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Unconventional Double-Current Circuit for Deflection and Temperature Simultaneous Measurement

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***Abstract*—In this paper some interesting and novel features of a four-terminal (4T) network are presented. A single DC current source (J) is switched over and connected in turns to opposite arms of the four-element bridge circuit. This two-output circuit with two voltage outputs is called a double current circuit (2x1J). The output voltages are differently dependent on the arm resistance increments and their values are given in absolute and relative units. An original application with two sensors acting as strain gauges and RTD's is presented. Signal conditioning formulas of 2D measurement of deflection and temperature of a cantilever beam are discussed in detail. Some results achieved with the use of the circuit are presented, as well.**

***Index Terms*—Error analysis, sensor systems, strain control, thermal analysis.**

I. INTRODUCTION

Wheatstone's bridge is one of basic and well known measurement tool. This circuit, equipped with additional elements of modern technology such as analog-to-digital converter (ADC) or microprocessor systems provides great accuracy and speed of continuous measurement [1]. Moreover, the result of measurements can be approximated to the value expected if proper programming techniques (including statistical methods) are applied [2]. Despite of such progress, in commonly done measurements such as strain, pressure, force, torque etc., metrological properties of parts of analog measurement circuit are vital.

Most of those systems are based on measuring one quantity [3], [4]. However, a group of measurement methods which are used to measure several quantities at the same time is also worth noticing [5]–[8]. A system measuring immittance variation, based on simultaneous measurement of two parameters of resistance increments in a four-terminal (4T) network, can be an example [9].

According to the authors' knowledge, the proposed circuit and its application (measurement of two quantities) is a novelty. This solution (with a double differential sensor) is another way of controlling (or compensation) the temperature change on strain measurement.

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II. MEASUREMENT OF TWO VARIABLES

A solution where two current sources are switched over among appropriate arms of the circuit (2J), or only one source is switched over (2x1J), is applied in practical realization of such system. Theoretical description and the principle of operation of the systems mentioned above can be found in [7], [9]. Both systems are called double-current bridges [10].

In order to illustrate the concept of operation of a system measuring two parameters at the same time, a prototype version was worked out. The system presented in Fig. 1 can be used to examine strain in one axis (e.g. x-axis by strain gauge R_1) and temperature (strain gauge or resistance thermometer R_2). Simultaneous measurement of strain in two axes (e.g. x-axis strain gauge R_1, y-axis strain gauge R_2) is another possibility. This type of measurement system can be also applied to measure other quantities which can be measured with the use of resistance parametric sensors.

Possibility of compensation of temperature influence on a measurement strain gauge resistance (without using additional temperature sensors) is also great advantage of such solution. It can be achieved through simultaneous measurement of temperature and resistance of a strain gauge by indirect method, examining appropriate voltage on the diagonals of a double-current bridge.

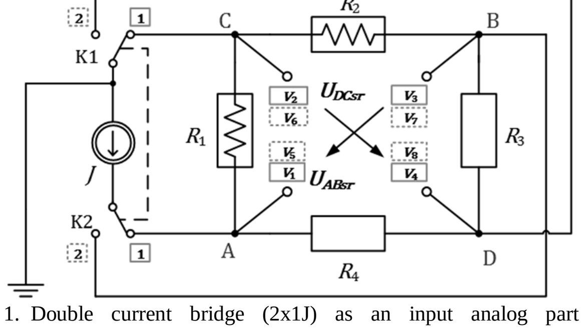

Fig. 1. Double current bridge (2x1J) as an input analog part of measurement system (J-current source, R_1, R_2 – sensors, R_3, R_4 – resistors, K1, K2 – electronic switches).

As shown in Fig. 1, the electronic switches K1, K2 work simultaneously in pairs. Two of them are switched on while the other two – switched off. They are controlled by a microprocessor. Then the output voltages U_{ABsr} and U_{DCsr} are connected to ADC via conditioning module (Fig. 2). It is built of instrumentation amplifiers (AD620AN) and ultra-precision voltage-dividers (MAX5491). This type of voltage-divider is used because of 24-bit Σ-Δ ADC (AD7718) requirement for positive sign voltages of (056 V–2.56 V) [10].

