Unconventional Double-Current Circuit for Deflection and Temperature Simultaneous Measurement

Adam Idzkowski¹, Wojciech Walendziuk¹, Zygmunt Lech Warsza²
¹Department of Electrical Engineering, Bialystok University of Technology, Wiejska 45D St., 15-351 Bialystok, Poland
²Research Institute of Automation and Measurements PIAP, Al. Jerozolimskie 202, 02-486 Warszawa, Poland
a.idzkowski@pb.edu.pl

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.

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 R₁) and temperature (strain gauge or resistance thermometer R₂). Simultaneous measurement of strain in two axes (e.g. x-axis strain gauge R₁, y-axis strain gauge R₂) 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.

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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 \( U_{AB\text{sr}} \) and \( U_{DC\text{sr}} \) 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 \( \Sigma-\Delta \) ADC (AD7718) requirement for positive sign voltages of (0.56 V – 2.56 V) [10].

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

\[
U_{DC} = J \frac{R_1 R_3 - R_2 R_4}{\Sigma R_i} = J \tau_{DC} (e_i),
\]

\[
U_{AB} = J \frac{R_1 R_2 - R_3 R_4}{\Sigma R_i} = J \tau_{AB} (e_i),
\]

where \( \Sigma R_i = R_1 + R_2 + R_3 + R_4 \), \( \tau_{DC}, \tau_{AB} \) – 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

\[
R_i = R_i^0 (1 + \epsilon_i),
\]

where \( R_i^0 \) – initial (nominal) resistances, \( \epsilon_i \) - relative increments of resistances \((i = 1, 2, 3, 4)\).

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

\[
U_{DC} = U_{0\text{DC}} (1 + \epsilon_1 + \epsilon_2 - \epsilon_3 - \epsilon_4),
\]

\[
U_{AB} = U_{0\text{AB}} (-\epsilon_1 - \epsilon_2 + \epsilon_3 + \epsilon_4 - \epsilon_2 - \epsilon_3),
\]

where \( U_{0\text{DC}} = \sum R_{i0} e_i \) are initial voltages of the circuit.

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

\[
U_{DC} = U_0 (1 + \epsilon_1 - \epsilon_3 - \epsilon_4),
\]

\[
U_{AB} = U_0 (1 - \epsilon_1 - \epsilon_3 + \epsilon_4).
\]

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

In Fig. 3 two equal current supply sources \( J = J_1 = J_2 \) are connected in parallel to opposite arms \((R_1, R_2)\). 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:

\[
\begin{align*}
U_{AB1} &= V_1 - V_3, \\
U_{DC1} &= V_4 - V_2, \\
U_{AB2} &= V_5 - V_7, \\
U_{DC2} &= V_8 - V_6.
\end{align*}
\]

Subsequently, they are averaged:

\[
U_{DC\text{sr}} = 0.5(U_{DC1} + U_{DC2}).
\]
The equations for small relative resistance increments $e_i$ can be formed as follows:

\[
U_{\Delta sr} = 0.5(U_{A1} + U_{A2}).
\] (11)

The changes in resistance of strain gauges consist of two components: $e_1 = e' + e''$, $e_2 = e' - e''$, respectively. One of them is the increment of temperature change $T$ (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:

\[
\varepsilon_1' = e_1', \quad \varepsilon_1'' = -e_2'.
\] (16)

\[
\varepsilon_2' = e_2', \quad \varepsilon_2'' = -e_2''.
\] (17)

Changes in resistance can be considered as linear for both determined quantities, i.e.: $e' = \alpha_T T$, $e'' = \kappa e_B$, where: $T$ – change of temperature, $k$ – gauge factor which is connected with sensitivity to strain, $e_B$ – bending strain $\alpha_T$ – 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)

\[
\Delta T = K_1 \frac{U_{DCsr}}{\alpha_T U_0}
\] (20)

\[
\varepsilon_B = K_2 \frac{U_{ABsr}}{k U_0}
\] (21)

A linear relationship between bending force $F_B$ and strain $e_B$ 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).

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 $e_1$ intercept. The slope is nearly the same.
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.

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.

In Table I, temperature measurements and their differences are presented.

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].

**REFERENCES**


