Investigation of Bucket Wheel Excavator Lattice Structure Internal Stress in Harsh Environment through a Remote Measurement System

M Risteiu¹, R Dobra¹, I Andras², M Roventa² and A Lorincz³
¹ Computer Science and Engineering Department, “1 Decembrie 1918” University of Alba Iulia, Gabriel Bethlen Str. No.5, 510009 Alba Iulia, Romania
² Machinery Department, University of Petrosani, University Street, No. 11, Petrosani Romania
³ Automation Department, University of Petrosani, University Street, No. 11, Petrosani Romania

E-mail: mristeiu@uab.ro

Abstract. The paper shows the results of a lab model for strain gauges based measuring system for multiple measuring heads of the mechanical stress in lattice structures of the bucket wheel excavator for open pit mines- harsh environment. The system is designed around a microcontroller system. Because of specific working conditions, the measuring system sends data to a processing system (a PC with Matlab software), we have implemented a secure communication solution based on ISM standard, by using NRF24L01 module. The transceiver contains a fully integrated frequency synthesizer based on crystal oscillator, and a Enhanced ShockBurst™ protocol engine. The proposed solution has a current consumption around 9.0 mA at an output power of -6dBm and 12.3mA in RX mode. Built-in Power Down and Standby modes makes power saving easily realizable for our solution battery powered. The stress from structures is taken by specific strain gauges adapted to low frequency vibrations.

We are using a precision 24-bit analog-to-digital converter (ADC) designed for weigh scales and industrial control applications to interface directly with a bridge sensor-instrumentation device, with low drift voltage, low noise, common mode rejection signal, frequency and temperature stability. As backup implementation for measurements a high speed storage implementation is used.

1. Introduction
The investigation of the bucket wheel excavator is done focusing on two different aspects: energy management in terms of efficiency, and excavator stability.

On the other hand, the two aspects are related each other because, because the stability issue influences the consumption of electrical energy, and/or the bucket wheel spare parts consumption.

The bucket wheel excavator is a structure complicated from mechanical and electrical point of view. Main parts of the excavator are mechanical connected each other through lattice frames and supporting cables (figure 1).
As it can be seen, the lattice structure transmits the mechanical efforts in entire structure, when there is an excitation. Along its structure, the lattice is stressed differently in different points of suspension.

The purpose of this paper is to investigate the mechanical stress in site and harsh environment. The method of the investigation starts from two traditional solutions (analogic strain gauges measurement and transmission).

2. Infrastructure and Methods

For the stress monitoring, literature doesn’t recommend a specific strain gauge, but the prototyping purpose, we have used Kyowa products with gauge characteristics: Uniaxial, 120 Ω, 37.00 mm x 5.20 mm, 11 ppm/°C, two wires.

2.1. Stress measurement considerations

When a material receives a tensile force F, it has a stress σ that corresponds to the applied force. In proportion to the stress, the cross-section contracts and the length elongates by ΔL from the length L the material had before receiving the tensile force (see figure 2).

The ratio of the elongation to the original length is called a tensile strain and is expressed as follows:

$$\varepsilon = \frac{\Delta L}{L}$$

(1)

According with measuring experience, the tensile strain is expressed with a numeric value plus x10⁻⁶ strain, με or μm/m.

The relation between stress and the strain initiated in a material by an applied force is expressed as follows based on Hooke’s law:

$$\sigma = E \varepsilon$$

σ: Stress, E: Elastic modulus, ε: Strain.
Stress is thus obtained by multiplying strain by the elastic modulus. When a material receives a tensile force, it elongates in the axial direction while contracting in the transverse direction. Elongation in the axial direction is called longitudinal strain and contraction in the transverse direction, transverse strain [11]. The absolute value of the ratio between the longitudinal strain and transverse strain is called Poisson's ratio, which is expressed as follows:

\[ \nu = \frac{\varepsilon_1}{\varepsilon_2}, \text{ with } \nu \text{ is Poisson's ratio, } \varepsilon_1 \text{ is longitudinal strain, } \varepsilon_2 \text{ is transverse strain} \]  

(2)

Poisson's ratio differs depending on the material. For reference, major industrial materials have the following mechanical properties including Poisson's ratio.

