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TWO-PARAMETER MEASUREMENTS AND SIGNAL CONDITIONING IN DOUBLE-CURRENT SUPPLY FOUR-TERMINAL RESISTANCE CIRCUITS

A new type of the four-terminal (4T) bridge circuit unconventionally supplied by current sources connected in parallel to opposite arms, named **double current bridge** (2J) is presented. It has two different outputs from both diagonals. Three variants of such circuit are proposed. Their output voltages are given as functions of arm resistance increments in absolute and in relative units . Signal conditioning formulas of the two-parameter (2D) measurement of these increments and also of two external variables differently influencing them are discussed in detail. First results of instrumentation designed experimentally using 2J bridge circuits are shortly presented. A summary and prospective applications of 2J bridge circuits in multivariable measurements are given. Literature is included.

1. INTRODUCTION

Most of the measured objects, commonly used sensors and their sets are of an analogue nature. In most applications actual AD converters and digital parts of the measurement systems have adequate resolution, speed and universality due to programming facilities. Then the later **improvement of measurement systems depends mainly on the metrological properties of their initial analogue parts.** Apart from the measurement of different single quantities, development of continuous indirect multivariable (nD) measurements is urgently needed. As examples are the higher accuracy measurements of increments of internal immittances of an equivalent n-terminal circuit and of quantities influencing them. Problems arising in this case are shortly discussed elsewhere, including the monograph [2]. Methods based on testing values of impedances or admittances on different terminals as used in tomography are not accurate enough for the measurement of small internal increments and their differences. New methods for such particular applications should be developed. One of them is presented below.

Measurement should be considered of parameters on terminals of:

- given tested objects, sensors and their sets with their internal circuit not accessible and measurable only on external terminals or by point-type sensors.
- ones that are specially designed for multivariable measurements.

Both problems are in the Author's interest, but the second one is specially analyzed below. Arising problems have been considered on the examples of two-dimensional (2D) simultaneous measurement of resistance increments of the four-terminal (4T) circuit. The author developed a few structures of circuits for such measurements and signal conditioning to be used at the inputs of instrumentation channels. One of them is the circuit of two bridges connected in cascade. It has been described in [2] and [3]. The background of another one and its application are presented in this paper. It is the resistance 4R bridge circuit unconventionally supplied by current sources in parallel to opposite bridge arms, as described below.

2. A NEW TYPE OF 4T CIRCUITS FOR 2D MEASUREMENTS

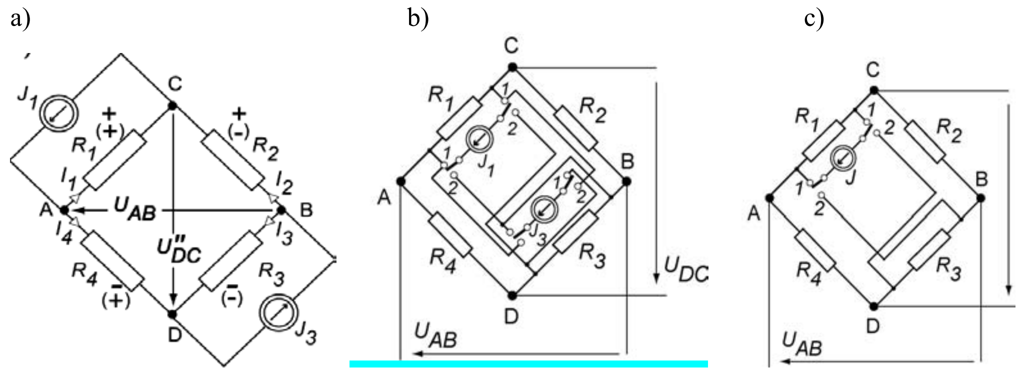

Fig. 1. Double-current 4R bridge circuits for two-variable (2D) measurements:
a) 2J - of equal two current supply sources $J1 = J3$;
b) 2x2J - of two replaced current sources $J1$?$J3$;
c) 2xJ -of a single switched current source J.

Three 4T circuits for use in 2D measurements are given in Fig. 1a-c. Their properties have been already described partly in [1, 3, 4] and in detail in the monograph [2]. All of them apply a four-arm (4R) resistance loop, differently supplied by current sources, each of them connected in parallel to opposite bridge arms, permanently in circuit a) or switched between them - circuits b) and c). For this new type of circuit the Author proposes the provisional common name: **double-current bridges** [1-3] and the acronym **2J bridges**. These circuits have two voltage outputs on both bridge diagonals. Two current sources J_1 and J_3 of the circuit a) of Fig. 1 should be equal, i.e. $J_1=J_3$. In circuits b) and c) all measurements should be made twice with replacing two unequal sources $J_1 \neq J_3$ (in b), or even switching only the single one J (in c). Two results obtained for each output are averaged. Proper understanding of the operation of circuits of Fig. 1 in 2D measurements makes it necessary to present a short description of their equations and terminal parameters.

