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METHODS OF STRAIN MEASUREMENTS IN CONSTRUCTION MONITORING SYSTEMS

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ABSTRACT

Results of analysis of recent accidents in public buildings are presented. It is shown that construction state identification systems are integral part of public and local warning and security systems. Structure of construction of state identification system is proposed and analysed. It is established that in order to ensure wide usage of such systems it is necessary to solve some scientific problems. Solution for multipoint measurement of strain as one of the most important parameter for construction state identification is proposed. It is shown that measurements of strain by using closed-loop self-balancing system ensure necessary resolution with high accuracy and can be used in multipoint measurements. Two closed-loop self-balancing systems using digitally balanced Wheatstone bridge and balancing of currents are presented and analysed.

KEYWORDS

Stain measurement, Multi-channel strain measurement, Digitally Balanced Wheatstone Bridge, Digital balancing of currents

1. INTRODUCTION

Several buildings constructed of lightweight steel or concrete structures have collapsed in recent years. Unfortunately in some of these collapses people lives were lost and every case huge financial losses were sustained. There were several accidents in the Europe recently – in Lithuania, Russia, Poland and Germany. Most frequently such collapses occur during winter time when structures are exposed to additional load because of the snow and ice which is accumulating on a roof, strong winds, and other exposures that overload the structures of the building.

It would be possible to save human lives if people were notified about a critical condition of building structures at least 10 – 20 minutes before collapse. In case it is known of critical conditions 1 – 2 hours before the collapse it is even possible to keep a building itself. In this case for example it is possible to clear roof of a building from snow reducing critical loads or take other measures to reduce critical load or strengthen the structure to be able to carry increased loads. It is not possible to determine the load of a structure visually or by other simple observation methods. Therefore automatic signalling systems are to be used. When certain parameters of the structure are exceeding defined threshold values, the system must set an alarm informing about arising danger. Development and implementation of such constant monitoring systems is not common yet. Authors are analyzing possibilities to build and use such systems.

2. REQUIREMENTS FOR THE MONITORING SYSTEM

Basic constructive elements of a light structures used in various buildings are usually steel farms. To identify state of steel constructions automatically some parameter that can be changed to electrical value and then measured should be found. A set of different parameters that are measured on the construction with the mathematical model of a construction applied will result in the unique state of the construction which is evaluated for the threshold value.

A set of the physical parameters that are to be measured on the construction may be different in each case and each unique construction. But for the most cases displacement (deformation), strain, force and acceleration parameters are measured. Nevertheless most of these above-mentioned parameters are converted to the strain measurements and therefore measurement of strain is one of the most important issues to be solved for such systems.

There is a rigid relation between durability and strain of a structure element in steel structures [1]. On the other hand, size of strain of a steel construction even in case of exposure of high loads is rather small. For example, if on a steel wire with cross-section $A = 4\cdot10^{-4}$ m^2 and length l = 10 m, modulus of elasticity $E = 6{,}89\cdot10^{10}$ Pa, force of size F = 1000 N is applied the relative strain will be

$$\varepsilon_t = \frac{F}{EA} = 3.63\cdot10^{-5}. \tag{1}$$

Strain can be measured using different techniques but, for constant monitoring and applications where higher number of points needs to measured, reliable and comparably low-cost resistive strain gauges are used. Resistive strain gauges transform strain of the gauge to small change of its resistance. These small changes are to be measured.

In a complex building there are many carrying structures (or to say typical points of those structures) condition of which individually or in groups defines state of the building and as a result safety of building operation. Therefore monitoring systems should be multi-channel and in most cases would have up to several hundreds or even more channels. Designers of a building or a structure should apply mathematical model and obtain such critical points for measuring parameters of the construction and threshold values for these parameters. During the construction respective gauges should be implemented into the structure and connected to the measurement system.

Concluding the aforementioned it is clear that monitoring system must a) determine the current condition of a building (structure, bridge, roof, etc.); b) define small changes of parameters (strain, vibration, acceleration, etc.) of physical quantities in specific points of a structure; c) transfer results of an estimation to the data-processing centre where results are processed, mathematical model of a structure is applied and result is carried out [2]. According to these results decision on the current condition of a structure is made (automatically or by human operator).

3. MULTI-CHANNEL CONSTRUCTION MONITORING SYSTEM

According to earlier experience further conclusions are made:

1. The system should be as simple as possible. In this case the quantity of error sources, amount of

errors and therefore the price is relatively low ensuring relatively low-cost service of the system.

2. The system should have the feedback configuration ensuring that the influence of a part of error sources is compensated.

3. The system having many channels (up to several hundreds) should be designed in a block principle. In this case measurement units are placed in a relatively short distance from measurement points and the system can be easily adapted for different purposes.

