\left|\delta_{i0}\right| - \left((\varepsilon')^2 + \varepsilon' - (\varepsilon'')^2\right)\left(\left|\delta_{10}\right| + \left|\delta_{20}\right| + \left|\delta_{\varepsilon 1}\right| + \left|\delta_{\varepsilon 2}\right|\right) + \varepsilon'\left(\left|\delta_{10}\right| + \left|\delta_{20}\right|\right) + \varepsilon''\left(\left|\delta_{\varepsilon 1}\right| - \left|\delta_{\varepsilon 2}\right|\right)\right] \tag{19}$$

$$|\Delta t_{AB}| = \frac{R_{10}}{2(1+\varepsilon'')}\left[\sum|\delta_{i0}| + \varepsilon'(\sum|\delta_{i0}| + |\delta_{\varepsilon 1}| + |\delta_{\varepsilon 2}|) + \varepsilon''(|\delta_{AB0}| + |\delta_{\varepsilon 1}| - |\delta_{\varepsilon 2}|)\right] \quad (20)$$

where:
δ_{i0} – maximum error of nominal resistance R_{i0}, $i = 1,2,3,4$,
$\delta_{\varepsilon i}$ – maximum error of gauge resistance increment (ε_i), $i = 1,2$,
δ_{AB0} - zero error ($\delta_{10}+\delta_{40}-\delta_{20}-\delta_{30}$).
The errors depend on the values of gauge resistance increments ε' and ε''. Component δ_{AB0} in (20) can be eliminated by internal zero adjustment.

IV. Conclusions

This experimental simulation confirms that the Warsza idea of the double current supply 4T circuits is a valuable supplement for well-known techniques of conditioning of analogue signals. As shown in Fig. 5 relative increments of resistance of both strain gauge*s* are linear in a function of beam deflection. There is not needed additional hardware or software linearization. In this application double current bridge can be competitive with respect to other circuits and its advantages are as follows:

- two output voltages depend on two measuring quantities, e.g. strain (stress) and gauge temperature, respectively,
- temperature reading and compensation in whole measuring span are done without using any additional sensor (thermistor or thermistor-resistor parallel networks [2-3]).

The repeatability of the measurements is promising and strictly depends on quality of a current source (in this work the low-cost circuit LM317 was used).
The method of 2D measurement with supplying from double current sources can be also applied for semiconductor strain gauges. In Micro-Electro-Mechanical Systems (MEMS) mechanical elements and electronics are integrated. The electronics process the information derived from the sensors. The sensors are typical piezoresistive elements connected in Wheatstone bridge or any other circuit. In case of force, stress, pressure measurements the mechanical elements are constructed as specially designed cantilever beams.
The piezoresistive strain gauges have not only higher sensitivity in comparison to metallic ones, but in the same time are also more dependent to the temperature. As an example: the piezoresistive 4T pressure sensors named X-ducers™ [3], made by electron technology together with semiconductor membrane, have span and offset calibration and temperature compensation.

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