3. PRINCIPLES OF OPERATION OF DOUBLE-CURRENT BRIDGES

Open-circuit output voltages of the circuit on Fig. 1a are given by equations:

$$U''^{\infty}_{DC} = J_1 \frac{(R_1R_2 - R_3R_4)}{\sum R_i} - \frac{\Delta J(R_1 + R_4)R_3}{\sum R_i}, \tag{1}$$

$$U^{\infty}_{AB} = J_1 \frac{(R_1R_4 - R_2R_3)}{\sum R_i} - \frac{\Delta J(R_1 + R_2)R_3}{\sum R_i}, \tag{2}$$

where: $\Delta J = J_1 - J_3$.
Their two balance conditions (when $U''_{DC} = 0$ or $U_{AB} = 0$) depend on supplying currents J_1, J_3. When the supply currents are equal, then $J_3 = J_1$, $\Delta J = 0$ and Eqs. (1), (2) are simplified to:

$$U''^{\infty}_{DC} = J \frac{R_1R_2 - R_3R_4}{\sum R_i} \equiv J\, t_{DC}, \tag{3}$$

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

where: t_{DC}, t_{AB} - open-circuit voltage to current sensitivities of DC and AB outputs of the 2J bridge.
From (3), (4) balance conditions of both outputs for initial resistances are now obtained as follows:

$$R_{10}R_{20} = R_{30}R_{40} \qquad (5)$$

and

$$R_{10}R_{40} = R_{20}R_{30}\,. \qquad (6)$$

Hence, the 2J bridge of two equal current supply sources is in balance when pairs of the impedance products of the neighbouring arms to terminals of its output diagonal (CD or AB) are equal.

New formulas of balance conditions (5), (6) together with one for the classically supplied bridge complete the set of all three possible equalities of two products of impedance pairs of the four-arm bridge.

If the three initial resistances, e.g. R_{10}, R_{20}, R_{40} have the same values in the Wheatstone and 2J bridge of Fig. 1a and they are balanced by adjusting R_{30}, twice for the last one - separately for each output, then in general cases these three resistances are different.

Let us now consider two circuits of the 2J bridge developed by the Author and given in Fig. 1 b, c. In this method each of the output voltages should by measured twice with exchange of two unequal supply current sources (circuit b) or even a single one (circuit c). From (1) and (2) it is clear that the second components in both voltages have the same absolute values, but opposite signs. Then the mean value of two results of each output is proportional to the mean value of the supply currents as follows:

$$\overline{U}_{DC}^{\prime\prime\infty} = \frac{J_1 + J_3}{2}\,\frac{(R_1R_2 - R_3R_4)}{\sum R_i}\,, \qquad (7)$$

$$\overline{U}_{AB}^{\infty} = \frac{J_1 + J_3}{2}\,\frac{(R_1R_4 - R_3R_2)}{\sum R_i}\,. \qquad (8)$$

These equations are even valid if only the single current source $J_1 = J$ ($J_3 = 0$) is switched between opposite arms, as shown in Fig. 1c. In this case the mean value of measured output voltages is proportional to $0.5J$.

Equations (3), (4) and (7), (8) of the double current bridges have a similar form as those of the Wheatstone bridge supplied by current, but in these formulas arm impedances are taking other places depending on the method of supply and of the output diagonal.

Every one of Fig. 1a-c circuits would be in balance for both outputs only, when $R_{20} = R_{40}$ and $R_{10} = R_{30}$, i.e. such bridges are initially antisymmetric. All of them and the classic 4R bridge are in balance together when all initial arm resistances R_{i0} are equal, i.e. $R_{10}=R_{20}=R_{30}=R_{40}$.

With the notations: $R_i \equiv R_{i0}(1+\varepsilon_i) \equiv r_{i0}R_{10}(1+\varepsilon_i)$ and $R_{20} \equiv mR_{10}$, $R_{40} \equiv nR_{10}$, as used before for the classic 4R bridge and after the transformation of (3) and (4), rationalised formulas of unbalance voltages of the 2J bridge in relative values are as follows

$$U''^{\infty}_{DC} = Jt''_0 f''(\varepsilon_i) \equiv T''_0 f''(\varepsilon_i), \tag{9}$$

$$U^{\infty}_{AB} = Jt'''_0 f'''(\varepsilon_i) \equiv T'''_0 f'''(\varepsilon_i), \tag{10}$$

where: T''_0, T'''_0 - initial sensitivities of open-circuit output voltages,

$$t''_0 = \frac{R_{10}\, R''_{20}}{\sum R''_{i0}} = R_{10}\frac{mn}{(n+m)(1+n)}, \tag{9a}$$

$$t'''_0 = \frac{R_{10}\, R'''_{40}}{\sum R'''_{i0}} = R_{10}\frac{mn}{(n+m)(1+m)}, \tag{10a}$$

- ratios of initial sensitivities of open-circuit output voltages to supply current J,

$$f''(\varepsilon_i) \equiv \frac{(\varepsilon_1 + \varepsilon_2 - \varepsilon_3 - \varepsilon_4 + \varepsilon_1\varepsilon_2 - \varepsilon_3\varepsilon_4)}{1 + \dfrac{\sum R''_{i0}\varepsilon_i}{\sum R''_{i0}}}, \tag{9b}$$

$$f'''(\varepsilon_i) \equiv \frac{(\varepsilon_1 - \varepsilon_2 - \varepsilon_3 + \varepsilon_4 + \varepsilon_1\varepsilon_4 - \varepsilon_2\varepsilon_3)}{1 + \dfrac{\sum R'''_{i0}\varepsilon_i}{\sum R'''_{i0}}}, \tag{10b}$$

- unbalance functions of U''^{∞}_{DC} and U^{∞}_{AB}, respectively.

