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VIRTUAL INSTRUMENTATION FOR STRAIN MEASERUMENT USING WHEATSTON BRIDGE MODEL

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Abstract. *Strain measurement is a very important procedure in mechanical engineering. It has been the subject of the research in theoretical and experimental work. Wheatstone bridge or resistance strain measurement is the most widely used method in experimental stress analysis. Using the advanced virtual instrument technology, there is a possibility to solve the problems of traditional resistance strain instruments. In this paper we give an overview of strain measurement and then introduce the concept and characteristics of virtual instruments applied for that purpose.*

Key words: *strain measurements, Wheatstone bridge, virtual instrument, LabVIEW, students' education*

1. INTRODUCTION

In order to know the stress-strain state of the materials applied in systems they are developing, there is a need for engineers to realize the measurements of mechanical strain. The special interest is to fully understand every part of the system, reliability and energy efficiency, and usually to test the parts before use. Due to that fact, the special subject must be experimental stress analysis and the strain measurement.

There are several methods used to measure strain and the most frequently used one is with the strain gauge (SG). This is an important measurement technique, often applied to the mechanical quantities. Strain gauge is defined as a sensor used to measure the linear deformation in the material during loading [1] and it is a device whose electrical resistance changes in proportion to the amount of strain in the device. When the force is applied, the amount of deformation affects the strain, but it can also be caused by some other external effects, such as a moment, pressure, heat, structural change of the material etc. Mechanical strain is one of the mechanical variables, measured in many engineering applications [2] and, using resistive, inductive, capacitive and piezoelectric sensors and related circuitries, it can be converted into electrical voltage or current [3].

The most common type of strain gauge, composed of an insulating flexible backing, which supports a metallic foil pattern, was invented more than 70 years ago [4]. The gauge is attached to the object and when the object is deformed, the foil is deformed too, causing the change in its electrical resistance. Usually measured by Wheatstone bridge,

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this resistance change is related to the mechanical strain by the quantity known as the gauge factor [5]. The deformation of an object can be measured by mechanical, optical, pneumatic or electrical means [6].

Many types of strain gauges depend on the electrical resistance to strain, such as wire gauge, foil gauge and semiconductor gauge. Wire gauges, developed in 1938, are larger and more expensive than foil gauges. Foil gauges are most commonly used gauges and well described in the literature. When the mechanical strain is very small, semiconductor strain gauges called piezoresistors are applied [7]. This SG type is more expensive than the previously mentioned foil gauge, very sensitive to temperature change and with the larger gauge factor.

The strain measurement is important in many technical fields, such as automotive and aerospace industries, medical or biomedical applications. In the design and testing phase of many aerospace vehicles, accurate measurement of strain is decisive. An interesting example is application on the Boeing 777, where, in engineering design, it is important to test hardware for stress and strain capabilities. To monitor the loads on the vehicle during the free-floating body test, the 777 was equipped with more than 1.000 electrical strain gauges [8].

The strain gauge is very frequently used in biomedical studies. In one of them, by mounting a strain gauge suitably on the walls of the cardiac muscles, the force of contraction of the cardiac muscles can be measured continuously. For the special needs, for example, for blood flow/tissue swelling in biological measurements, the so-called mercury in-rubber strain gauge is used. Several other applications in the field of medicine are described in the literature [9].

As mentioned above, it is very important for engineers and scientists to design the parts of the working system, but it is also important to check or test them before their production and final application. To address these needs and to solve the test problem, the "virtual instrumentation" was developed. Today it is applied in automotive and electronics industries, as well as in many others fields. The idea of virtual instrumentation enables engineers to apply appropriate software running on a computer, combined with the instrumentation hardware, in order to define a custom and to do some measurements tests. The concept of virtual instrumentation has several benefits in work of the scientists who require high accuracy and more flexibility in their work, including importance in distance learning which is very popular today [10].

This paper introduces a virtual instrumentation for mechanical force measurement, with its ability to be used as an educational tool.

