MECHATRONIC APPROACH TO INVENTING A NOVEL KIND OF DEFORMETER

Giuma Ali Shneba, Aleksandar Veg, Dražan Kozak, Aleksandar Sedmak

1 Introduction

Strain gauge is a core sensing element in many types of sensors. Substantially they are used for the stress-strain measurements on different kinds of frames and structures. A vast variety of strain gauges are available either for simple or verse specific measurements. Conventional design of deformeter is a resilient piece of metal flexible enough to detect induced stress.

Sometimes, placement of strain gauge (SG) is difficult, particularly in harsh ambient. Under such circumstances application of the deformeter, instead of a single strain gauge, becomes a real need.

Deformeter is a simple sensing element containing one or more strain gauges. History of strain gauge invention is fractioned in two stages. Early, theoretical considerations were introduced by Charles Wheatstone as long ago as 1843, in his first publication on the bridge circuits [1], as well as by William Thomson (1824÷1905, Lord Kelvin after 1892) in his publication in 1856 [2]. Later on, in 1930s an applicable technical solution is invented deformeter (CLD) developed by a fundamental Mechatronic approach [5]. That means, the virtual modeling and other techniques are utilized in order to create a satisfactory operation of the CLD, as the integral part of the measuring chain. Several improvements of CLD were introduced in the optimization process. 3D modelling was aimed not only at pure design, but also at adjustment of its performance under the simulation. The conducted analysis went even a step further, generating a proportional signal on the output contacts of the embedded strain gauge.

2 The strain gauge operation - in principle

When a bar receives a tensile force \( P \), a certain stress \( \sigma \) arises in its body, proportional to the applied force. The cross-section of the bar contracts and the length elongates by \( \Delta L \) from the original length \( L \).

\[ \varepsilon = \frac{\Delta L}{L}, \]

The elongation is called a tensile strain and is expressed as follows:

The concept of a Closed Loop Deformeter (CLD) was invented by Charles Wheatstone as long ago as 1843, in his first publication on the bridge circuits [1], as well as by William Thomson (1824÷1905, Lord Kelvin after 1892) in his publication in 1856 [2]. Later on, in 1930s an applicable technical solution is invented deformeter (CLD) developed by a fundamental Mechatronic approach [5]. That means, the virtual modeling and other techniques are utilized in order to create a satisfactory operation of the CLD, as the integral part of the measuring chain. Several improvements of CLD were introduced in the optimization process. 3D modeling was aimed not only at pure design, but also at adjustment of its performance under the simulation. The conducted analysis went even a step further, generating a proportional signal on the output contacts of the embedded strain gauge.

The elongation is called a tensile strain and is expressed as follows:

\[ \varepsilon = \frac{\Delta L}{L} \]

Strain \( \varepsilon \) is proportional to stress \( \sigma \) (Hooke’s law):
\[ \sigma = E \cdot \varepsilon \]  

up to elastic limit of the material.

Strain gauge consists of electrical resistance material and when stressed detects a proportional change in resistance

\[ \varepsilon = \frac{\Delta L}{L} = \frac{\Delta R}{R} K \]  

where \( R \) is the gauge resistance and \( \Delta R \) is the resistance modulation due to strain, and \( K \) is the gauge factor.

Normally, a resistance change is a tiny amount and requires a Wheatstone bridge circuit to convert it to a perceivable voltage output.

\[ e = \frac{R_1 R_3 - R_2 R_4}{(R_1 + R_2)(R_3 + R_4)} E. \]  

Quantity \( e \) is the voltage output, \( E \) is the excitation voltage, \( R_1 \) is the gauge resistance, and \( R_2 \sim R_4 \) is fixed resistances.

### 3 System description

Signal conditioning of the strain gauge output Fig. 3 develops over several consecutive blocks Fig. 3. In the first step EMI (Electric Magnetic Impulse) unit suppresses high frequency noise. Then the signal undergoes significant amplification rate (500 times) over an instrument amplifier. The main feature of this component is a low noise and low signal offset. Finally, low pass filter removes high frequency impurities from the signal. The operation of such a block composition is simulated in a dedicated software (Filter Lab and LTS piece) before completing the final design of the electronic circuit. After successful virtual verification, the design process continues with PCB manufacturing and component integration.

Much alike, this Mechatronic approach to measuring device development, an innovative CLD is optimized throughout 3D modelling and virtual testing and engineering.