Even with the same values of R_{20} and R_{40} in Wheatstone bridge and in circuits of 2J bridge, denominators of formulas for initial sensitivities t'_0, t''_0, t'''_0 and of their unbalance functions are in general cases different, because their resistances R_{30} may be different. Only the initially antisymmetric and unloaded 2J bridge ($R_{10} = R_{30}$, $R_{20} = R_{40}$) has initial sensitivities equal, i.e. $t''_0 = t'''_0 = \dfrac{mR_{10}}{2\,(1+m)}$ and as well both output open-circuit resistances $R_{AB0} = R_{CD0} = 0.5R_{10}\,(1+m)$. It is important also to know that the antisymmetric 2J bridge should be unloaded on both outputs to keep balance conditions (5), (6) valid together.

Currents, voltages and powers of the arms of 1a-c circuits depend on values of all R_{i0} resistances and of their relative changes ε_i. In the unbalanced and unloaded double-current 4R bridges with equal sources $J_1=J_3$, the opposite arms' currents are always equal: $I_1= I_3$ and $I_2= I_4$.

From (9b) and (10b) it is also obvious that output voltages depend differently on signs of bridge arms' resistance increments. Examples of signs, of increments changing the output in the same direction are given in Fig. 1a. If absolute values of these increments $|\varepsilon_i|$ are equal, the output voltages are exactly proportional to the number of variable arms, e.g. multiplied by 2 or 4. Linearity conditions of unbalance functions of 2J bridge are different for each voltage output. It is discussed in detail in [2].

Basic formulas of the open-circuit resistances on both output terminals of the 2J bridge are the same as for the classic 4R bridge, but their values in the balance states are different to satisfy the balance condition (5) or (6). Due to the similarity of equation forms of both type circuits, the accuracy analysis of the classic 4R bridge, after adequate transformations of formulas, was adopted for 2J bridges [2, 3].

4. 2D MEASUREMENTS BY DOUBLE-CURRENT BRIDGES

Principles of two types of 2D measurements of terminal parameters of the double-current bridges 2J of Fig. 1a when $J_1 = J_3 = J$, will now be discussed in detail in order to compare them with the classic bridge. The 2J bridge initially balanced in both diagonals, and of two variable arms R_1, R_2, is only taken for consideration. Main cases of terminal parameter formulas in related values of such initially antisymmetric 2J bridge ($m = n$, i.e. $R_{10} = R_{30}$, $R_{20} = R_{40}$) are presented in Table 5.1 in monograph [2].

If absolute values of increments $|\varepsilon_1|$, $|\varepsilon_2|$ are small enough, i.e. $|\varepsilon_1\varepsilon_2| << |\varepsilon_1+\varepsilon_2|$ and $|\varepsilon_1+m\varepsilon_2| << 2(1 + m)$, or $|\Delta R1 + \Delta R2| << 2(R_{10} + R_{20})$, output voltage formulas (9) and (10) are simplified to:

$$U''_{DC} = T_0(\varepsilon_1 + \varepsilon_2), \quad (11a) \qquad\qquad U_{AB} = T_0(\varepsilon_1 - \varepsilon_2). \quad (11b)$$

The first voltage is proportional to the sum and the second one to the difference of increments.

Formulas of both arm increments are directly obtained from basic 2J bridge equations. In the general case of the presented bridge it is as follows:

$$\varepsilon_1 = \frac{m+1}{m}\frac{U''_{DC} + U_{AB}}{JR_{10} - U_{AB}}, \quad (12a) \qquad\qquad \varepsilon_2 = \frac{m+1}{m}\frac{U''_{DC} - U_{AB}}{JR_{10} + U_{AB}}. \quad (12b)$$

Output signals should be processed in the digital part of the measuring system due to these univocal solutions. In the bridge with equal all initial arm resistances (m=n=1), the first coefficient of (12a) and (12b) is 2 and both relations become very simple.

The above method of 2D measurement may be directly useful in the testing and diagnostics of each of two sensors, for example in arms R_1, R_2, without disconnection of the bridge loop.

If relations between arm increments and measured external quantities x_1, x_2 are also known (e.g. as nominal or experimental sets of two-variable characteristics of both sensors), then after inverse transformations it is possible to obtain both their values.