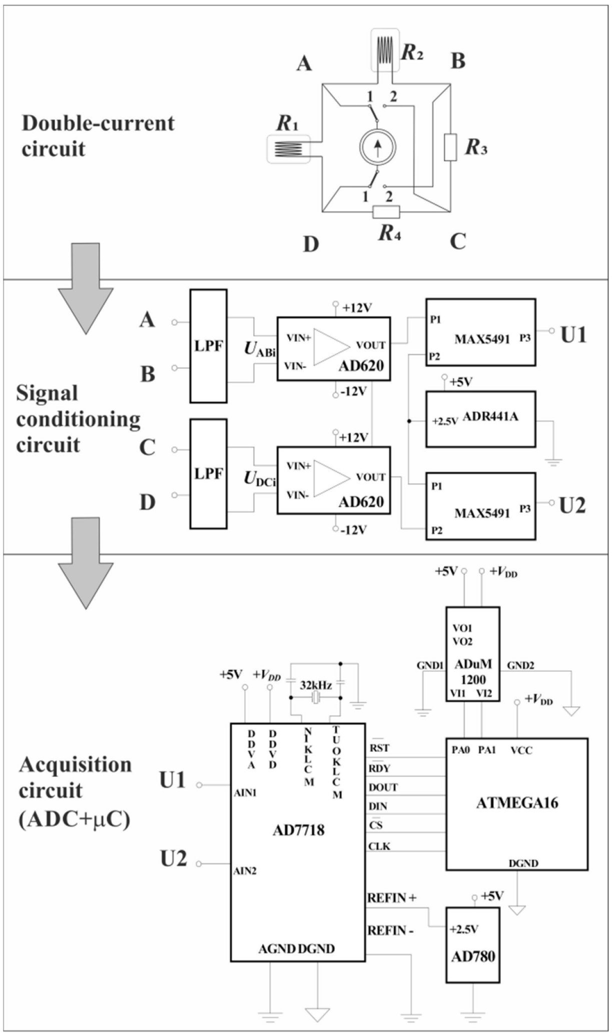

Fig. 2. Double current bridge for measurement of two variables [10].

III. Double Current Bridge as Two-Output Resistance to Voltage Converter

In this section, the simple relations in a double current bridge are described.

A. Output Voltages of 2J bridge and their Dependence on the Increments of Resistance

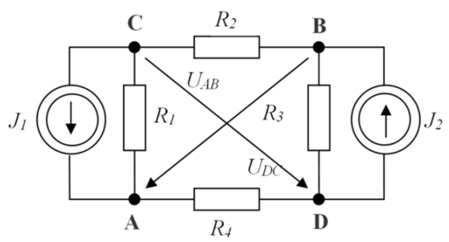

Fig. 3. Double current bridge (2J) – theoretical circuit [7].

As shown in Fig. 3, a double current bridge is supplied by two equal current sources $J = J_1 = J_2$. The output voltages of the bridge are:

$$U_{DC} = J\frac{R_1R_2 - R_3R_4}{\Sigma R_i} \equiv J^2{}_{DC}\left(\varepsilon_i\right), \tag{1}$$

$$U_{AB} = J\frac{R_1R_4 - R_2R_3}{\Sigma R_i} \equiv J^2{}_{AB}\left(\varepsilon_i\right), \tag{2}$$

where $\sum R_i = R_1 + R_2 + R_3 + R_4, {}^2{}_{DC}, {}^2{}_{AB}$ – open-circuit voltage to current parameters of D-C and A-B outputs.

In further analysis, it is assumed that resistances R_i in the bridge are variables and are represented by equation

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

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

After separation of the relative resistance increments ε_i, (1) and (2) of unbalanced bridge are:

$$U_{DC} = U_{0DC}\frac{\varepsilon_1+\varepsilon_2-\varepsilon_3-\varepsilon_4+\varepsilon_1\varepsilon_2-\varepsilon_3\varepsilon_4}{1+\dfrac{\Sigma R_{i0}\varepsilon_i}{\Sigma R_{i0}}}, \tag{4}$$

$$U_{AB} = U_{0AB}\frac{\varepsilon_1-\varepsilon_2-\varepsilon_3+\varepsilon_4+\varepsilon_1\varepsilon_4-\varepsilon_2\varepsilon_3}{1+\dfrac{\Sigma R_{i0}\varepsilon_i}{\Sigma R_{i0}}}, \tag{5}$$

where $U_{0AB} = U_{0DC} = JR_{10}R_{20} / \sum R_{i0}$ are initial voltages of the circuit.