2 Electrical Resistance Strain Gauge

The deformation of the material can be produced by an external force applied to an elastic material. When a tensile force is applied, the lenght L of the material will increase to $L+\Delta L$ (Figure 1). The ratio $\Delta L/L$ is defined as a mechanical strain (longitudinal strain). When the compresive force is applied, the lenght is reduced to $(L - \Delta L)$ and the mechanical strain will be $(-\Delta L/L)$. The mechanical strain is usually marked by ε. The ratio between the applied force F and the cross sectional area of the material A, is called stress σ. These two values are connected by the equation known as the Hooke's law:

$$\sigma = E \cdot \varepsilon \tag{1}$$

where E is the elastic modulus (Young's modulus) of the material.

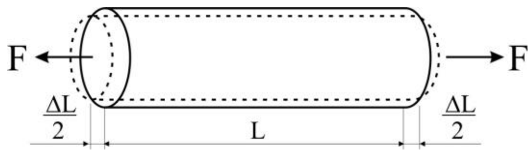


Fig. 1 The force applied on the material

Under the influence of an external force, there will be a change in electrical resistance of a metal (resistor). When a resistor is bonded on the surface of a sample that we examine (with an electrical insulator between them), due to expansion or contraction of the sample, the metal will change its dimensions and, as a consequence, there will be a change of its resistance. Based on this explanation**,** a strain gauge (electrical resistance strain gauge) is described as a sensor (which detects) to detect the strain of a sample by this resistance change. In the practical application, or in the laboratory experiments, a strain gauge is attached to the object surface, in order to detect the deformation, and it can be connected to measuring instruments.

The general relation between electrical and mechanical properties is derived as follows. If the electrical conductor has length − L, cross-section area − A and resistivity ρ of the material, the resistance can be calculated by the equation:

$$R = \frac{\rho \cdot L}{A} \tag{2}$$

What we take into consideration here is the gauge made of a uniform wire and subjected to the elongation, as shown in Figure 1. With a strain, the electrical resistance of wire will change, and the wire has higher resistance, because of the increase of length (ΔL) and decrease of cross section area (ΔA).

Taking into account that $\Delta L \ll L$, $\Delta A \ll A$ and $\Delta\rho \ll \rho$, the relationship between strain and resistance variation is almost linear. The constant of proportionality between them is known as the "sensitivity factor" (G) and can be described by the equation:

$$\frac{\Delta R}{R} = (1 + 2\mu) \cdot \varepsilon = G \cdot \varepsilon \tag{3}$$

The Poisson's ratio (μ) for most of the metals is in the range 0.3−0.5, and the gauge factor G is around 2.

In order to measure mechanical strain, we have to measure this resistance change because the resistance of a strain gauge changes proportionally to the received strain. This resistance change is usually very small, related to the strain by gauge factor. Due to very small resistance changes, we need the appropriate method to measure them. Wheatstone bridge is an electrical circuit with the ability to convert small resistance changes into voltage, and is usually used in mechanical strain measurements.

The Wheatstone bridge. A very precise method with the ability to detect very small resistance change, measured with strain gauges, is the Wheatstone bridge configuration.

The Wheatstone bridge circuit, which consists of four resistances arranged in a square, is fundamental to the use of strain gauges for measurement tasks. In a bridge measurement system, an excitation voltage (V_{in}) is applied across the bridge, and the voltage is measured in the diagonal, between points A and B (figure 2).

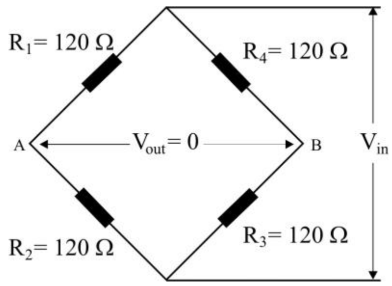
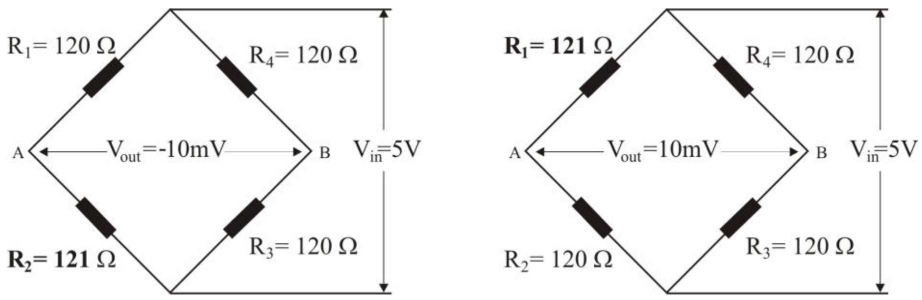


Fig. 2 The Wheatstone bridge in balance

In such an application, one or more of the resistive elements will be strain gages. For the bridge in balance, the voltage across the center of the bridge will be zero volts (Figure 2). If the stress is applied, the change of resistances of the strain gauge causes the voltage change across the center taps. The change in the resistance of the strain gauge was indicated by the voltage change, proportional to the mechanical strain. To explain this connection between the electrical and mechanical parameters, we calculated the voltage change, detected in the Wheatstone bridge in two examples [11].