For the experimental setup, we detail here the mechanical properties of the used material—Carbon steel (C0.1 - 0.25%) with:

- Young's Modulus E (GPa) - 205;
- Shearing Modulus G (GPa) - 78;
- Tensile Strength (MPa) - 363 - 441;
- Poisson's Ratio - 0.23 - 0.3

Each metal has its specific resistance. An external tensile force (compressive force) increases (decreases) the resistance by elongating (contracting) it. Suppose the original resistance is R and a strain-initiated change in resistance is \( \Delta R \). Then, the following relation is concluded:

\[ \frac{\Delta R}{R} = K_s \frac{\Delta L}{L} = K_s \varepsilon , \text{ where, } K_s \text{ is a gage factor, the coefficient expressing strain gage sensitivity.} \]

General-purpose strain gauges use copper-nickel or nickel-chrome alloy for the resistive element, and the gage factor provided by these alloys is approximately 2.

2.1.1. Hardware implementation

Next picture shows standard referencing of the strain gauge used [5]:

\[ \text{Figure 3. Typical structure of the KFG-2-120-C15-11 strain gauge.} \]
Positioning the strain gauge in site:

![Image](image1.png)

**Figure 4.** The designed positioning and shielding of the strain gauge.

One measuring head consists in a structure like next figure:

![Image](image2.png)

**Figure 5.** Bridge connected typical architecture of the two active gauges (RG1 for measuring, RG2 for compensation).

With the mathematical model:

\[
e_{o} = \frac{R_{1}R_{3} - R_{2}R_{4}}{(R_{1} + R_{2})(R_{3} + R_{4})} E = \frac{1}{4} \frac{\Delta R}{R} E = \frac{1}{4} K_{se} E
\]

Then we decided to use an instrumentation amplifier (see AO from upper figure) who is providing a high quality reference voltage, and it takes both gauges signal and processes them.

![Image](image3.png)

**Figure 6.** The proposed interface for one measuring head (with two active gauges).
2.2. Layout design considerations

The output of the AO (who includes analog digital converter) is then led to the processing device. The block diagram of the measuring system is shown next.

![Block diagram of the measuring system](image)

**Figure 7.** The proposed architecture of the designed measuring system.

One’s the data is acquired from ADC (figure 6) it is provided to a microcontroller-based architecture that executes some processes locally, then sends values of elongations outside of the lattice structure (up to 60 m away), to a coordination device.

In our experimental approach, we have used 10 measuring heads (for 10 measuring points in lattice).

The values of all 10 measured elongations are sent synchronously for latter processing.

The dimensional layout of the system looks like next figure:

![Dimensional layout](image)

**Figure 8.** The dimensional layout required for harsh environment protection.

2.3. Measuring system architecture considerations

Because this research activity is a part of a research project, that requires a larger measurement infrastructure, the measuring system architecture is shown in figure 9.

The measurement module (supplied locally) measure and process some data, prepare and send to another module (called coordinator) that is connected via USB to a PC (figure 9) where runs an LabVIEW application that display real time values, historical data (figure 10).

This application is able also to control in PWM signals some hydraulically motor (as expansion) – see next figure.
Figure 9. The architecture of the open and extensible system for complex and heterogeneous measurements.

Figure 10. The software interface for real time data monitoring and control.

The intermediary device, called coordinator, is able (by software) to receive simultaneously data from more than one measuring modules.

3. Results and discussions
The application acquires data and processes it according with well-known and typical procedures. It has been calibrated to display relative elongations (µm/m).
During measuring procedures, two significant measurements have been detected:
- Simultaneously distribution of the elongation in the complex contour of the frame (figure 11).
- Comparison measurements between top and bottom horizontal parts of the frames (heads 1 and 2);

First, in the overlapped graphs, two of them are distinguished- high amplitude and fixed repetition.
It is required a spectral analysis of these measured values. All the other are a least 10 times lower.
For the second part we have used a typical function from LabVIEW [5]:

Figure 11. The synchronous display of six measured elongation values (1-6 are measurement heads).