It appears that the structure and problems to be solved for such systems are practically identical irrespective of measured parameters of a structure, an end result or a scope of the system and is a general distributed data-acquisition system. Similar system design was proposed [3] but it was relying on the individual sensors and not implementing groups of sensors. Grouping of sensors ensure that the relatively expensive measurement unit is not used for one individual sensor but rather a sensor group which simplifies the system and decrease its price. Created general block diagram of monitoring system is submitted on a Figure 1.

The developed structure is highly agile – it is possible to measure and store various parameters of the object state, if necessary adding additional measuring units. Virtually it is possible to achieve a non-limited number of measurement points. It is possible to construct monitoring system gradually by adding additional measurement units upon necessity. It is possible to measure, accumulate data, and to analyze other important parameters of structure by only changing sensors, measuring units and/or programs.

In this system all signals from measuring units have digital form and can be transferred through the Internet or Intranet. It is possible to apply standard Wireless LAN systems and overcome one of the biggest lacks of the systems currently in use – communication lines that are relatively short and dealing with analogue signals. It is established that implementation of measurement lines in buildings (it is especially applicable in already build-up "working" buildings) is quite heavy and expensive job. At the same time measurement lines are mounted near cables of communications, electric supply and control lines are subject of influence of noises. It results to increase of errors and reduction of reliability of the system.

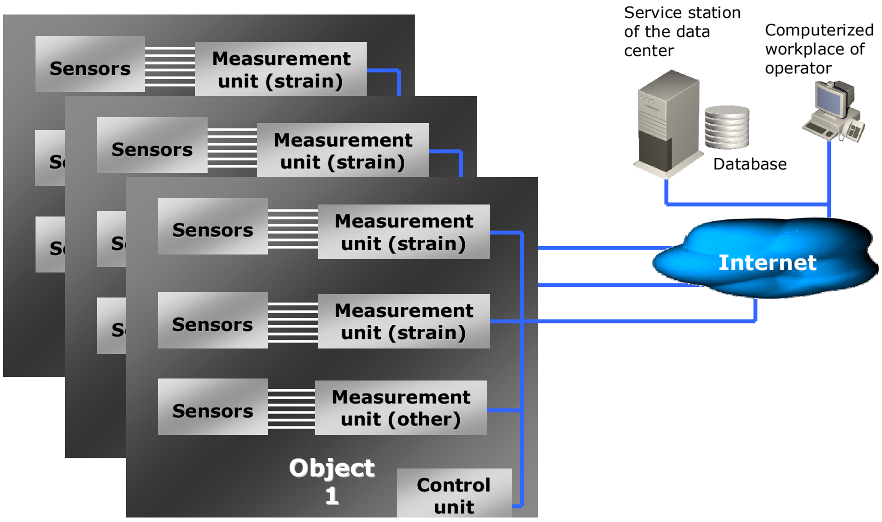

Figure 1. Block diagram of monitoring system

Therefore structure of the system that allows reducing of the measurement and communication lines is more preferable and cheaper at the same time. System proposed ensures that location of separate measuring blocks can be established in immediate proximity from measured structures and at the same time length of connecting cables can be reduced reducing errors of measurement.

The central server and workplace of tracking and management in this case can be placed at any location that is the same or different from the building monitored. Furthermore the centralized system can monitor several buildings or even all required to monitor buildings of the city and build metropolitan area monitoring system. Later such system might be integrated into centralized emergency services system (such as 112, etc.) for fast reaction to any alarms generated by the system.

Building of such systems based on strain measurement has several difficulties to deal with. Earlier it has been shown; that the size of deformation is rather small, therefore the change of strain-gauge resistance is also small:

$$\Delta R = RS\varepsilon_t; \quad (2)$$

where R – strain-gauge resistance; ε_t – strain of construction; S – sensitivity ratio.

For example in case of change of strain of steel farm is in range $\varepsilon_t = 10^{-6}...10^{-3}$, strain-gauge resistance is $R = 120\ \Omega$ and sensitivity ratio $S = 2$, the change of resistance of strain gauge is $\Delta R = (0.00024…0.24)\ \Omega$. It is a very small value and typically non-balanced Wheatstone bridges are used for such measurements. It has been shown that application of non-balanced Wheatstone bridge without feedback is not convenient for such type of applications where several strain gauges are connected to the same measurement unit [4, 5]. Nevertheless nearly all resistive strain gauge measurement systems in the market are based on non-balanced Wheatstone bridge application and therefore are struggling to expand systems as implementation, expansion and maintenance of such systems are costly. Authors have developed a digitally balanced Wheatstone bridge that allows implementation of the monitoring system proposed.

