Design, construction and Testing of a strain gauge Instrument

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Abstract— The research work is on the design, construction and testing of a quarter bridge strain gauge based measuring instrument. This was achieved by dividing the whole measurement system to power section which consist of batteries, voltage regulators and operational amplifier, arithmetic, logic section consist the microcontrollers that arithmetically compute the strain, and finally input and output section for user dialog. The governing equation for the design revolves around Hooke's law and ohm's law. In the design we considered the instrumentation of the measuring strain gauge system which includes the Wheatstone bridge set up, microcontroller, IC programming followed by simulation using proteus design software. After the construction we carried out a uniaxial stress analysis testing with the designed strain gauge measurement instrument on a clamped wooden beam that has a modulus of elasticity $10700\ \mathrm{N}/mm^2$, length of 250mm and cross-sectional area of h = 4.5 mm , b = 25mm applying load in an incremental succession, the strain and stress at different load interval is then determined. Theoretical strain calculation is then used to validate experimental analysis. For applied load 0.9806N we have the experimental strain value to be 250.14×10^{-6} while the theoretical strain value is $271.54\ \times10^{-6}$ and for applied load 1.4709 the experimental strain value is 362.12×10^{-6}, while theoretical strain value is 407.31×10^{-6}. Experimental strain and theoretical calculated strain value obtained agreed to some extent.

Index Terms— Strain gauge, stress, strain, load

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1 INTRODUCTION

Any device that is used to measure surface deformation can be classified as a strain gauge (Perry, 1984). A strain gauge, in mechanical term, is a device for measuring mechanical strain. However, in instrumental term, it is generally taken to mean the electrical resistance strain gauge, and as the name implies, the strain gauge is an electrical conductor whose resistance varies in proportion to the amount of strain in the device. It is thus transducer, whereby strain is converted into change of electrical resistance (Hilal M & Mohamed.S. 2011). Strain gauges are popular means to measure mechanical movements in micro components. They are employed, e.g., in acceleration sensors, vibration sensors, acoustic sensors and especially pressure sensors (Middelhoek S and Audet S, 1994). Since their invention in 1938 by Arthur Ruge and Edward Simmons, strain gauges are all around us. The measurement of the small displacements that occur in a material or object under mechanical load can be accomplished by methods as simple as observing the change in the distance between two scribe marks on the surface of a load-carrying member, or as advanced as optical holography. In any case, the ideal sensor for the measurement of strain would have good spatial resolution, implying that the sensor would measure strain at a point, be unaffected by changes in ambient conditions; and have a high-frequency response for dynamic (time-resolved) strain measurements. A sensor that closely meets these characteristics is the bonded resistance strain gauge (Richard & Donald 2011).

During the course of his seismic insulation research, Ruge discovered that he needed to measure the stress on the water tanks that was caused by the earthquakes, and so he set about devising a means for attaining this measurement. According to Ruge, he had a Eureka moment on April 3, 1938 when "the invention just popped into my mind, whole. I could see it clearly and knew that it would work." His solution was to glue a piece of cigarette paper on the tank and glue a small wire with end connections to the paper. Ruge and his assistants quickly developed this rudimentary device into the more advanced version that would later be patented (MIT, 2011). According to Karl (1989:1), "The usual way of assessing structural parts of machines, buildings, vehicles, aircraft, etc. is based on strength of material calculations. This method is satisfactory provided the component loads are known both qualitatively and quantitively. Problems arise particularly where the loads are unknown or where they can only be roughly approximated. Formerly the risk of overloading was countered by using safety margins, i.e. through over dimensioning. However, modern design strategies demand savings in material, partly for reasons of cost and partly to save weight; this is clearly illustrated, for example in aeronautics. In order to satisfy the safety requirements and to provide an adequate component service life, the material stresses must be known. Therefore measurements under

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operational conditions are necessary. The quantity employed in the evaluation of structural parts is the mechanical stress to which the material is subjected."With the development and refinement of the finite element analysis approach, experimental stress analysis has receded in popularity. However, experimental methods remain a very relevant tool for engineering design and research since simplified analysis techniques can often lead to misleading results. Experimental investigations can lead to a "more precise accounting of redundancy and all the various other statistical variables" that cannot be determined by other techniques (ASCE 1980, 2).