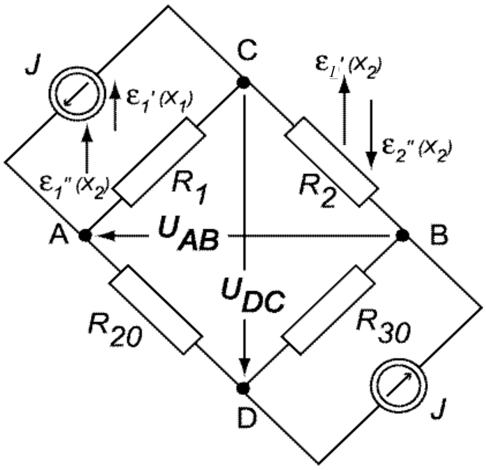

Fig. 2. Principle of two variable x_1, x_2 measurements by the antisymmetric double current bridge of R_1=R_{30}, R_{40}=R_{20}.

In Fig. 2 the operation idea of 2D measurements in the initially antisymmetric 2J bridge is shown. It is a very frequently practised particular case, where two resistance increments dependent on two variables x_1, x_2 as different their additive functions, described so:

$$\varepsilon_1'(x_1) = \varepsilon_2'(x_1) = \varepsilon', \quad \text{and} \qquad \varepsilon_1 = \varepsilon' + \varepsilon'',$$

$$\varepsilon_1''(x_2) = -\varepsilon_2''(x_2) = \varepsilon'', \qquad \varepsilon_2 = \varepsilon' - \varepsilon''.$$

The two output signals are now:

$$U_{DC} = JR_{10}\frac{m}{(1+m)}\frac{\varepsilon' + \frac{(\varepsilon')^2 - (\varepsilon'')^2}{2}}{1+\frac{\varepsilon'}{2}+\frac{\varepsilon''(1-m)}{2i(1+m)}}, \quad (13a) \qquad U_{AB} = JR_{10}\frac{m}{(1+m)}\frac{\varepsilon''}{1+\frac{\varepsilon'}{2}+\frac{\varepsilon'(1-m)}{2(1+m)}}. \quad (13b)$$

Initial sensitivities and denominators of the above formulas are equal. If ε' and ε'' are not too great the difference of their squares in the last nominator of the Eq. (13a) is negligible. Additionally, if both sensors are linear for both measured quantities, i.e. $\varepsilon'_1(x_1) = k_1x_1$; $\varepsilon''(x_2) = k_2x_2$, then from (9) and (10) these voltage signals could be written in slightly different forms.

$$U_{DC} = \frac{J R_{10} R_{20}}{\sum R_{i0} + \sum_i \Delta R} 2k_1x_1, \quad (14a) \qquad U_{AB} = \frac{J R_{10} R_{20}}{\sum R_{i0} + \sum_i \Delta R} 2k_2x_2. \quad (14b)$$

Sensitivities of the above two signals to x_1 or x_2 are equal and could only slightly depend on them, if $\sum_i \Delta R \neq 0$. When $\varepsilon_1 << 1$, $\varepsilon_2 << 1$, these formulas are simplified further, up to:

$$U_{DC} = JR_{10}\frac{m}{1+m}\varepsilon'(x_1), \quad (15a) \qquad U_{AB} = J R_{10}\frac{m}{1+m}\varepsilon''(x_2). \quad (15b)$$

Each of the above voltages depends linearly only on one component of the resistance increments, which depends only on one of the influencing variables. For higher values of ε', ε'' the output voltages become not linear functions, but both sensitivities are always proportional to each other.

In such a simple method as above it is possible to realize a simultaneous measurement of two variables: x_1 and x_2 by one or two pairs of sensors. For higher resistance increments ($0<|\varepsilon_i|\leq 1$) it is also possible to obtain separately nearly linear relations of the output voltages for the 2J bridge, if both components $\varepsilon_i'(x_1)$ and $\varepsilon_i''(x_2)$ separately satisfy linearity conditions of the unbalance functions [2], [3]. Even if only one quantity is to be measured and the influence of the second one, e.g. temperature should be corrected, it is more efficient and accurate to do it digitally on the basis of a second signal from the sensor bridge than to use an additional sensor.

If four measurements are made at diagonals of the particular 4R bridge, e.g. two of them when it is supplied classically and two for the 2J supply method, then it is possible to obtain individual increments in all four arms of that bridge [1, 2]. For such a reason the input and output resistances of this circuit could be measured also but it is more complex and is not considered here.

Measurement of two parameters could be done also by an Anderson current loop (see discussion in [2]). This circuit uses a standard resistor and two-terminal sensors, all of similar initial resistances only, connected in series and supplied by the current. For the measurement of differences of the voltage drops a couple of special double-input differential active circuits are applied. Each one is used for every sensor and every mathematical operation on signals and includes a few operational amplifiers. Seven connections for each pair of sensors are needed. Thus, the circuitry of this loop is much more complex.

An accuracy analysis of double-current DC bridges is given in paper [3] and wider in monograph [2].

Experimental verification of the operation of 2J resistance DC bridge circuits is not needed, as all relations and properties of terminal parameters follow directly from Kirchoff's laws.It is more interesting to present some preliminary application results in 2D measurements. They could be applied in practice if, in particular, one needs:

- simultaneous indirect testing of increments of few internal immitances on the network's terminals,
- initial signal conditioning of indirect measurements of few quantities by non selective multi-parameter monolithic sensors or sensor sets.