The core idea is to investigate a substantially different design of, particularly, its behavior when exposed to selected loads. Unlike the standard deformeter shape, CLD has tied up opposed ends with a crossed position. In this concept, linear extension of deformeter ends cause very intensive bending in its central part. Thus the measurement of subtle deformation becomes viable, producing a significant signal. The idea of 3D modeling and its verification in a virtual environment is overtaken from former researches in the same Laboratory [4]. The innovative design of CLD is, however, originally arranged the prototype is also carefully tested, by its applicability, linearity and repeatability.

### 3.1 Signal conditioning composition

A fundamental parameter of the strain gauge is its sensitivity to strain. It is expressed as the gauge factor \( (GF) \) depicting the ratio of relative change in electrical resistance to the relative change in length (strain):

\[ GF = \frac{\Delta R}{\Delta L / L} = \frac{R}{\varepsilon}. \]  

The Gauge factor for metallic strain gauges is typically around 2.

Regular strain measurements involve quantities in the range \( 0 \div 10 \, 000 \, (\varepsilon \times 10^{-6}) \). Therefore, a measurement with the strain gauge requires accurate detection of very small changes in resistance. That change of resistance \( \Delta R \) is within overall span \( 480 \, \mu\Omega \div 2,4 \, \Omega \).

### 3.2 Bridge excitation

Strain gauge signal conditioners typically provide a constant voltage source to power the bridge. Most commonly the voltage level is either 3 V or 10 V. A higher excitation voltage generates a higher voltage...
signal, but also causes larger errors due to self-heating. It is of a crucial importance to have very accurate and stable excitation voltage.

If the strain gauge circuit is located a distance away from the signal conditioner and excitation source, a significant error arises due to resistance in the connecting wires. It is advisable to have all electronic devices in the immediate vicinity.

### 3.3 Signal conditioning

The output signal from the strain gauge and bridges is relatively small. In practice, most strain gauge bridges and strain-based transducers will output less than 10 mV/V (10 mV of output per volt of excitation voltage). Therefore, strain gauge signal conditioners usually include amplifiers to boost the signal level to increase measurement resolution and improve signal-to-noise ratio. In order to design a stable, harmonized measuring chain a brief analysis of crucial performance of each stage is conducted. Tab. 1 shows several in consecutive stages in signal generation and conditioning.

The main target in system development is to find out if there are weak points or any misconceptions. Since the CLD is conceived as a spring deformer, and its core element is strain gauge, the output from these two is compared, in order to determine degradation extent. Later analysis, applied over 3D model and lab prototype showed that the 4 time signal rating is within acceptable margins. A very poor output signal from CLD must be significantly amplified and filtered in electronics. Tab. 1 shows obviously that the nature of the signal is preserved, and the filter does no harm in it, while the AD block truly interprets a digital form of the signal. Measuring chain consists of the instrumentation amplifier LTR 1167 which is a high performance component with alow power, and low noise. When processing several signals in parallel a CMOS, 8 channel multiplexer is utilized (MAX 4617). It is popular as a single voltage operated COMS device with low leakage current (1 ± 10 mA). The filter block is designed with modern components which have no effect on signal stability and intensity. Practically all the noise is removed, while the useful signal is kept untouched. Finally the signal is converted into a numerical record within the A/D converter (LTC 1864). It is a 16 bit, 250 ksps ADC.

### Table 1 Overview of signal degradation rate within measuring chain

<table>
<thead>
<tr>
<th>Device</th>
<th>Range</th>
<th>Resolution</th>
<th>Dynamic Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain Gauge</td>
<td>± 0.1 mm</td>
<td>± 0.28 mm</td>
<td>1 : 300</td>
</tr>
<tr>
<td>Proportional Strain</td>
<td>± 10 mm</td>
<td>± 0.1 mm</td>
<td>1 : 100</td>
</tr>
<tr>
<td>CLD</td>
<td>± 30 mm</td>
<td>± 0.28 mm</td>
<td>1 : 100</td>
</tr>
<tr>
<td>Pre-Amplifier</td>
<td>± 2.4 mV</td>
<td>± 0.6 μV</td>
<td>1 : 4000</td>
</tr>
<tr>
<td>SG to AMP voltage</td>
<td>± 13.25 V</td>
<td>± 0.3 mV</td>
<td>1 : 100</td>
</tr>
<tr>
<td>AMP/SG output voltage</td>
<td>± 2.4 mV</td>
<td>± 0.6 μV</td>
<td>1 : 4000</td>
</tr>
<tr>
<td>CLD to AMP voltage</td>
<td>± 7.95 V</td>
<td>± 0.3 mV</td>
<td>1 : 100</td>
</tr>
<tr>
<td>AMP/CLD output voltage</td>
<td>± 1.25 V</td>
<td>± 0.3 mV</td>
<td>1 : 4000</td>
</tr>
<tr>
<td>Measuring instrument (ADC)</td>
<td>± 32 786</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Useful signal degrade</td>
<td>No effect</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 4 CLD 3D modelling