One of the most common nominal resistance values of strain gauges is 120Ω [12]. If the resistivity R_2 (Figure 2) is replaced by the strain gauge of resistivity 121Ω (1Ω is an increase, caused by the force) and the input voltage is (V_{in}=5V), the resistivity increase will produce the positive output voltage (Figure 3.a) of an approximately 10mV (0,01037V). On the other hand, if we change R_1 (Figure 2) with an active strain gauge, an increase of 1Ω produces certain output voltage, but the output voltage is negative of around -10mV (Figure 3.b). After the similar check with the other resistivities in the bridge (R_3 and R_4), the conclusion is: the resistivity increase of R_1 and R_3 has the positive influence on the bridge output and negative influence on the output voltage, when the values R_2 and R_4 are greater.



a) b)

Fig. 3 The change in voltage: a) positive output voltage, b) negative output voltage

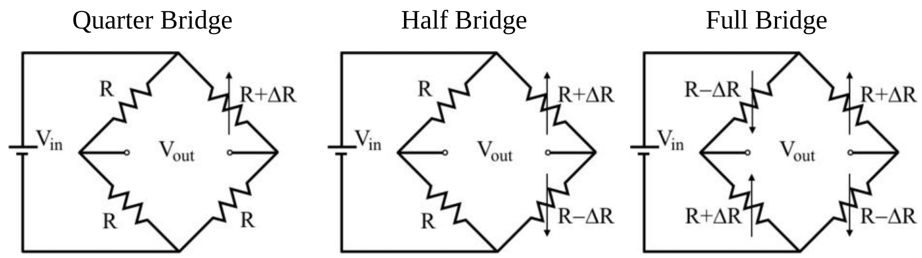
These results and conclusions are important when we use the Wheatstone bridge to strain gauges applications.

In the Wheatstone bridge with four resistors, one or more of them can be replaced by a strain gauge. When the gauges are strained, there will be a change in the gauge resistivity, accompanied by an imbalance in the bridge, i.e. the relation between input and output voltage can be given as follows:

$$\frac{V_{out}}{V_{in}} = \frac{1}{4}\frac{\Delta R}{R} = \frac{1}{4} B \cdot G \cdot \varepsilon \tag{4}$$

where B is the Bridge factor value, depending of the strain gauge layout on elastic element.

The two most crucial factors, that determine the correct strain equation**,** are bridge configuration [13] (quarter, half, or full) and stress type (tension, compression or bending), as shown in Figure 4.



$\mathrm{B} = 1,\ \frac{\mathrm{V_{out}}}{\mathrm{V_{in}}} = \frac{1}{4}\mathrm{G}\cdot\varepsilon$ $\quad \mathrm{B} = 2,\ \frac{\mathrm{V_{out}}}{\mathrm{V_{in}}} = \frac{1}{2}\mathrm{G}\cdot\varepsilon$ $\quad \mathrm{B} = 4,\ \frac{\mathrm{V_{out}}}{\mathrm{V_{in}}} = \mathrm{G}\cdot\varepsilon$

Fig. 4 Types of Wheatstone bridge

The aim of this work is to show the development and use of virtual instrument system for the force measurement using the Wheatstone bridge model with a strain gauge as a sensor. The system we have made should be suitable for the laboratory applications, especially in the measuring of mechanical quantities by electrical means.

3. Wheatstone Bridge Model

The model of Wheatstone bridge, described in this paper, consists of four variable resistance elements (R_1 to R_4), representing strain gauges. The characteristic of strain gauges, an increase or decrease in their resistance, compared to the nominal one, as a consequence of their deformation in our example, is provided by variable potentiometers (resistors).