2 INSTRUMENTATION SIMULATION

The resistance (R) of materials are known to be directly proportional to their length (l) and inversely proportional to their cross-sectional area (A). The constant of proportionality is known as resistivity (ϱ) of the material. The strain of a material, which is important in the study of materials, has the measurement of extension as very crucial. Extension in a material implies the change in material length (l) thereby causing the change in material resistance. Resistance can be measured directly by the use of ohm meter; measuring the potential drop across the material when known current passes through can also give information about resistance when ohm's law is applied. One of the widely known apparatus setup that helps to measure change in resistance is the Wheatstone bridge. The Wheatstone bridge functions on the principle that current flows from high potential to low potential, and there will be no current flow between two points at the same potential. A simple description of the Wheatstone bridge is shown in Figure 1. Below

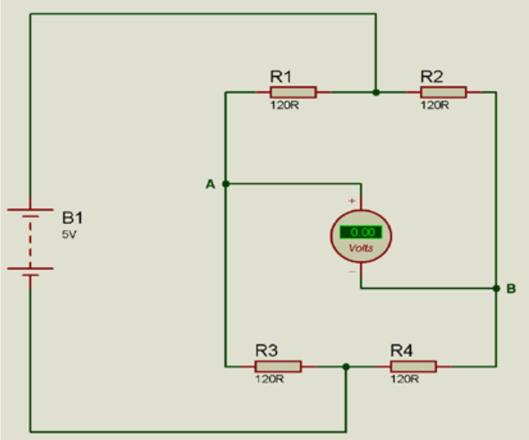

Fig. 1. Wheatstone bridge discription

From Figure 1, the resistance of resistors R1, R2, R3 and R4 will determine if there will be potential difference between points A and B. When the potential difference is zero, it means A and B are at the same potential and the Wheatstone bridge is said to be balanced. This is achieved when R1*R4=R2*R3. Assuming R2 is the test material and is made to undergo extension; the extension causes change in resistance, the change in potential difference between points A and B helps to measure the change in resistance of R2, thereby measuring extension. When extension is obtained, strain is just a step away. Relatively small extension value is expected to be measured, this implies that the change in potential difference between points A and B will be infinitesimal. Measuring small changes in potential difference with satisfactory precision and accuracy is very difficult since the measuring instruments cannot be ideal (100% efficient). This brings the need for magnifying the potential difference between points A and B before measurement, therefore the potential drop across the measuring instruments is negligible when compared to the magnified potential difference. To achieve satisfactory potential difference amplification, an operational amplifier (op-amp) is employed. The operational amplifier used is LM741 and is configured to operate as a differential amplifier. It amplifies the potential difference between points A and B with an amplification of 100. The amplifier configuration was achieved by consulting datasheet for LM741. In order to obtain quick strain measurement from the available potential difference, a microcontroller is used. The ability of a microcontroller to take analog voltage input, make required calculations and display result makes it the ideal candidate for the assignment. PIC18F4550 microcontroller; manufactured by Microchip Technology Inc. was selected considering features such as, in-built Analog-to-Digital Converter (ADC), sufficient program flash and random access memory, high speed and performance, in-built clock source and local availability. The amplified voltage from the op-amp is fed into the microcontroller through its Analog-to-Digital Converter (ADC) pin. The user communicates to the microcontroller through push buttons attached to its input pins, while the microcontroller communicates to the user through a 2X16 Liquid Crystal Display (LCD) with module connected to its output terminal. The microcontroller was programmed with C Language and compiled using the PCWHD compiler by Custom Computer Services (CCS) Inc. The output of the compilation is an *.hex file which contains hexadecimal numbers (which is meaningful to the microcontroller) was tested using ISIS Professional computer simulation software by Labcenter Electronics. The simulation helped to optimize the program to a reasonable extent. The program (in*.hex file) was transferred to the microcontroller using Easy PIC 6 development board manufactured by MikroElektronika Inc.. The Easy PIC 6 development board serves as the interface between the microcontroller and the computer (where the required program originally resides). The Easy PIC 6 board communicates to the computer by the help of the PicFLASH software also designed by MikroElektronika Inc. The choice of using the Easy PIC 6 board is due to the fact that it was designed for specific Microchip microcontrollers such as PIC18F4550 - which is used in this design. Since we are measuring electric potential difference with high degree of accuracy, regulated power supply will be needed. In order to achieve portability in the design, our construction is made to operate on 4 pieces of 6F22 battery with 9 volts rating. The first battery is used to power the microcontroller and LCD, while the second powers the Wheatstone bridge, while the last two power the op-amp. 5V power supply is needed from the first two batteries, this brought the need for 7805 voltage regulator ICs. The Portable measuring Strain Gauge designed can be broadly classified into sections namely, power section, Arithmetic & Logic section, Input & Output Section.

2.1 Power Section

This section consists of batteries, voltage regulators and operational amplifier. This section ensures that required voltage supply is available for every segment of the device. The amplification of the small voltage from the Wheatstone bridge is also classified under this section.

2.2 Arithmetic & Logic Section

This is the heart of the device consisting of the microcontroller. The microcontroller measures the amplified analog voltage from the op-amp through its ADC input. The microcontroller arithmetically computes the strain.