For example, the simultaneous measurement of stress and temperature needs to apply only two strain gauges without additional circuit branches for compensation of temperature influence on their parameters. Two signals obtained from 2J bridge diagonals allow to make all corrections of their zero and sensitivity temperature changes on the digital side, even when sensors are not exactly similar.

On the basis of the Author's earlier publications about the idea and background of new bridges unconventionally supplied by double-current sources[1] and as a result of his invitation during several conferences to cooperation, other Authors started to continue their development. They tested the possibility to apply the 2J bridge in some particular cases of 2D measurements.

Miczulski, in the beginning together with the author and later with Kulesza, both of them from the University in Zielona Góra analyzed the possibilities of use of the double-current RC bridge in AC measurements. It is used together with the method of conversion of some impedance components to phase shifts of voltages between selected circuit nodes developed by Miczulski [5, 6]. Then these shifts could be measured with high resolution and accuracy by digital methods. Preliminary results of this analysis show that the simultaneous measurement of two impedance increments is possible but output signals are strongly nonlinear. It is similar to 1D measurement by this method in the classically supplied AC bridge.

Tync has developed digital 2J bridges [7]. Iżkowski and Makal have built a laboratory stand with a 2J bridge to test simultaneously two types of stresses on a beam bent by force [9-11]. As the results of both applications are very promising, they are shortly described below.

5. DIGITAL 2J BRIDGES

An experimental model of the digital circuit containing a 2J-bridge and original high accuracy linear converter of resistance increments to frequency has been designed by Tync [7]. It was built and tested in the laboratory for 1D and 2D measurements of resistance increments and of two quantities differently changing resistances of bridge arms. Obtained results are so prospective that they should be shortly presented below.

The circuit given in Fig. 3 illustrates the idea of digital 2J-bridge operation in 1D measurements. The additional circuit denoted as R_{ZC}, R_{ZD}, not shown in detail, allows supplying the input terminals of 2J bridge by two equal-value currents J from a single non-stabilized voltage source U. Bridge output AB is connected to an integrating amplifier. Its output voltage is converted to a frequency signal switching the key K. This feedback path sets

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[1] More than 20 author's publications about 4T circuits and backgrounds of 2D measurements with them are given in the bibliography of monograph [2]. In the earliest author's works the term '*anti-bridge*' (in Polish - *antymostek*) was used, because in balance conditions of 2J bridges are products of neighbouring immitances, but for classic bridges – of opposite ones.

the frequency until a charge balance on the bridge output (as in Σ-Δ converters) is obtained. The output frequency is digitally measured and read out with very high resolution.

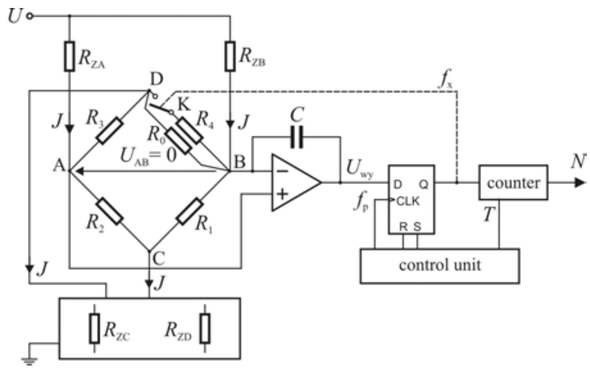

Fig. 3. The double-current bridge balanced in charge by means of feedback on one switch K [7].

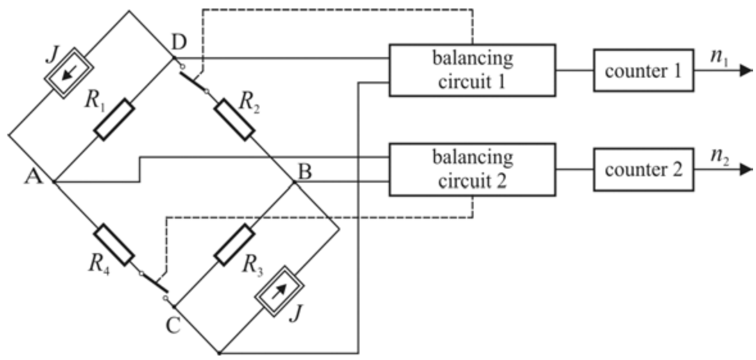

Fig.4. Charge-balanced double-current bridge with two balancing circuits [7].

The output frequency of the circuit of Fig. 3 is given by the equation:

$$N = 2k\left\{\frac{R_1 R_4}{R_2 R_3} - \frac{R_4}{R_0}\right\}. \tag{16}$$

If the first component in brackets could be equal to 1, it is similar to the balance condition of the AB output of the analogue 2J bridge. Resistance R_0 connected in parallel to arm BD shifts the beginning of the frequency range. It is equal to the setting of the initial balance of the analogue bridge. A physical model of this circuit was tested with a low switching frequency of the key K and the experimentally obtained relations are similar to the theoretical ones. The circuit with switches in two bridge arms could be also built for one variable measurement.