The electrical connection

In order to build the physical model, linear slider resistors with maximum resistance of 1kΩ have been used. On the model, shown in Figure 5a, the initial position of the slider of the potentiometer on the scale is marked with zero (0). It is a position corresponding to the unloaded state, when the resistance of strain gauges is equal to their nominal value. In this example, all four resistors, in their initial position, have the resistance of 400 Ω. Depending on the direction of the external loads (forces), there may be either the contraction or the elongation of the strain gauges, which respectively leads to a decrease or increase of their resistance. Marks on the scale, next to resistors, indicate increase (+1 and +2) or decrease (-1 and -2) of resistance. It was chosen that each mark on the scale corresponds to an equal change in resistance of ΔR = 100 Ω.

The resistors are connected in the Wheatstone bridge. The bridge input voltage (V_{in}) of 8 V is provided by a standard 220 V adapter to 12/24 V, using the voltage stabilizer 7808CT and 7805CT. The output voltage is measured with a digital voltmeter. In order to facilitate the balancing of the bridge in unloaded (initial) state, parallel with the resistors R_3 and R_4, another variable resistor is connected. Its maximum resistance is 10 kΩ and its fine adjustment is possible by 15-turn gear drive. The block diagram of the system is shown in Figure 5b.

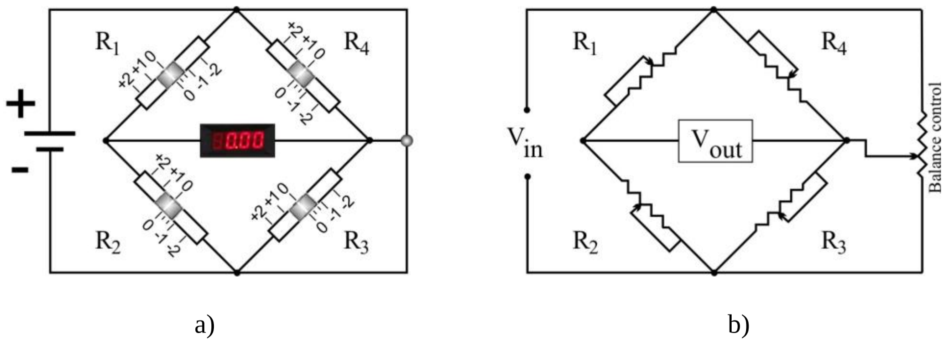


Fig. 5 Model of the Wheatstone bridge and the corresponding block diagram

Gauge factor of the model

In order to define the strain by the resistance change, the sensitivity factor (gage factor G) of the strain gauge material must be determined. In industrial measuring strain gages, the sensitivity factor is predetermined and known. For example, for the strain gauges made of constantan, the gauge factor is G = 2. However, in our model, the value of G is unknown and must be calculated.

On the model, one mark on the scale corresponds to the change of resistance ΔR = 100Ω. Suppose that the change is caused by strain ε = 0.1. Taking the previous assumption into account, the gauge factor can be determined by the calculation below:

$$\frac{\Delta R}{R} = G \cdot \varepsilon, \frac{100\,\Omega}{400\,\Omega} = G \cdot 0.1, \frac{1}{4} = G\frac{1}{10} \rightarrow G = \frac{10}{4} = 2.5 \tag{5}$$

The mechanical quantities, such as force, can be measured using transducers, whose electrical resistance is changed, as a result of the variation of dimensions. In the example of a uniaxial stress state, the application of force transducer virtual instrument, using the National Instruments LabVIEW software, together with the Wheatstone bridge model will be described.

4. Force Transducer Virtual Instrument in the Case of Tensile Forces

LabVIEW is a graphical programming language where icons are "wired together" to form a working program. The LabVIEW program is called a virtual instrument (VI). Each VI has a "front panel" and "block diagram".

The Wheatstone bridge model is wired to a low cost**,** but very versatile USB data acquisition module - National instrument "NI myDAQ". The scheme of the wiring diagram is present at Fig 6.