2.3 Input & Output section

This is interface where the user dialogs with the device. The Wheatstone bridge and push buttons are input channel through which the user communicates to the device. The LCD module is the output interface of the device, which provides the user with the results of the calculation made by the microcontroller.

2.4 Derivation of the Governing Equation

$$\frac{R_4}{R_1+R_4}V_s$$

$$\frac{R_3}{R_2+R_3}V_s$$

$$V_0(Potential\ difference\ at\ Aand\ B\ )$$

$$V_0 = \left(\frac{R_4}{R_1+R_4} - \frac{R_3}{R_2+R_3}\right)V_s$$

$$V_0 = \frac{R_{4(R_2+R_3)}-R_3(R_1+R_4)}{(R_1+R_4)(R_2+R_3)}V_s$$

$$V_0 = \frac{R_2R_4+R_3R_4-R_1R_3-R_3R_4}{R_2R_1+R_2R_4+R_1R_3+R_3R_4}V_s$$

$$R_2R_3V_0+R_3R_4V_0+R_1R_3V_s = R_2R_4V_S - R_2R_1V_0 - R_2R_4V_0$$

$$R_2 = \frac{R_1R_3V_0+R_3R_4V_0+R_1R_3V_S}{R_4V_S-R_1V_0-R_4V_0}$$

If $R_1 = R_3 = R_4 = \gamma$= constant

$$\mathrm{R} = \frac{\frac{\gamma\left(V_S+2V_0^{(2)}\right)}{V_S-2V_0^{(2)}}-\frac{\gamma\left(V_S+2V_0^{(1)}\right)}{V_S-2V_0^{(1)}}}{\frac{\gamma\left(V_S+2V_0^{(1)}\right)}{V_S-2V_0^{(1)}}}$$

$$\mathrm{F}\varepsilon = \frac{\gamma\left(V_S+2V_0^{(2)}\right)}{V_S-2V_0^{(2)}}\frac{V_S-2V_0^{(1)}}{\gamma(V_S+2V_0^{(1)})} - 1$$

$$\varepsilon = \frac{1}{F}\left(\frac{\left(V_S+2V_0^{(2)}\right)V_S-2V_0^{(1)}}{V_S-2V_0^{(2)}(V_S+2V_0^{(1)})} - 1\right)$$

$$\frac{V_0}{V_S} = \frac{A*F\varepsilon}{4}$$

$$\varepsilon = \frac{4V_0}{V_{in}*A*F}$$

Where,

$\varepsilon = strain$

$V_0 = output\ voltage\ reading$ V

$V_{in} = Excitation\ (input\ voltage)$

$F = gauge\ factor$

$A = Strain\ gauge\ circuit\ amplifier\ gain, 100)$

Note: In derivation of the above equation, it is assumed that positive strain gages ($R1$ and $R3$) are chosen for positive strain (tension), and negative strain gages ($R2$ and $R4$) are chosen for negative strain (compression). If instead we were to wire the circuit such that the positive gages are in compression and the negative gages are in tension, a negative sign would appear in the above equation.

3 CONSTRUCTION AND ASSEMBLY

Three 120Ω resistors are arranged to form a Wheatstone bridge the fourth arm of the wheatstone bridge is left open for metal foil strain gauge. Amplifier unit of type ~100) is then connected in series with the circuit, to amplify our strain signal. Mikro C software was used to programme the PIC and compiled using the PCWHD compiler which translates source code into a code which microcontroller can understand or execute after which we assemble our microcontroller with the wheatstone bridge. We must give life to the microcontroller by connecting it to a power supply. The microcontroller is then connected to a source of power supply of 5V. Reset button is then attached to the circuitry system, reset is used for putting the microcontroller into a 'known' condition. That practically means that microcontroller can behave rather inaccurately under certain undesirable conditions. In order to continue its proper functioning it has to be reset, meaning all registers would be placed in a starting position. Reset is not only usedwhen microcontroller doesn't behave the way we want it to, but can also be used when trying out a device as an interrupt in program execution, or to get a microcontroller ready when loading a program.

The last part of the assembly is the LCD (Liquid crystal display board). It automatically display our strain result in an interactive manner as mentioned earlier.

4 SPECIFICATIONS

Electrical resistance of 120Ω
Gauge factor (S) = 2.0
For beam application $10^{-6} < \varepsilon_a < 10^{-3}$
$V_S = 5.00$ V
Strain gauge circuit amplifier gain (external amplifier unit, typ. ~100)

5 BENDING BEAM EXPERIMENTAL ANALYSIS WITH QUARTER BRIDGE

Preparation of the cantilevered beam workpiece surface

1. Removal of grease and dirt with cleansing agent.
2. Complete mechanical removal of rust, Oxide using carbide paper.
3. Marking the position of the strain gauge

The metal foil strain gauge is glued onto the cantilever beam on which the load is to be applied, when load is applied to metal foil strain gauge, the resistance of the gauge changes in accordance with the strain applied to bend the board. When used in a Wheatstone bridge configuration, this property of the strain gauge is exploited to convert the change in resistance of the strain gauge to a voltage which corresponds to the strain applied.

