ELECTRONICS AND ELECTRICAL ENGINEERING
ISSN 1392 – 1215 2011. No. 8(114)
ELEKTRONIKA IR ELEKTROTECHNIKA

T 170 ELECTRONICS
ELEKTRONIKA

Analysis of Balancing Methods of Measurement of Small Resistance Changes

R. Masiulionis, V. Kvedaras, R. Kvedaras
Electronics Faculty, Vilnius Gediminas Technical University,
Naugarduko str., 41, LT-03227, Vilnius, Lithuania, phone:+370 5 2744762, e-mail: ricardas.masiulionis@el.vgtu.lt

crossref http://dx.doi.org/10.5755/j01.eee.114.8.683

Introduction

During design, construction and use of constructions of different materials quite often there is a need to investigate different parameters [1, 2] and deformations of such constructions under various loads [3]. This is also important for investigation of newly designed constructions when it is important to find out how new design is resistive to various loads and what are the weak points and to find out the ways of further improvement or reinforcement of such constructions.

Monitoring of the strains of a construction allows to perform various modelling of the construction current state and avoid dangerous conditions or collapses during earthquakes storm winds, etc. [1].

For such strain measurement resistive strain gauges along with unbalanced Wheatstone bridge circuits are widely used [5]. In this kind of measurement the accuracy of strain measurement is limited to the accuracy of the measurement of small resistance changes of strain gauges. In earlier works it has been shown that better results are obtained with the proposed digitally balanced Wheatstone bridge circuits and circuits using digitally balanced current sources [1] which are investigated in this paper.

For digital balancing digital-to-analogue converters (DAC) are used along with the closed-loop automatic balancing system [2]. Nevertheless these methods are still not enough investigated. Some of the circuits do not have equations for measurement code relation to a measured resistance change.

The purpose of this paper is to investigate these circuits and to obtain main missing equations.

Method of digitally balanced Wheatstone bridge

It has been shown that DAC can be used as digitally controlled resistance for balancing Wheatstone bridge. Resistance between reference voltage input and R-2R matrix output is changed by changing of the digital DAC input code. Typical resistance R of such DACs is between 3 and 10 kΩ. Resistance of the typical strain gauges is between 100 and 500 Ω. Therefore it is not possible to directly use DAC in Wheatstone bridge.

Model of the digitally balanced Wheatstone bridge with DAC connected in parallel with bridge resistance R_3 and taking into account resistance of the strain gauge connection cables is shown in Fig. 1, where R_{s1} – active strain gauge, R_{s2} – passive (compensating) strain gauge, R_3 and R_4 – constant resistors, R_{w1}, R_{w2} – resistance of connections wires, R_{DAC} – digitally controlled resistance.

Nevertheless there is no analysis regarding measurement code dependence on strain measured in references.

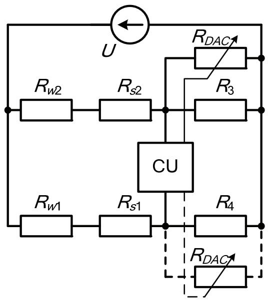

Fig. 1. Model of the Wheatstone bridge with resistance of the connecting wires

Resistance of the multiplying DAC with code m on the input

$$R_m = \frac{2^n R_{DAC}}{m}, \quad (1)$$

where R_{DAC} – typical resistance of the DAC matrix; m – decimal DAC input code.

Total resistance of one side of the Wheatstone bridge when R_{3R} is changed by DAC connected in parallel is

$$R_{3DAC} = \frac{2^n R_3 R_{DAC}}{R_3 m + 2^n R_{DAC}}. \quad (2)$$

Equation of the balanced bridge

$$\frac{R_4}{R_{s1R}+R_4}=\frac{R_{3DAC}}{R_{s2}+R_{3DAC}}, \quad (3)$$

where $R_{s1R} = R_{s2} + \Delta R_{s1} + \Delta R_w$, R_{s2} – resistance of the compensating strain gauge, $\Delta R_{s1} = R_{s1} - R_{s2}$ – difference between resistance of the active strain gauge and compensating strain gauge; $\Delta R_w = R_{w1} - R_{w2}$ – difference of the connecting wire resistance of active and compensating strain gauges.

When bridge is balanced R_{3DAC}

$$R_{3DAC}=\frac{-R_4 R_{s2}}{R_{s1R}}. \quad (4)$$

Set in (2) into (4) code value is

$$m=2^n R_{DAC}\left(\frac{-R_{s1R}}{R_4 R_{s2}}-\frac{1}{R_3}\right). \quad (5)$$

Resistance (strain) change is gained from difference of two measurements. First measurement is done just after mounting strain gauges (without additional load on the construction) and next measurement is done after applying loads on the construction.