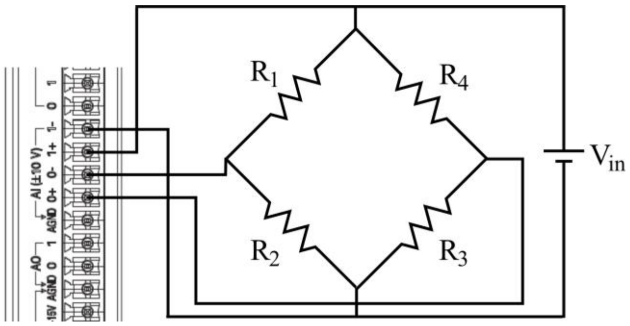


Fig. 6 Wiring diagram

In the LabVIEW program, data will be acquired as a voltage and converted to a strain, force, or other mechanical quantity. Figure 7 shows the main part of the LabVIEW program i.e. block diagram.

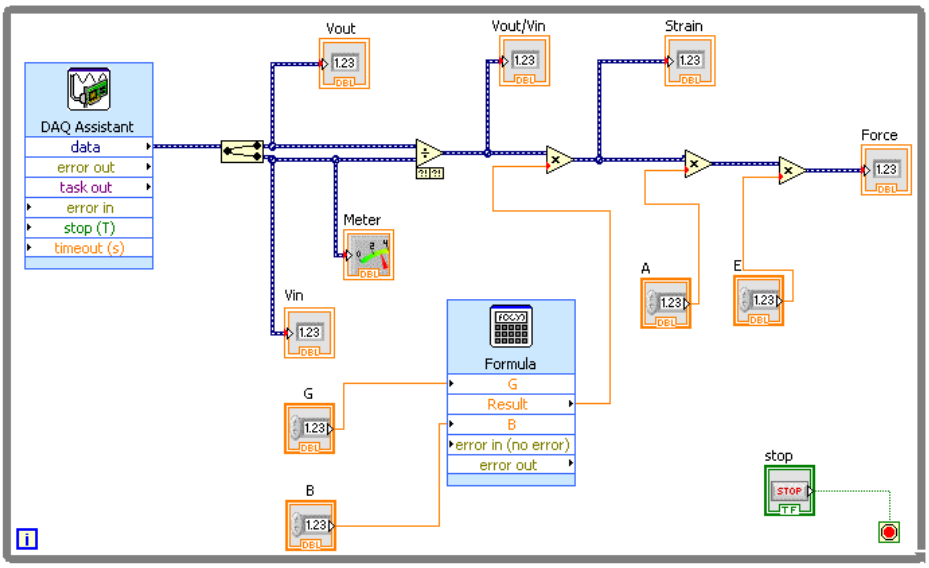


Fig. 7 Force transducer VI's block diagram

Inside the "while loop", there is the DAQ Assistant. It is configured to read a single value from the myDAQ two analog input terminals, one to measure V_{in}, and the other to measure V_{out}. Then the ratio of V_{out} / V_{in} is calculated and displayed on the front panel.

The tensile force F, acting on a rod, as shown in Fig. 8, leads to elongation of the rod in the direction of the load. At the same time, the normal stress appears in the rod material (σ). The stress values cannot be measured, but can be calculated from the strain.

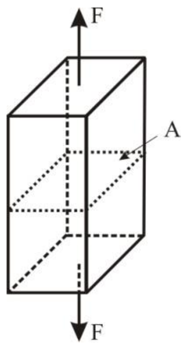


Fig. 8 Rod loaded with tensile forces

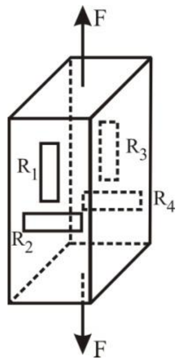


Fig. 9 Bridge configuration for uniaxial tensile load

To measure the value of the tensile strain and reject the possible bending strain, we have to glue four active strain gauges on the surface of the rod (two in the direction, and two perpendicular to the direction of the force). They are electrically connected to form a full Wheatstone bridge, as shown in Figure 9.

For configuration displayed in Figure 9, where the two strain gauges (R_1 and R_3) are elongated, and the other two (R_2 and R_4) compressed, the value of the Bridge factor B is 2.6.