The gauge is located near the end of the beam and aligned with the longitudinal centerline of the beam, with the solder tabs toward the free end of the beam. The strain gauge is bonded on the beam by an adhesives to cure for 5minutes, and then (150-mm) lead wires is carefully solder to the gauge, A single strain gauge is bonded on the upper part of the beam lead wire which is then connected to the strain indicator as a Quarter bridge. We connect up and switch on measuring instrument and Load beam of distance 250mm with small set of weights. We then Increase the load in steps and note down reading.

From the strain obtained we can now calculate our stress from Hooke's law.

$\sigma = \varepsilon . E$ (13) $Callister\ D$, 2002

According to **Hooke's law** the stress being sought is obtained with the modulus of elasticity **E** (Modulus of elasticity for wood: 10700 N/mm^2)

5.1 Theoretical determination of stress in the suspended column under uniaxial static loading

The stress at the surface of the bending beam can be calculated from the bending moment $\boldsymbol{M_b}$ and the section modulus **Wy**

$\sigma = \frac{M_c}{Wy}$ (12) $Measurements\ Group, Inc.$,1982

To calculate the Bending moment for a cantilever beam

$M_b = F.L$ (13) $Measurements\ Group, Inc.$,1982

where **F** is the load and **L** the distance between the point at which the load is introduced and the measurement point. The section modulus for the rectangular cross section of width **b** and height **h** is

$W_y = \frac{b.h^2}{6}$ (14) $Measurements\ Group\ , Inc.$

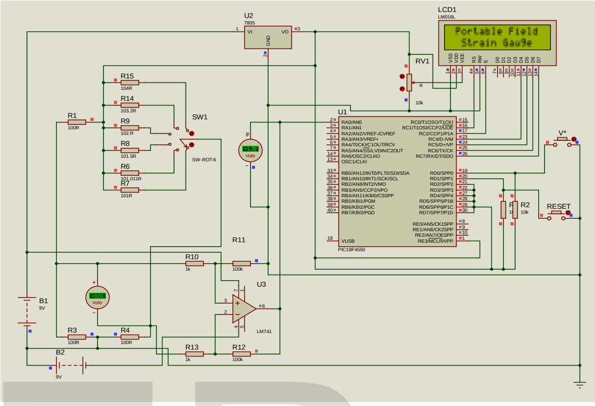

Fig. 2. Proteus simulation model for the strain gauge circuitry design

Fig. 3. Strain gauge measuring instrument

6 RESULT AND DISCUSSION

The measured stress for each applied load is to be compared to the theoretical result in the following. The section modulus for the rectangular cross section is Wy = 74.26 mm^3.

6.1 Results

TABLE 1 Load, Experimental Strain and Theoretical Strain Result

LOAD(N)	EXPERIMENTAL STRAIN($\boldsymbol{\mu\epsilon}$)	THEORETICAL STRAIN($\mu\epsilon$)
0.9806	250.14	271.54
1.4709	362.12	407.31

6.2 Discussion of result

Experimental strain test outcome on a wooden beam For load 0.9806N has the corresponding experimental strain value to be 0.000250.14, and load 1.4709N has its strain value to be 0.000362.12.

6.3 Theoretical strain result discussion

According to Hooke's law the stress is obtained with the modulus of elasticity **E** (Modulus of elasticity for wood: $10700\ \mathrm{N}/mm^2$). From which strain was theoretically calculated for load 0.9806N the corresponding strain is 0.00027154, load 1.4709N has its strain value to be 0.00040731.

Strain gauge measurements vary insignificantly between cycles of different load applied to the wooden beam and typically within the six microstrain.

From table 1, it was observed that theoretical calculated strain value is higher than the strain result obtained experimentally for load 0.9806N, and 1.4709N.

7 CONCLUSION

With this research, the design and construction of a field portable quarter bridge strain gauge measuring instrument has been achieved. Through the design, basic instrumentation principle of strain gauge was understood, right from the circuitry design to the conversion of the analog signal to digital signal with the help of the programmed microcontroller that make required calculations and display the result. The experimental strain analysis on a wooden beam produced strain values for different applied load which agreed to some extent with the theoretical calculated strain result. The theoretical calculated values validated the experimental strain result. With this validation which has satisfied the research intentions, it was concluded that the field portable strain gauge instrument constructed give a good agreement with little discrepancy.

The design was a quarter bridge type, therefore it can only be use for quarter bridge experimental strain assessment.

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