Figure 12. The designed subVI of the application- diagram window.
One of the most recognized facilities of the LabVIEW functions is the easy access to the parameters configuration. According with [6,7], the accuracy of the FFT processing is influenced by the sampling rate, the number of samples taken into account for each FFT period, and the “envelope” of the interpolating function of the main frequency.

With the dedicated front panel:

![Figure 13. The designed subVI of the application- front panel window.](image)

Then we “insert” the values from the measuring heads 1, 2, and after FFT filtering and processing we obtain:

![Figure 14. The designed FFT application- front panel window.](image)

There are two main frequencies (4 Hz, and 8 Hz).

The frequency of 4 Hz represents the transmitted tension when a bucket enter into the coal (they wheel has 16 buckets, with a speed rotation 15 rot/min). According with our processing method, the second frequency is double on the “excitation” frequency. It looks like a second harmonics, with almost similar amplitude. On the other hand, the effects of cutting are transmitted along the frame as a mechanical oscillation. It is propagating along the frame and it reflects it back to the bucket wheel, with the behavior of elastic rope. It has been described complete in [8,10], where they propose an investigation of this behavior when metallic and elastic structure is very long- which is also our case. In them conclusions, in typical conditions, there is a sum of oscillating energy.

3.1 Discussion. Future work

Even it is a huge work, it is important to create a model for this elastic structure, than to test it by measurements in different frames the elongation of the sensor 1 and 2. The purpose of this investigation is to find the worst case elongation.
By creating the elastic model of the system, a better investigation might be done by vibration monitoring. The measurements might include also the suspension cables. The compression stress in lattice’s frame should be also investigated thinking that in the frames are welded.

4. Conclusions
In this paper we have investigated elongations, than stress in frames that composed the lattice structure of the bucket wheel excavator.

We have identified, in real site investigation, that the stress generated by the elongation is significant in top and bottom parts of the lattice frames.

The elongation, in dynamic process, has an oscillating behavior. It should be tested according with this variation. The measurement of bucket wheel excavator lattice structure internal stress was performed using KFG-2-120-C15-11 strain gauge.

They are still parameters that must be taken into account for advanced processing.

References
[1] *** ITAtech Report n°3-V2 2015 – Guidelines for Remote Measurements Monitoring Systems – Layout: Longrine – Avignon – France
[2] *** Move into the future with reliable measurement 2016 KYOWA technical report
[3] Bandyopadhyay L K and Chaulya S K 2015 Wireless communication in underground mines 2015
[4] *** Kyowa strain gauges application note 5
[5] Lin W 2015 FAST Fourier Transform (FFT) and Digital Filtering Using LabVIEW Application Note
[6] Tomar S K and Arora A 2007 Erratum to “Reflection and transmission of elastic waves at an elastic/porous solid saturated by two immiscible fluids” [Int. J. Solids Struct. 43 (2006) 1991–2013] International Journal of Solids and Structures 44 (17) 5796-5800
[7] Bošnjak S, Petković Z, Zrnić N, Pantelić M and Obradović A 2010 Failure analysis and redesign of the bucket wheel excavator two-wheel bogie Engineering Failure Analysis 17(2) 473-485
[8] Gottvald J 2010 The calculation and measurement of the natural frequencies of the bucket wheel excavator SchRs 1320/4x30 Transport 25(3) 269-277
[9] Savković M et al. 2011 Analysis of the axle fracture of the bucket wheel excavator Engineering Failure Analysis 18(1) 433-441.
[10] Bošnjak S, Pantelić M, Zrnić N, Gnjatović N and Đorđević M 2011 Failure analysis and reconstruction design of the slewing platform mantle of the bucket wheel excavator O&K SchRs 630 Engineering Failure Analysis 18(2) 658-669
[11] Zoller C, Kovacs I and Ridzi M C 2007 Interpolation software to measure mechanical forces on the bucket wheels of the excavators 2nd International Conference ICQME

Acknowledgments
The paper is based on research activity that is the subject of the invention, Installation for in-situ measuring and recording the forces acting upon the teeth of the cutting element in rock shattering machines, Patent number RO 123483 B1

The paper is a part of an European Union research project founded by the Coal and Steel Founding, RFCS agreement No. RFCR-CT-2015-00003 (BEWEXMIN)