Figure 4 illustrates the operation of the 2D-measurement digital circuit with a 2J bridge at the input. Both measurement channels are working sequentially. When $R_1 = R_3 = R$, the following two relations for output frequencies are obtained:

$$N_1 = n_1 + n_2 = 2k\frac{R_2 + R_4}{R}, \quad (17a) \qquad N_2 = n_1 - n_2 = 2k\frac{R_2 - R_4}{R}. \quad (17b)$$

If resistances R_2, R_4 are differently related to two variables x_1 and x_2, e.g. on two additive functions, the same ones as considered before for the unbalanced analogue 2J bridge, i.e.:

$$R_2 = f_1(x_1) + f_2(x_2)\,, \qquad (18a) \qquad\qquad R_4 = f_1(x_1) - f_2(x_2)\,. \qquad (18b)$$

Then the output frequencies are

$$N_1 = 4kf_1(x_1)/R\,, \qquad (19a) \qquad\qquad N_2 = 4kf_2(x_2)/R\,. \qquad (19b)$$

Number N_1 is proportional to $f_1(x_1)$ and N_2 to $f_2(x_2)$. Such two-parameter measurements are equivalent to ones made by the 2J analogue bridge balanced twice, separately for each diagonal by adjusting one of the arm resistances [2]. They are also equivalent to 2D measurements by the unbalanced 2J bridge with stabilized supply currents when increments are small enough - see (15 a, b).

The charge-balanced converter used above was developed by Tync some time ago and applied in a few types of high accuracy measuring instruments with differential sensors or classic sensor bridges at the input. They have been used for measurements of different single quantities only, e.g. temperature, stress or deflection. High resolution and accuracy was obtained. As an example, for a Pt 100 sensor even with a very small current <10μA, the accuracy was 0.02°C, i.e. it corresponds to less then 0.01% of this sensor's initial resistance. It is better than is really needed for most of commonly used sensors. The accuracy of the circuits described above with a 2J bridge at their inputs could be of the same order because supply currents J have been adjusted so that the difference between them is negligible. Also circuits shown in Fig. 1 b, c with switched current sources could be used with this converter.

6. LABORATORY STAND FOR SIMULTANEOUS MEASUREMENT OF STRESS COMPONENTS AND TEMPERATURE WITH A 2J BRIDGE

Idźkowski and Makal from Białystok University of Technology started with computer simulation of 2J bridges in the *PSpice* program [8] to better understand their operation. Then they built and tested a physical experimental model of analogue 2J bridge for 2D measurement of resistance increments dedicated for strain gauges [9, 10]. Presently, they completed the laboratory stand for 2D measurements with the 2J-bridge with switched current source of simultaneously applied axial and bending forces [11]. It is now under tests and subject to upgrading. Some details concerning this stand are presented below.

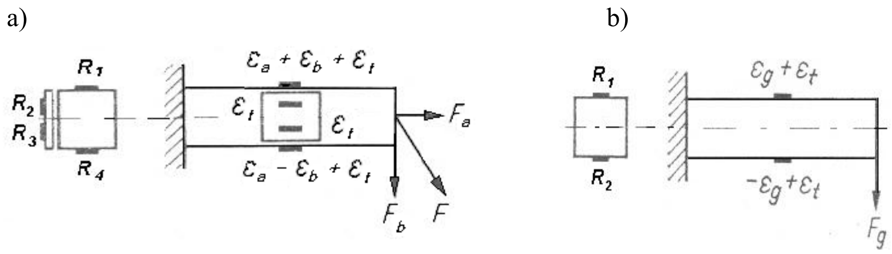

Fig. 5. a) A beam with strain gauges for the measurement of two force components [11]; b) Measurement the bending force F_g and temperature of a beam [10].

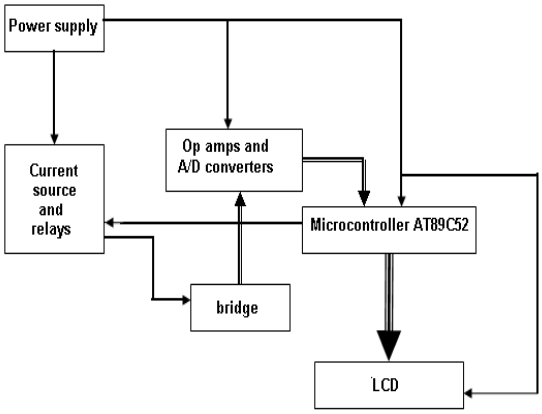

Fig 6. Generalized scheme of the 2J bridge measurement system.