Resistance change result is obtained from difference of balancing codes

$$m_m=\frac{2^n R_{DAC}}{R_4}\left(\frac{\Delta R_{s1i}+\Delta R_{w1}}{R_{s2}}\right), \quad (6)$$

where ΔR_{w1} – difference of wire resistance after first measurement (after m_0 measurement).

As it is shown above $\Delta R_{w1} = R_{w0} - R_{wi}$, R_{w0}, R_{wi} – resistances of the connecting wires at the initial measurement and i-th measurement.

As it is seen from (6), difference of two codes is directly proportional to strain gauge resistance change including change of the resistance of connecting wires and thus equal to strain change. By measuring two times difference of resistance of active and passive strain gauges and influence of resistance of connecting wires are eliminated. Difference of connecting wires resistance ΔR_{l1} represent difference of resistance which is caused by environment conditions, wear of wires, etc. By using cables with two twisted pairs this difference is neglectively small. Change of resistance of active strain gauge caused by environmental conditions is compensated by passive strain gauge.

Bridge with changing R_4. In Wheatstone bridge DAC can be connected in parallel with R_4. In this case total resistance R_{4DAC} would change the same ways as resistance R_{3DAC} change in previous circuit (2), and equation of the balanced bridge would be

$$\frac{UR_{4DAC}}{R_{s1R}+R_{4DAC}}=\frac{UR_3}{R_{s2}+R_3}. \quad (7)$$

In analogy with previous case difference of the codes of two measurements (equal to resistance change difference) is:

$$m_m=\frac{-2^n R_{DAC} R_4 R_{s2}}{R_3 R_4}\times$$
$$\times\frac{\Delta R_w+\Delta R_{wp}}{(R_{s2}+\Delta R_{s1i}+\Delta R_s+\Delta R_w+\Delta R_{wp})(R_{s2}+\Delta R_{s1i}+\Delta R_s)}. \quad (8)$$

It is seen that the equation is rather complex and not linear.

Therefore it is more convenient to use change of resistance R_3 for bridge balancing.

Limits of measurement of resistance change are set by change limits of resistance R_{3DAC}. From (2) it is seen that these limits are influenced by resistance values of R_3 and DAC typical resistance R_{DAC}. Value of R3 resistance for required change limits is

$$R_3=\frac{\delta R_3\cdot R_{DAC}}{(1-\delta R_3)}, \quad (9)$$

where δR_3 – the required limits of change of R_{3R}.

In case typical resistance of the multiplying DAC $R_{DAC} = 3.5$ kΩ, $\delta R_3 = 20$ %, then $R_3 = 875$ Ω, if $\delta R_3 = 30$ %, then $R_3 = 1500$ Ω. Therefore constant resistances of the bridge are quite high compared to the typical resistances of the strain gauges (100–500 Ω). This kind of setup is not preferred.

Required step of R_{3DAC} resistance change is [4]

$$\delta R_{3DAC}=\frac{\delta R_d\,\delta R_m}{M\cdot 100}, \quad (10)$$

where δR_d – value of the maximum measured strain (upper limit); δR_m – maximum allowed error of the strain measurement; M – minimal required number of steps in measurement range.

Required number of DAC's bits

$$n\geq\frac{1}{\log 2}\log\frac{\Delta R_3}{\Delta R_{ml}}, \quad (11)$$

where ΔR_3 – change range of resistance R_3; ΔR_{ml} – maximum strain measurement inaccuracy allowed.

In case $M = 100$ and $\delta R_d = 10$ %, it is obtained that $n \geq 12$ bit, in case $M = 1000$, and $\delta R_d = 5$ %, then $n > 17$ bit.

Methods of digital balancing of currents

Methods for measuring small resistance changes using balancing of currents are proposed in [3]. Possible implementation of digitally regulated current sources is shown in [4].

Model of the circuit implementing digital balancing of currents and taking into account resistances of connecting wires is shown in Fig. 2.

Circuit with regulated current I_2. Circuit is balanced ($U_{12} = 0$), when $I_1 = I_2$, $R_{11} = R_{12}$. Changing resistance of the active strain gauge R_{s1} circuit gets unbalanced and voltage U_{12} is not zero. Controller unit CU generates control code which changes current I_2 of the regulated current source so that U_{12} is zero again, and equation is true

$$0=I_1 R_{11}-I_2 R_{22}, \quad (12)$$

where $R_{11} = R_{s1} + R_{w1} + R_{A1}$ and $R_{22} = R_{s2} + R_{w2} + R_{A2}$ – resultant resistance of the first and second part of the scheme; R_{A1} ir R_{A2} – resistance of supporting resistors of parts of the scheme with active and compensating strain gauge.