In order to make a truly operational deformer some design analysis was carried out. Selected geometric parameters (spring diameter) were varied, to achieve an optimal stiffness. As a boundary acceptable deformer stiffness it is defined $k_o = 9 \text{ N/mm}$. Fig. 7 shows final shape and size of CLD.

![Final Shape of CLD](image)

During the CAD modelling quite a range of different diameters has been examined. Each CLD model was equipped with the bonded virtual Strain gauge of 10×5 mm dimension. CLDs have been stretched from unloaded, undefined state to the maximal line extension of 10 mm. The margin of the least detectable extension was set to 0.01 mm.

### Table 2 Range of CLD diameters

<table>
<thead>
<tr>
<th>Spring model</th>
<th>$D$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td>60</td>
</tr>
</tbody>
</table>

Numerical analysis was done using the Finite Element Methods. Calculations were done for 4 CLDs different schemes of displacement on CLDs [7] [8]. The most appropriate for calculations of CLD cases of boundary conditions is to fix one end of CLDs and apply displacement at the other end in horizontal direction as shown in Fig. 8. For diagonal tension, the CLD was fixed in direction $-x$-axis and in the $x$-axis direction the displacement was allowed without rotational movement [9].

Any among the selected CLDs 1, 2, 3 and 4 fulfills the required stiffness margin $k_o = 9 \text{ N/mm}$ as shown in...
The next parameter to verify was maximal stress, achieved in the spring by its full line extension. This parameter was important in order to induce redundant signal on the strain gauge, incorporated in CLD. Diagram, Fig. 10 shows the proportion between introduced line extensions vs. stress created at the point of the bonded strain gauge. Springs are exposed up to the yield strength of the spring steel, $\sigma_{0.2} = 1080$ MPa, or up to the absolute line extension of 10 mm.

Except the spring no. 1, all other springs are far from the critical margin $\sigma_{\text{max}} < 1080$ MPa at the rate of 10 mm extension Fig. 11. If mutually compared, the stresses on the strain gauges of virtual springs are very close, that is, neither spring is prominent by the signal intensity. From an operational point of view, a measurement resolution of $4.064 \times 10^{-6}$ mV/V, which corresponds to 0.4 MPa strain, depicts an acceptable sensitivity threshold of the strain gauge. Therefore springs no. 3 and 4 do not satisfy this criterion Fig. 12.

Further on, virtual testing in ANSYS [8, 10] was oriented to the spring 2 model, which is both resilient in the sense of measurement sensitivity and strong enough to resist possible overload.
In the mid-span of the beam, a strain gauge pair is mounted (one active and one temp. Compensating strain gauge), configured as a half-bridge. Right above the active strain gauge, a CLD is fixed to the steel beam Fig. 16.

Two active strain gauges are glued to the CLD, one on the outer and one on the inner side of the loop. For the stress calculation on CLD, the following formula is applied [12]:

$$\varepsilon = \frac{1}{B} \frac{4}{K} \frac{U_A}{U_E}.$$ (6)
$K$ is the gauge factor $= 2,12$, $B$ is the bridge factor, $U_A$ is the bridge output voltage, and $U_E$ is the bridge input voltage.

The bridge factor $= 2$ for configuration with two active strain gauges. For the data acquisition a dedicated device, DynaLog instrument, RoTech (www.rotech.rs) make, was used. The device is a multi channel Data Logger, equipped with 16 bit resolution ADC Fig. 17.

Figure 17 DynaLog instrument

Lab test is conceived in the same manner as the virtual experiment. The steel beam is exposed to bending, induced by adding on lumped masses. As well a random load is applied to justify compliance between direct and CLD measurement Fig. 18.