Four standard type strain gauges shown in Fig. 5a are active only in the direction of their length and have the same nominal sensitivity factor *k*. They are located on the beam, one at the top, one at the bottom and two perpendicularly to them, as sketched in Fig. 5. The last two could be located also on a separate plate made from the same material as the beam and it must be not stretched. All strain gauges are connected to the bridge circuit supplied by two equal-current *J* sources, as shown in Fig. 1a. Absolute increments of R_1, R_2, R_3, R_4 resistances are as follows:

$$\Delta R_1 = \Delta R_{1a} + \Delta R_{1b} + \Delta R_t, \ (20a) \qquad \Delta R_2 = \Delta R_3 = \Delta R_t, \ (20b) \qquad \Delta R_4 = \Delta R_{4a} - \Delta R_{4b} + \Delta R_t, \ (20c)$$

where: ΔR_{1a}, ΔR_{4a}, ΔR_{1b}, ΔR_{4b} are resistance increments due to axial F_a and bending F_b components of the applied force F; ΔR_t - the resistance increment due to the temperature change from the nominal one, of the same value for all sensors.
Increments ΔR_{1b}, ΔR_{4b} are of opposite sign, as the strain gauge R_1 is stretched and R_4 is compressed. After putting (20a, b, c) to (15a, b) one can obtain two expressions for output voltages:

$$U_{AB} = \frac{J}{2}\Delta R_b = \frac{JR_{10}}{2} k\varepsilon_b, \qquad (21a) \qquad\qquad U_{CD} = \frac{J}{2}\Delta R_a = \frac{JR_{10}}{2} k\varepsilon_a. \qquad (21b)$$

The first of them depends on the bending strain and the second is a function of the axial strain.

The bridge has to be powered by stabilized and equal-value current sources. Strain gauges have the same factor *k* and nominal resistance R_{10}. The advantage of this circuit is the elimination of the temperature changes of strain gauge resistances. Relative temperature changes of the sensitivity factor *k* and voltages of both channels are of the same values. This can be corrected by processing the output signals in the connected microprocessor unit. The technical data of strain gauges are presented in Table 1.

Table 1. Technical data of strain gauge TF-5/120 [7].

Material	Nom. Resistance R_{10} [Ω]	Strain gage factor k	Young's Modulus E [Pa]	Temperature coeff. of resistance [1/°C]
Constantan foil	120 ± 0,2%	2,1-2,2 ± 0,5%	$16{,}3 \cdot 10^{10}$	$0{,}04 \cdot 10^{-3}$

When ε_b is equal to 40000 microstrains (that represents a deformation of 4% and elastic limit of strain gauge), the voltage U_{AB} is 0,126V (3,15μV per 1 microstrain). The values of bending forces for particular cross-sections of a beam can be calculated with the use of the formula below for $\varepsilon_b = 40000$ and l=1m.

$$F_b = \frac{\varepsilon_b EW}{l}, \tag{22}$$

where: W - the coefficient of strength for a given cross-section of the beam; l - the distance between the placed strain gauge and the acting point of the force F_b.
The maximal force F_b is about 4800 N for a steel cylinder of diameters: OD 0.02m and ID 0.01m; 5120 N - for the steel bar of the OD diameter 0.02m and 5410 N - for the rectangular bar of cross-section 0.05m x 0.01m.

The largest axial strain ε_a can be obtained for a thin-wall cylinder beam. If as an example, the outside diameter D = 10cm and the internal one d = 8cm of the 1m long steel beam, then the related extension for the axial component of the 1000N force is about 100ppm. Because the sensitivities of both output voltages are the same, its signal would be smaller than for the bending forces. Signals with the use of semiconductor strain gauges should be several tens of times higher.

In Fig. 5b arrangements for measurement of the bending force F_g and temperature changes are shown [10]. Equations for this case are:

$$U_{AB} = \frac{J}{2}\Delta R_t = \frac{JR_0}{2}\alpha\Delta T, \quad \text{(23a)} \qquad U_{CD} = \frac{J}{2}\Delta R_g = \frac{JR_0}{2}k\varepsilon_g, \quad \text{(23b)}$$

where: α - the temperature coefficient of resistance; ΔT - the difference of specimen and reference temperature.

In Equation (23a) the voltage is in practice a linear function of temperature increment ΔT. Temperature coefficients of resistance of metal strain gages are very low (0.04×10-3/°C - constantan, 4.5×10^{-3}/°C - tungsten, 0.13×10^{-3}/°C - nichrome V). This causes the voltage sensitivity of U_{AB} to be equal to a decimal part of μV/mA0C, but this voltage is measurable for allowed strain gage currents J. The current J cannot increase it much because it is limited by the allowed value (up to 50mA - depends on the gauge) of the limited dissipation power of the strain gauge on the particular substrate.

The UCD voltage in (23b) depends on factor k and bending strain ε_g. The nominal values of factors k of both strain gauges should be equal. The factor k depends also on temperature. For many strain gauges k is in practice a linear function of temperature in a wide range. Having the value of the temperature signal it is easy to correct the measurement results. The 2J bridge can be applied for metal and semiconductor strain gauges in a high range of temperatures for two-parameter (2D) signal conditioning.

The general scheme of a 2J bridge measurement system is presented in Fig. 6. The bridge circuit as shown in Fig. 1c is supplied properly with the use of a current source (up to 25mA) and four relays to switch it. Op amps and 16-bit A/D converters condition the electrical potentials of the four bridge nodes. The signals are processed by a micro-controller AT89C52 which also controls the switching of the relays. This circuit generates two output signals according to equations (20a, b) and each of them depends on one component of the force. With strain gauges placed upon a beam like in Fig. 5 it is possible to measure axial and bending forces independently and simultaneously. Two dummy gauges and two channels of this system could eliminate the influence of temperature on the result. One knows that when the temperature change is significant it has an influence on the value of the strain gauge factor k and on the bridge transmittance formula too. The use of a micro-controller for conditioning of both output signals at the same time causes elimination of the temperature change problem.