3.1. Digitally Balanced Wheatstone Bridge for strain measurement system

The method for measurement of small resistance changes by using automatically digitally balanced Wheatstone bridge has been developed by authors [4–6]. Method is based on using of R-2R DAC as balancing element. General structure of the method is provided in Figure 2. The resistance of the sensor in this case is:

$$R_x = R_1 = R_2 R_3 \frac{R_4 N + 2^n R_{IN}}{2^n R_4 R_{IN}}; \quad (3)$$

where n – number of DAC bits, R_{IN} – resistance of DAC input (resistance R-2R matrix elements), N – decimal DAC control code.

It is established that proposed method allows avoiding multiple disadvantages that are typical to the classic system. The created method is a closed-loop method. Wheatstone bridged is balanced by changing resistance of DAC and checking whether the balance is exceeded or not. As code controlled resistance DAC of R-2R type is used. MOSFET switches are used for connection and disconnection of different channels. These switches have resistance of the open channel less than 0.05 Ω and therefore the influence of these resistors to the measurement result is minimal.

The main advantages of this method are:

Closed-loop system is regulating itself and therefore reducing influence of external noise to evaluation results.

System is not highly influenced by length and resistance of the gauge connecting wires and therefore can be easily used as multi-channel system by multiplexing gauges using low resistance switches.

The strain measurement in the system is made in two stages: the status of the bridge after gluing gauges on a construction to be measured, and the load is not applied to the structure. Then the status of the loaded construction is measured. The size of strain is defined as a difference of these two measures. Analysis and experimental research has shown that this method can be used for monitoring tasks with

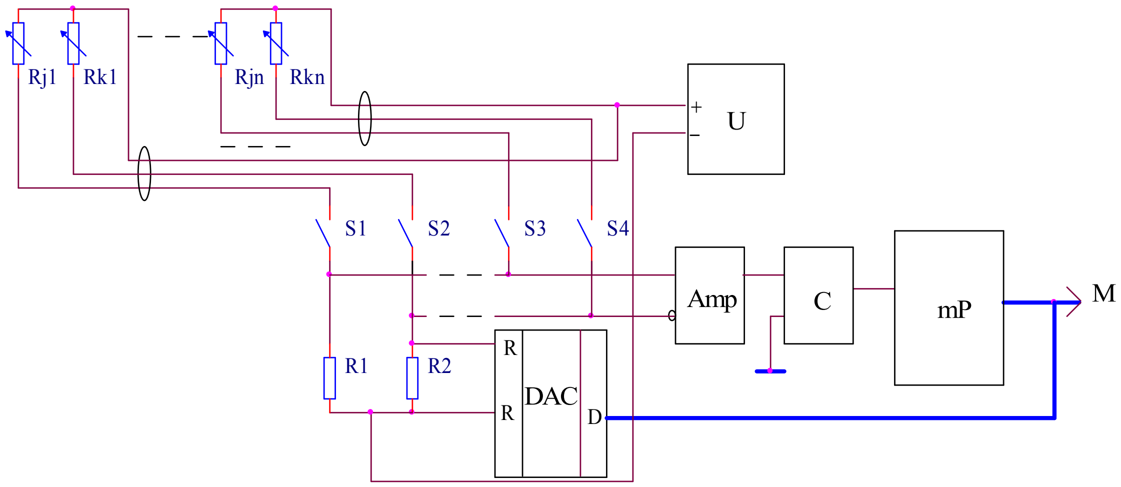

Figure 2. Functional scheme of the method for evaluation of small resistance changes by using automatically digitally balanced Wheatstone bridge with R-2R DAC. U – Bridge excitation supply unit; Amp – Op Amp; C – comparator; mP – microprocessor; DAC – digital-to-analog converter; S – switch; Rji – strain gauge; Rki – compensation gauge; M – output code

resolution up to 2^8. The model of the system was checked during 24 hours and worked with 10 m length cables. The measurement errors are not established for all this period of time.

Nevertheless system with digitally balanced Wheatstone bridge has several disadvantages:

The length of the wires from the measurement unit to the gauges is limited by the resistance of the wire and influence of the noises.

Resistance range of usable strain gauges and maximum resistance change limits are limited by the internal resistance of R-2R matrix.

Selection of DAC's with direct access to the R-2R matrix is rather limited.

Therefore for the specific applications with non-standard strain gauges or in applications where comparably longer wires (> 10 m) are necessary a new closed-loop system has been developed by authors.

3.2. Digital Balancing of Currents for Strain measurement system

The new closed-loop system is based on the balancing two resistive circuits by changing current on one of the circuits. The change of current to maintain balance is proportional to the change of resistance of strain gauge in the corresponding resistive circuit.