New code value is obtained. Result of the strain measurement as in previous cases is difference between initial code value (resistance of a strain gauge on the construction without load) and code value after construction is under load. Code of the measured resistance change (strain) is

$$m_i = \frac{2^n I_1}{I_{\max}} \delta R_{s1i}, \quad (13)$$

where n – number of bits of DAC in regulated current source, I_1 – obtained value of current of the first current source, $I_{\max}$ – maximum value of the regulated source output; $\delta R_{j1i} = \Delta R_{s1i}/R_{s2}$, ΔR_{s1i} – resistance change of the active strain gauge.

As it is seen from (13), the obtained value of difference of currents is directly proportional to the measured resistance change. In analogy with digital balancing of bridge in this case difference of resistance of active and passive strain gauges and influence of resistance of connecting wires are eliminated as well.

From (10) it is also seen that using current sources with $R_{A1} = R_{A2} = 0$ (Fig. 2) measurement result will not change.

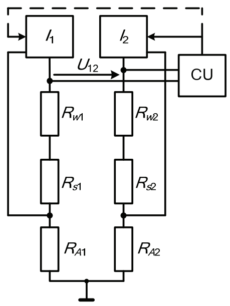

Fig. 2. Model of the circuit of digital current balancing: I_1, I_2 – digitally regulated current sources; CU – control unit

Circuit with regulated I_1 (current through active strain gauge). Using the same model (Fig. 2) after balance is lost because of change of resistance of active strain gauge, current I_1 is changed until circuit is balanced again.

After the same calculations difference of codes of two measurements is

$$m_a = \frac{2^n I_2}{I_{\max}} \frac{\Delta R_{s1i}(2R_{s1} + 2\Delta R_{s10} + 2\Delta R_{w1} - R_{s2})}{(R_{s1} + \Delta R_{s10} + \Delta R_{w1} + \Delta R_{s1i})(R_{s1} + \Delta R_{s10} + \Delta R_{w1})}. \quad (14)$$

The equation obtained is rather complex and code is not directly proportional to the measured resistance change and therefore it is obvious that it is better to use circuit with balanced current I_2.

Balancing of currents by using one current source. A new circuit of measurement of small resistance changes implementing one current source is proposed (Fig. 3). In analogy with previous circuits circuit contains two parts – measurement part and compensating part but in this case only one digitally regulated current source is used. Current is switched between measurements and compensating circuits by electronic switch S. Measurement is performed in the following way.

Switch is set to upper position. Control unit compares voltage drop U_j of active strain gauge with current I_i through it and reference voltage U_0.

Control unit changes digital code of the regulated current source so that the equation is true

$$U_0 = I_i R_i, \quad (15)$$

where I_i – obtained current value and R_i – resistance of the measured circuit (measurement or compensating).

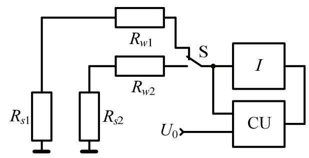

Fig. 3. Model of the digital balancing using one current source

After that switch is set to the bottom position and measurement is repeated for compensating circuit.

It is obvious that after performing these 2 measurements equation (12) is true just the measurements are compared not between each other but rather to the reference voltage U_0 one after another.

Circuit is less complex compared to Fig. 2. In this case influence of differences of current sources such as drifts (as measurements may be performed in long period of time – hours, days, months or even years in monitoring applications) are eliminated.

In multipoint applications electronic switches S are widely used for switching channels to the measurement circuits. By using MOSFET high-current low resistance electronic switches with resistance of the open channel $\leq 0{,}1\ \Omega$ it is possible to eliminate drifts of the current source as measurement process is short (millisecond range) and therefore drifts between measurement of the active gauge and the compensating one may be neglected. By using twisted pair cables for strain gauge connection it is possible to move electronic switch directly to the gauges and for both measurements connecting wires will be the same eliminating differences of the wires. Therefore this newly proposed circuit has certain advantages.

Resistance change is measured the same way as in previous cases: first in two steps difference of resistance of strain gauges and connecting wires are obtained and then measurement of the strain (resistance change of active strain gauges) of loaded construction is performed in preset moments of time. Using (13) and codes obtained from CU resistance change is calculated.

Required range of current source depends on max possible range of the measured resistance. In case strains gauges have strain range from ± 1,5 % to ± 20 %.

In this case range of current source should be

$$I_m \geq \frac{I_1 R_{mm}}{R_A + R_{s1}}, \quad (16)$$

where R_{mm} – range of resistance change of strain gauge.