If the sensors are situated in all arms of the bridge circuit and their nominal resistances are equal (R_{10}) 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:

$$U_{DC} = U_0(\varepsilon_1+\varepsilon_2-\varepsilon_3-\varepsilon_4), \tag{6}$$

$$U_{AB} = U_0(\varepsilon_1-\varepsilon_2-\varepsilon_3+\varepsilon_4). \tag{7}$$

B. Output Voltages of 2x1J Circuit and their Dependence on the Increments Resistance

In Fig. 3 two equal current supply sources J are connected in parallel to opposite arms (R_1, R_3). There are two outputs of the bridge: A-B and D-C. In practice it is supplied by one current source J switched over to the same arms, similarly as in the previous circuit (Fig. 1). Then, the measurement of output voltages is conducted subsequently:

$$\begin{cases} U_{AB1} = V_1 - V_3, \\ U_{DC1} = V_4 - V_2, \end{cases} \tag{8}$$

$$\begin{cases} U_{AB2} = V_5 - V_7, \\ U_{DC2} = V_8 - V_6. \end{cases} \tag{9}$$

Subsequently, they are averaged:

$$U_{DCsr} = 0.5(U_{DC1} + U_{DC2}), \tag{10}$$

$$U_{ABsr} = 0.5(U_{AB1} + U_{AB2}). \tag{11}$$

The equations for small relative resistance increments ε_i can be formed as follows:

$$U_{DCsr} = 0.5U_0(\varepsilon_1 + \varepsilon_2 - \varepsilon_3 - \varepsilon_4), \tag{12}$$

$$U_{ABsr} = 0.5U_0(\varepsilon_1 - \varepsilon_2 - \varepsilon_3 + \varepsilon_4). \tag{13}$$

It is observed that voltages U_{DCsr}, U_{ABsr} equally depend on relative changes (ε_1 - ε_3) and with inverse sign (ε_2 - ε_4). An example of this bridge-circuit application for two-parameter measurement is presented in the following sections.

IV. Two-Parameter Measurement of Deflection and Temperature with the Use of 2x1J Circuit

The experimental test on the 2x1J circuit was made. The goal was to measure the real change in temperature of strain gauges in the point of sensor placement and the mechanical stress (deflection of cantilever beam). The circuit was tested with two metal (foil) strain gauges TF-3/120 (Tenmex).

A. The Influence of Stress and Temperature Change on the Resistance of Two Strain Gauges

Assuming that there are only two strain gauges in adjoining arms, the resistances of other elements are: $R_3 = R_{30}$, $R_4 = R_{40}$ (which is tantamount to $\varepsilon_3 = \varepsilon_4 = 0$). If modules of the values $|\varepsilon_1|$, $|\varepsilon_2|$ are small enough, (6) and (7) are simplified to:

$$U_{DCsr} = 0.5U_0(\varepsilon_1 + \varepsilon_2), \tag{14}$$

$$U_{ABsr} = 0.5U_0(\varepsilon_1 - \varepsilon_2). \tag{15}$$

The changes in resistance of strain gauges consist of two components: $\varepsilon_1 = \varepsilon' + \varepsilon''$, $\varepsilon_2 = \varepsilon' - \varepsilon''$, respectively. One of them is the increment of temperature change ΔT (16), the other one is the increment (or decrement) of mechanical stress caused by bending force F_B (17). Using two identical strain gauges in a bridge, indicates the same sign and value of the relative increments in temperature. If one gauge is compressed (Fig. 4) and the other one is stretched at the same time, the increments of the mechanical stress have the opposite signs:

$$\varepsilon_1'(\Delta T) = \varepsilon_2'(\Delta T) = \varepsilon', \tag{16}$$

$$\varepsilon_1''(\varepsilon_B) = -\varepsilon_2''(\varepsilon_B) = \varepsilon''. \tag{17}$$

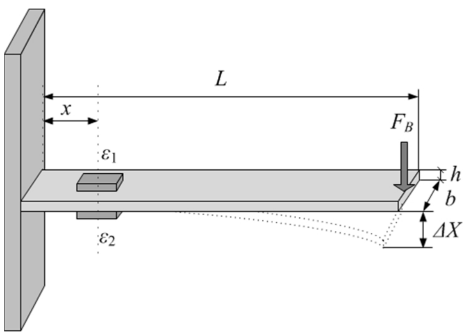

Fig. 4. Two metal strain gauges placed on the cantilever beam. The beam is bent by force F_B and heated in the same time.