Scheme of the method is presented in Figure 3. Both sides of the scheme are complemented of equal precise reference resistors $R_1 = R_2 = R_A$ and two strain gauges R_{j1} ir R_{j2}. Gauges are of the same type but their initial values may vary by value R_s. Because of this initial difference it is necessary to balance the circuit as it is done in Balanced Wheatstone Bridge method in order to achieve that voltage U_{12} is equal to zero. When this is achieved, the following expression is true:

$$0 = I_1 R_{j1} + I_1 R_A - I_2 R_{j2} - I_2 R_A . \quad (4)$$

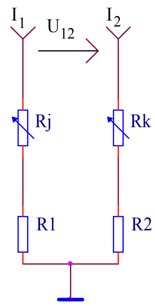

Figure 3. Scheme of Currents balancing method

Currents are digitally balanced using current source controlled by DAC. For example current I_2 is changed by steps I_{MRS}, where $I_{MRS} = \frac{I_m}{2^n}$ – the least step of current change, I_m – maximum value of current, n – resolution of DAC. Current I_2 after balancing is equal to:

$$I_2 = I_1 + m\frac{I_m}{2^n}, \tag{5}$$

where m – decimal number of I_{MRS} steps.

After applying load to the construction and change of resistance of gauges to $R_{j1} = R_{j2} + R_m + R_S$, balancing code of resistance change because of strain will be:

$$m_m = 2^n \frac{I_1}{I_m} \cdot \frac{R_m + R_S}{R_A + R_{j2}}; \tag{6}$$

where R_m – change of gauges' resistance because of load.

The resistance change of gauges because of strain is equal to:

$$M = m_m - m = 2^n \frac{I_1}{I_m} \cdot \frac{R_m}{R_A + R_{j2}}. \tag{7}$$

Based on this method functional diagram of current balancing system has been developed by authors and is presented in Fig. 4. By using current balancing method it is possible to avoid number of external influences such as electric noises and resistance of the connectors and connecting wires. DACs used for this method does not require direct access to the R-2R matrix and therefore the selection of low-priced DACs available in the market is much wider. By using current balancing method it is possible to use gauges of much wider resistance range and also gauges with higher strain resistance change rates.

4. CONCLUSIONS

1. It is possible to avoid unexpected construction collapses if the constructions are constantly monitored and preventive actions are taken.

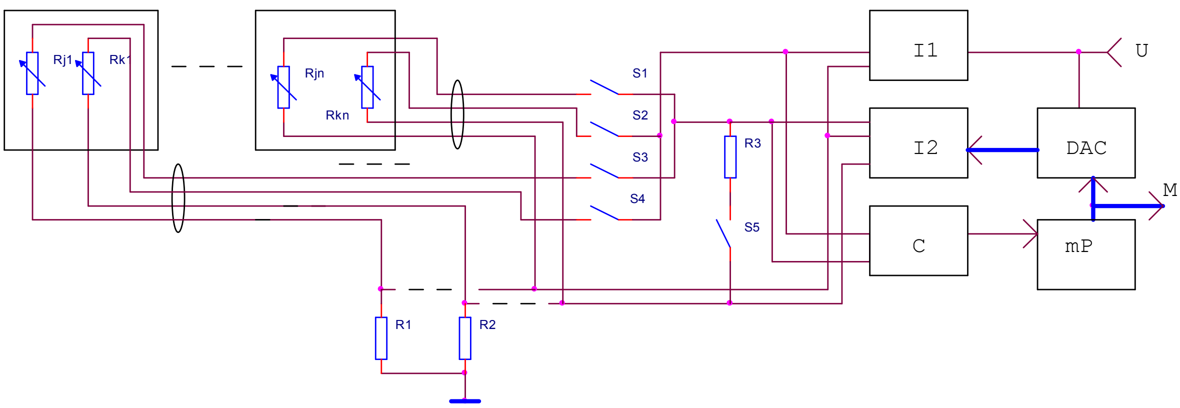

Figure 4. The strain measurement method with compensation of currents. S – switch; C – comparator; I1– current source; I2 – adjustable current source; DAC – digital to analog converter, mP – microprocessor; U – reference voltage; M – output code

2. Most of construction monitoring systems relying on direct and indirect measurement of strain on multiple points of construction.

3. The method for evaluation of small changes of resistance based on automatically digitally balanced Wheatstone Resistance Bridge using DAC R-2R matrix is developed and investigated. It enables to improve evaluation of small changes of resistance and to avoid disadvantages observed in classic non-balanced Wheatstone bridge applications. The accuracy of the method is not influenced by the stability of the bridge excitation voltage and the feedback nature of the system reduces the influence of external interferences to evaluation result.

4. In order to avoid influence of the connecting wires and to improve flexibility of strain measurement by using gauges of wider resistance range a new strain measurement closed-loop self-balancing method with balancing currents has been developed and investigated.

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