In case $I_1 = 5$ mA, $R_A = R_{s1} = 100\ \Omega$, $R_{mm} = 30\ \Omega$, required current range is $I_m \geq 0.75$ mA.

Resolution of measurement equipment should be M times less than maximum value. Similarly as well as in a case with Wheatstone bridge, it is necessary DAC the having

$$n \geq \frac{\log M}{\log 2} \tag{17}$$

bits. Therefore for monitoring equipment it is required to have $n \geq 7$ bit and for laboratory equipment – $n \geq 10$ bit regulated current source.

It is obvious that such current sources can be built by using standard DACs and even may be improved. Furthermore unlike in digitally balanced Wheatstone bridges DAC of any type can be used.

Conclusions

1. Equations of resulting code of digitally balanced Wheatstone bridge methods and digital balancing of currents methods are obtained.
2. In the case of digitally balance Wheatstone bridge it is recommended to use digitally controlled resistance on the side with passive strain gauge of the bridge. In this case resulting code is directly proportional to the resistance change measured (linear dependency).
3. New circuit of small resistance changes measurement by using digitally balanced currents with one digitally regulated current source is proposed and investigated. It is shown that the equations are the same as obtained for balanced currents method with two current sources. It is shown that the measurement results of circuit with one current source are less influenced by current source drifts.
4. It is shown that for circuits with regulated current sources it is possible to use any type of DAC and these may be 2-3 bits less for obtaining the same resolution.

References

1. **Kvedaras R., Kvedaras V.** Strain Measurements and Monitoring of Constructions // Electronics and Electrical Engineering. – Kaunas: Technologija, 2008. – No. 1(81). – P. 65–68.
2. **Kvedaras R., Kvedaras V., Martavičius R.** Elektroninė sistema unikalių konstrukcijų būsenos pokyčiams įvertinti // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2003. – Nr. 6(48). – P.28–32.
3. **Kasemaa A., Annus P.** CMOS Technology based Current Source with Harmonic Reducing Properties // Electronics and Electrical Engineering. – Kaunas: Technologija, 2010. – No. 10(106). – P. 143–146.
4. **Masiulionis R.** Deformacijų matavimo balansuojant sroves metodo tyrimas // Mokslas – Lietuvos ateitis. – Vilnius: Technika, 2010. – T. 2. – Nr. 1. – P. 68–72.
5. **Chen G., Deng Y., Sun L., Xu T.** A Modified Algorithm for Reducing Calculation Errors in Large Strain Measurement with Strain Gauges // Applied Mechanics and Materials. – Switzerland: Trans Tech Publications, 2008. – Vol. 13–14. – P. 261–264.

Received 2011 03 22

R. Masiulionis, V. Kvedaras, R. Kvedaras. Analysis of Balancing Methods of Measurement of Small Resistance Changes // Electronics and Electrical Engineering. – Kaunas: Technologija, 2011. – No. 8(114). – P. 3–6.

Methods of measurement of small resistance changes by using digitally balanced Wheatstone bridge and digitally balancing currents are analysed in the paper. Equations for resistance change measurement code are obtained for Wheatstone bridge using regulated resistance connected in parallel to bridge resistance as well as for measurements using digitally regulated current source. It is shown that using regulation on the passive side of the circuit is more preferred because linear simple dependencies of the measured resistance change to the resulting code are obtained in these cases. New serial method of digital balancing of currents is proposed and investigated. It is shown that this method has more advantages compared to using two current sources. Ill. 3, bibl. 5 (in English; abstracts in English and Lithuanian).

R. Masiulionis, V. Kvedaras, R. Kvedaras. Mažų varžų pokyčių balansavimo metodų analizė // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 8(114). – P. 3–6.

Straipsnyje pateikiama mažų varžų pokyčių matavimo balansuojamu Wheatstone‘o tilteliu ir balansuojant sroves metodų analizė. Sukurtos pokyčių matavimo metu gautų kodų išraiškos tiek balansuojant Wheatstone‘o tiltelį lygiagrečiai su jo pastoviosiomis varžomis prijungus skaitmeniniu būdu reguliuojamas varžas, tiek maitinant matavimo grandinę iš srovės šaltinio ir balansuojant schemą skaitmeniniu būdu keičiant srovės dydį. Gautos išraiškos rodo, kad tikslinga reguliuoti varžos ar srovės dydį pasyviojoje matavimo grandinės dalyje. Pasiūlytas ir išnagrinėtas naujas nuoseklusis srovių balansavimo metodas. Parodyta, kad naujasis metodas yra pranašesnis, palyginti su srovių balansavimu naudojant du srovės šaltinius. Il. 3, bibl. 5 (anglų kalba; santraukos anglų ir lietuvių k.).