The main reasons for designing this stand have been to show components of the stress and forces acting upon the single beam in the educational laboratory. It is now under tests and upgrading.

7. SUMMARY

Properties of bridge circuits supplied by double current sources connected unconventionally in parallel to opposite arms are presented in this work. It is an original idea of applying bridge circuits after the 170-year-long history of measurements. According to that, the new way to simultaneous signal conditioning of few variables measured in DC and AC immitance circuits is wide-open, not only in 4 terminal (4T) circuits but in many others too. In some applications, double-current bridges could be only the alternative to existing circuits, in others - they give new possibilities. The main application is in measurement of few individual values and different functions of the immitance increments of internal branches of the bridge or circuits of other topology. Measurements are performed at terminals without disconnecting this circuit and directly accessing its inside. It is also possible to create new 2D-measurement and signal conditioning double-current circuits, e.g. with different sensors, resistance to frequency converters [7], with analogue feedback to one of the bridge supply currents [2], with multipliers, Hall sensors etc.

The experimental development work presented here confirms that the ideaof the double-current supply 4T circuits introduced by the Author can be a valuable supplement for known ways of analogue signal conditioning. In particular some possibilities of application of 2J DC bridges for variable measurements and their signal conditioning are shown . Both presented 2J bridge measurement systems may be applied also to measure stresses or acting forces in lattice frameworks or to monitoring of large-scale building constructions. On a small scale they could test the operation of bimetal strips. Heating could be provided by current flowing throw the tested part. The 2J bridge measures the real temperature of strain gauges in its localization, depending on their dissipation power and heating of the substrate. An additional temperature sensor is not needed. For such applications additional experimental tests and some subsequent upgrading are still needed.

The method of 2D measurement with supplying from double-current sources can be also applied to semiconductor strain gauges. Semiconductor strain gauges have not only higher sensitivity than metallic ones, but they are also more vulnerable to temperature. As an example, piezoresistive pressure 4T sensors named X-ducers™ [12] can be given, made by newest technology together with a semiconductor membrane, need a temperature compensation of their zero and span. Their equivalent circuit is the 4R bridge. When they are working as a two-port, the voltage increment for the full pressure range is 50-90 mV. A temperature increase by 100°C from nominal 25°C decreases this voltage by 15mV (about 3%/10°C). A laser-trimmed thermistor is applied at the input circuit for span compensation but relations are nonlinear. This solution could be replaced by 2D measurements in the 2J bridge or by the cascade circuit of two bridges [2, 3] followed by digital processing of these two signals. Proper temperature compensation seems to be much easier to be obtained by the latter method.

A very large and perspective field of applications of double-current bridges seems to be in the domain of AC circuits. For every conventional AC bridge it is possible to create 2 (or even 4) of such double bridges. Balance could be achieved in 4-arm bridges which are structurally unbalanced for conventional supply, because sums of phases of the pairs of opposite arm immitances are permanently different. The Author analyzed double-current supplied AC bridges of single R or C element arms (as in simple phase shifters) and in bridges of two RC arms - as in the de Sauty bridge circuit (Vien of serial RC arms) [2], [13]. If the last ones are balanced twice, i.e. independently for each output, three immitance components of two arms can be measured in such single-bridge circuit without disconnecting it.

Analyses of other metrological properties of circuits which are supplied by two current sources including their sensitivity and accuracy are given in several Author's works, e.g. [1, 2. 4] *and in other publications included in the bibliography of monograph* [2]. *Particular conclusions and the scope of potential fields of applications of these circuits are discussed there also much widely then in the above paper.*

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DWUPARAMETROWE POMIARY I KONDYCJONOWANIE SYGNAŁÓW W DWUPRĄDOWO ZASILANYCH REZYSTANCYJNYCH OBWODACH CZTEROKOŃCÓWKOWYCH

Streszczenie

Przedstawiono nowy rodzaj czterokońcówkowego (4T) układu mostkowego o niekonwencjonalnym zasilaniu ze źródeł prądowych dołączanych równolegle do jego ramion przeciwległych. Nazwano go mostkiem dwuprądowym (2J). Ma on dwa różne wyjścia z obu przekątnych. Zaproponowano trzy warianty rozwiązania tego układu. Wyznaczono zależności jego napięć wyjściowych w funkcji przyrostów rezystancji ramion w wartościach bezwzględnych i względnych. Szczegółowo omówiono kondycjonowanie sygnałów przy dwuparametrowych (2D) pomiarach tych przyrostów oraz dwu wielkości zewnętrznych niejednakowo na nie oddziałujących. Omówiono w skrócie kilka pierwszych eksperymentalnych konstrukcji urządzeń pomiarowych z mostkami dwuprądowymi 2J. Podsumowano dotychczasowe rezultaty i wskazano perspektywiczne obszary zastosowania mostków 2J w pomiarach dwuparametrowych. Zamieszczono bibliografię.