The strain value based on both, known and measured electrical quantities, is:

$$\varepsilon = \frac{V_{out}}{V_{in}} \frac{4}{G} \frac{1}{B} \tag{6}$$

Using the strain-stress relationship (Eq.1), the stress value can be determined, i.e. force acting on the rod. For a known value of the strain, the material type (E− Young's modulus) and the cross-sectional area, the force can be calculated by the following formula:

$$\frac{F}{A} = E \cdot \varepsilon \rightarrow F = A \cdot E \cdot \varepsilon = A \cdot E \frac{V_{out}}{V_{in}} \frac{4}{G} \frac{1}{B} \tag{7}$$

Assuming that, for example, that an unknown force (F) causes the rod elongation of $\varepsilon = 0.1$. Under the load and according to a Wheatstone bridge configuration in Figure 9, the following layout is set on the model: resistances R_1 and R_3 are higher (position +1), while the value of the resistance R_2 and R_4 are smaller (position − 0.3), compared to the nominal one (unloaded condition).

In case of such a given load condition, the bridge output (V_{out}) value can be read (Fig. 10).

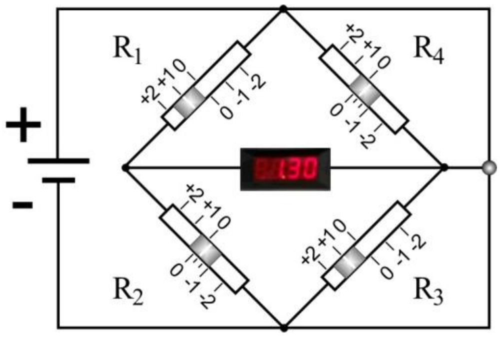


Fig. 10 The value of the output voltage for the given load condition

Substituting the values in the equation (7), for $A = a^2 = (10\ \text{mm})^2 = 100\ \text{mm}^2$, $E = 2.1 \cdot 10^5$ MPa, $G = 2.5$, B = 2.6, $V_{in} = 8$ V, $V_{out} = 1.3$ V, follows:

$$F = 100\,mm^2 \cdot 2.1 \cdot 10^5 \frac{N}{mm^2} \frac{1.3V}{8V} \frac{4}{2.5} \frac{1}{2.6}, \quad F = 2.1 \cdot 10^4 N = 21\,kN \tag{8}$$

The force transducer *VI*, according to the measured value of V_{out}, divided by the V_{in}, together with the electrical characteristics of the Wheatstone bridge (V_{in}, G, B), and the mechanical characteristics of the rod (A, E), is used for calculation of strain and force values. Finally, the results are displayed as numeric indicators on the front panel (Fig. 11).

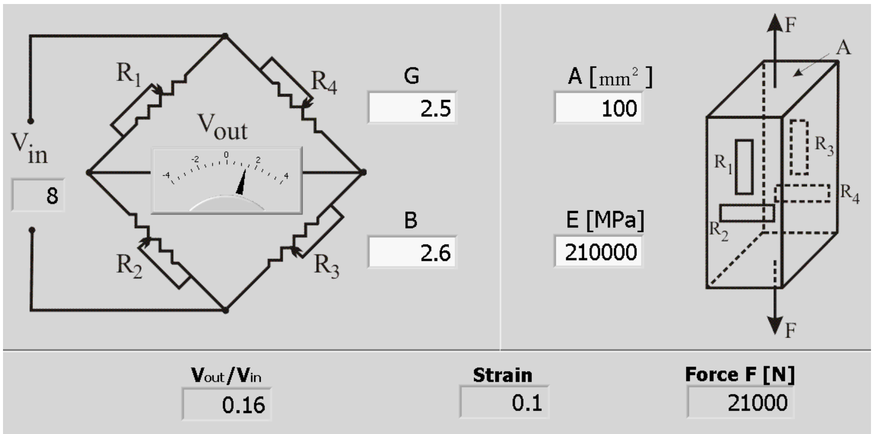


Fig. 11 Force transducer VI front panel

5. Conclusion

The objectives of this work were to provide students with practical experience on how the Wheatstone bridge is used in strain measurements and in virtual instrumentation. For that purpose, a very simple model has been made, in order to calculate the non-electrical quantities, such as force, by measuring electrical quantities, such as voltage.

Additionally presented virtual instrument introduces the several functions in the measurement procedure, such as the ratiometric calculation of the strain gauge bridge deformation, digital filtering of the measurement results, calculation of the other measurement values, based on the calculated deformation (the strain and the force at the measurement transducer) and numerical presentation of the measurement result.

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