After converting (14)–(17), it can be noticed that the output voltages U_{DCsr} and U_{ABsr} depend linearly and separately on both determined quantities:

$$U_{DCsr} = U_0\varepsilon', \tag{18}$$

$$U_{ABsr} = U_0\varepsilon''. \tag{19}$$

Changes in resistance can be considered as linear for both determined quantities, i.e.: $\varepsilon' = \alpha_T \Delta T$, $\varepsilon'' = k\,\varepsilon_B$, where: ΔT – change of temperature, k – gauge factor which is connected with sensitivity to strain, ε_B – bending strain α_T – the temperature coefficient of gauge's resistance. After converting (18) and (19), a change of temperature is proportional to output voltage U_{DCsr} (K_1 – calibration factor)

$$\Delta T = K_1 \frac{U_{DCsr}}{\alpha_T U_0}. \tag{20}$$

Also bending strain ε_B is linear function of the output voltage U_{ABsr}, where K_2 – calibration factor

$$\varepsilon_B = K_2 \frac{U_{ABsr}}{kU_0}. \tag{21}$$

Knowing geometrical parameters of the cantilever beam (L – length, b – width, h – height of cross section), the distance from the strain gauge to a clamp x (Fig. 4) and modulus of elasticity E, one can estimate a change of deflection ΔX at force point F_B

$$\Delta X = \frac{2F_B x^2 (3L - x)}{Ebh^3}. \tag{22}$$

A linear relationship between bending force F_B and strain ε_B applies in the elastic range.

B. The Results of Experiment with Bending and Heating the Beam

The measurements were taken for several (constant) temperatures of a cantilever beam (20 °C, 30 °C, 40 °C, 60 °C) while the beam was bent with the use of micrometer screw in the range from 0 mm until 10 mm (Fig. 5).

Fig. 5. Micrometer screw for bending the steel beam with mounted: heater, temperature sensor (Pt100) and two strain gauges.

Figure 6 presents the results of the experiment. The reference temperature is 20 °C. There is a significant influence of rising temperature T on the ε_i intercept. The slope is nearly the same.

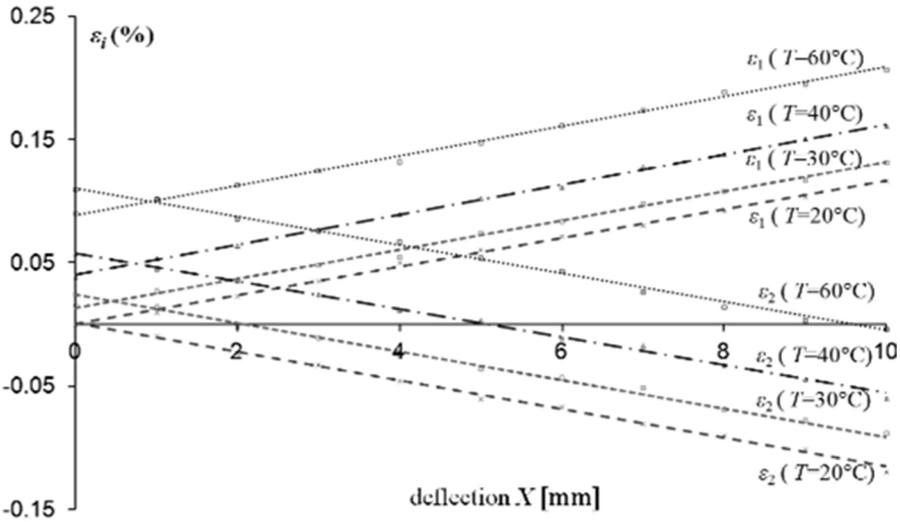

Fig. 6. The relative resistance increments ε_1, ε_2 in the function of the beam *X* deflection while temperature *T* is changing.

V. Temperature Measurements

Heating of a beam in the temperature range 20 °C–60 °C was done with the use of a resistance heater (Fig. 7).