Figure 18 Weight applied on beam

![Weight applied on beam](image)

Figure 19 Comparison of SG and CLD Measurement

After a series of repeated tests, it was determined experimentally that the Real Rectification Quotient ($RRQ$) of CLD is $RRQ = 20,36$. The outcome of the measurement is shown in the diagram Fig. 19. Blue and red line present raw signals collected from the transducers. Light orange line depicts a rectified ($RRQ = 20,36$) output from CLD. All of sampling points (range 1 ÷ 4000), is generated by a stepping load. Correlation function was applied for the justification of signal compliance. The formula is:

$$Correl(x, y) = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2 \sum (y - \bar{y})^2}}.$$  \hspace{1cm} (7)

$$x = \sigma_{SG} - \text{stress measured directly on the beam.}$$

$$y = \sigma_{CLD} \times RRQ - \text{stress measured by CLD.}$$

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i - \text{Average value of the } \sigma_{SG}.$$ 

$$\bar{y} = \frac{1}{n} \sum_{i=1}^{n} y_i - \text{Average value of the } \sigma_{CLD} \times RRQ.$$ 

The degree of the correlation is:

$$Correl [\sigma_{SG}; \sigma_{CLD} \times RRQ] = 0.99.$$  \hspace{1cm} (8)

6 Result analysis

Lab measurements explicitly proved a linear output characteristic of CLD. It was also indicated in 3D modelling. Next is a functional compliance between stress and dilatation in CLD. The stress on the original surface of the beam is related by a constant factor to the one detected by CLD. This relation is depicted by a spring coefficient. Its value for the CLD spring $2$ is $VRQ = 22.7$. In order to get the same order stress value after laboratory tests, it is necessary to convert detected voltage with the instrument into a physical value of the stress. Signal output, both from the strain gauge and CLD has been collected together.

Actual dilatation $\epsilon$, is calculated applying Eq. (6). For the Wheatstone half bridge, with one active and one temp. Compensating strain gauge, bridge factor is $B = 1$. This kind of configuration on a steel beam, yields the equation:

$$\epsilon = \frac{4}{k} \frac{U_{ASG}}{U_{ESG}}.$$  \hspace{1cm} (9)

Unlike, on CLD a half bridge comprises two active strain gauges, so the Wheatstone bridge factor is $B = 2$ [12]. The corresponding dilatation then is:

$$\epsilon = \frac{4}{2k} \frac{U_{ACLD}}{U_{ECLD}}.$$  \hspace{1cm} (10)

According to the Hook’s law, stress is directly proportional to the dilatation so it makes no difference whichever parameter is used for the calculation of $RRQ$ [13].

$$RRQ = \frac{1}{n} \sum_{i=1}^{n} \epsilon_{CLD}.$$  \hspace{1cm} (11)

$RRQ$ is derived as a mathematical average value from all collected points, considering just the points where either $\epsilon_{SG}$ or $\epsilon_{CLD}$ is greater than 0,001:

$$\epsilon_{SG} < 0.001 \land \epsilon_{CLD} > 0.001.$$  \hspace{1cm} (12)

Charts in Fig. 20 show the distribution of the $RRQ$ around an average value.
Red line represents the average coefficient value $RRQ = 20.36$, while the blue dots are varying around, as the ratio of $\sigma_{SG}$ and $\sigma_{CLD}$ fluctuates in Lab test.

![Graph of RRQ Value](image)

**Figure 20** $RRQ$ Value

### 7 Conclusion

An original idea of implementing 3D modelling in deformeter development [4], already known and introduced into practice, is much improved with our Mechatronic approach to the substantial harmonization of the deformeter output with an overall measuring performance. A novel kind of deformeter, called CLD is settled as a concept. On the other hand its conceptual design could not guarantee successful operation. Therefore a virtual measuring configuration is conceived and within it a true analysis is performed.

Having an outline of the complete system the appropriate virtual model of CLD is developed. Further virtual examination is conducted by ANSYS Software in order to select an optimal model of CLD. During laboratory testing, it was revealed that RRQ is slightly different from the VRQ. It is assumed that the detected difference is a result of imperfection in either modelling or selected material properties. However, by implementing RRQ in laboratory tests, almost perfect, 99% match is achieved between stress value from the original strain gauge and CLD. Final conclusion would be that CLD is a type of sensor that could substitute strain gauge wherever arise difficulties in attaching it, as well when intended operation is in a harsh area with extensive deflections. Further investigations of CLD performance will be oriented to the site testing on different structures and more complex loadings [14].

### 8 References


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