Temperature was measured by three devices. In Table I there are three temperature results T_1, T_2 and T. Temperature T_1 was calculated on the basis of resistance of RTD (Pt100) sensor. Temperature T_2 was read from NEC IR camera.

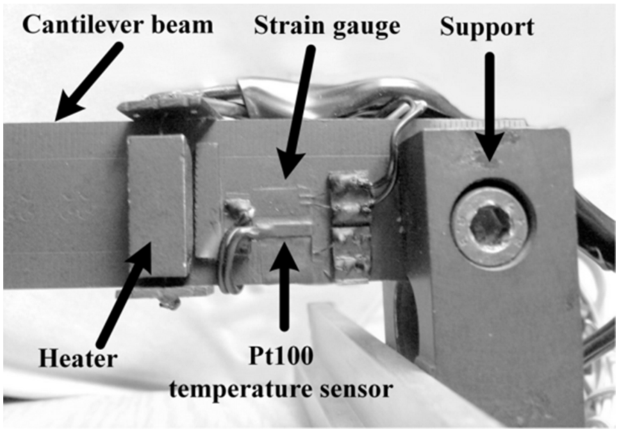

Fig. 7. Localization of heater, RTD sensor and strain gauge.

Temperature *T* was the result from 2x1J circuit (after calibration). In measuring span 20 °C–60 °C the differences in temperature were not higher than ±1.8 °C.

TABLE I. TEMPERATURE MEASUREMENTS AND THEIR DIFFERENCES.

T1 (Pt100)	T2 (IR NEC)	T1 - T2	T (2x1J)	T1 - T
°C	°C	°C	°C	°C
21.0	22.0	-1.0	20.5	0.4
24.0	25.4	-1.4	22.9	1.1
30.7	32.5	-1.8	31.5	-0.8
37.6	39.1	-1.5	37.0	0.6
43.0	43.8	-0.8	43.4	-0.4
46.8	47.6	-0.8	45.6	1.2
49.5	49.9	-0.4	48.9	0.7
54.3	54.9	-0.6	55.6	-1.3
56.6	56.5	0.1	56.2	0.4

Infrared thermal image of heater and temperature distribution on the beam is presented in Fig. 8. One can see the temperature was read (with emissivity 0.95) in the strain gauge localization.

Fig. 8. Temperature distribution on the beam and a measurement in the strain gauge localization (heater was hidden in order to better illustrate temperature distribution around a strain gauge).

Heating curve of the beam in the strain gauge localization is shown in Fig. 9.

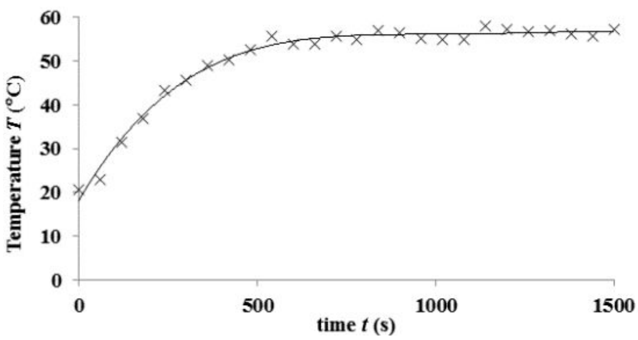

Fig. 9. The heating curve of the beam.

Heating curve of the beam in the strain gauge localization is shown in Fig. 9.

VI. Conclusions

The 2x1J circuit can measure simultaneously a mechanical strain and the change of temperature of strain gauges in a specific localization. The innovation of this method concerns the following issues:

– unconventional supplying by a current source (Fig. 1),

– continuous conditioning of analogue voltages on two diagonals of a four-resistor bridge (Fig. 2),

– measuring temperature and strain (deflection of a beam) with an RTD (Resistance Temperature Device),

– applying a double differential sensor (Fig. 4), instead of using a single one [5] and a thermocouple [6].

The tests confirmed that there is linear relationship between and deflection and relative resistance increments of strain gauges (Fig. 6). The error of measured temperature in the range 20 °C–60 °C was not higher than ±1.8 °C (Table I).

Some additional work to define the accuracy measures of the open-circuit voltage to current parameters (τ_{AB}, τ_{DC}) is planned further on the basis of paper [11].

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