Assignment 2 : Instrumentation

ES21Q Design of Measurement Systems

0013679

School of Engineering, University of Warwick

14/06/02

Abstract

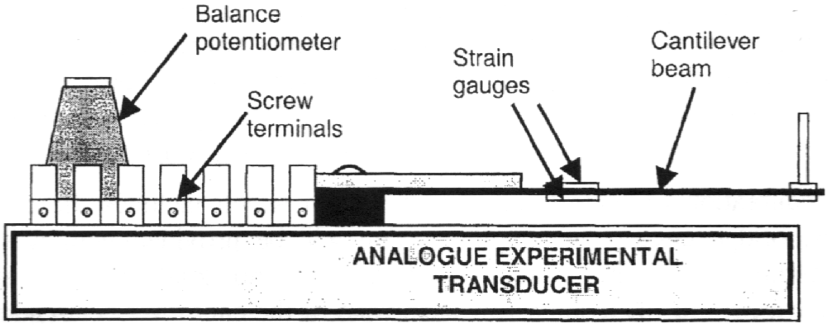
The purpose of this laboratory was to investigate a strain gauge force measurement system. The system was to be calibrated using washers weighing approximately 0.25g. The system consisted of two strain gauges mounted either side of a cantilever beam. The strain gauges formed part of a whetstone bridge configuration which had an output of a few mV. An amplifier based on a 741 op-amp was constructed to amplify this voltage. The cantilever beam was loaded with washers and the output voltage noted at each point using a DVM. Calculations were carried out and the relationship determined. The linear range is about 0 - 0.049N and the sensitivity about 5.214VN^{-1} Investigations were also carried out with an oscilloscope. The system output was investigated measured using a data acquisition A/D card plugged into a PC. Graphs were produced and the output analysed.

Introduction

The aim of the laboratory is to design and set up a force measuring system using a supplied 'Analogue Experimental Transducer' consisting of two strain gauges mounted either side of a cantilever beam. The beam, serving as the elastic member, has a plastic screw on the unsupported end to allow for easy loading. The strain gauges are connected to a whetstone bridge and through an amplifier to a DVM/Data Acquisition A/D card. As force is applied to the beam it bends producing a change in resistance in the strain gauges which is converted to a voltage by the whetstone bridge and amplified by an op-amp. The system will then be investigated to determine the linear range and sensitivity. An A/D card fitted into a PC will be used with suitable software (LABVIEW) to investigate data acquisition and logging for the device.

Design and Analysis

An 'Analogue Experimental Transducer' was provided for investigation. A diagram of this rig is shown below:



As a force is applied to the steel cantilever beam (via the plastic screw at the end) the strain gauges are deformed and produce a change in resistance proportional to the strain placed on the gauge.

The first thing to consider is the strain produced at the strain gauges in terms of the force applied at the end of the cantilever beam (i.e. at the plastic screw).

For a cantilever beam of length l, width w, thickness t, Young's Modulus E, and distance of the strain gauge from the beam support x. The strain is given by the formula below:

$$\varepsilon = \frac{6(l-x)}{wt^2E}F$$

The necessary rig dimensions were measured using a ruler and are given below:

t = 0.5mm w = 8.0mm l = 135mm x = 39mm

The Young's Modulus of steel is 210GPa.

This gives $\varepsilon = (1.371\times10^{-3})F$.

The maximum loading force allowed for this system assuming the gauges are located near the beam support and have the maximum moment is given by:

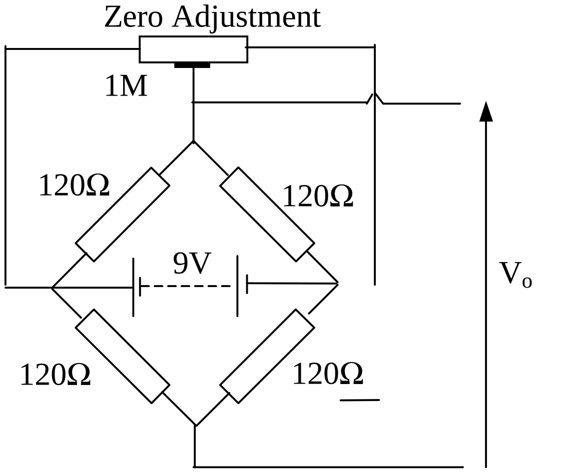
$\varepsilon = \frac{\sigma_f}{E}$ where σ_f is the fatigue strength of the material (Steel). This gives:

$$\varepsilon = \frac{540\times10^6}{210\times10^9} = 2.57\times10^{-3}$$

$2.57\times10^{-3} = 1.371\times10^{-3}F$

$F_{max} = 1.878N$ this is the maximum loading force allowed for the system.

The strain gauges are wired to the output screw terminals of the 'analogue experimental transducer' in a whetstone bridge configuration, powered by a 9V battery. A whetstone bridge is used to convert a change in resistance to an output voltage. This circuit is shown below:



Bridge Circuit

The output of this bridge circuit is given by:

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

Strain Gauge R=1k

However in this system R_1, R_2, R_3, and R_4 are all strain gauges and $R_1 = R_2 = R_3 = R_4$. Also the magnitude of ΔR will be the same for all the strain gauges since the effect is either the same or opposite (compression of tension depending of applied torque and orientation of strain gauges. Therefore:

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

$$\Delta V_o = \left(\frac{R + \Delta R}{2R} - \frac{1}{2} \right) V_s = \frac{1}{2} \left(\frac{\Delta \mathrm{R}}{\mathrm{R}} \right) V_s$$

Note that this is twice as sensitive as a single active gauge device but half as sensitive as a 4 active device. A linear relationship should be observed between ΔV_o and ΔR. The bridge will be balanced if $R_1R_3 = R_2R_4$. In theory, with the given circuit the circuit should be balanced without the need for the potentiometer. However factors such as component tolerances, strain gauge mounting and temperature differentials will mean the circuit will not be balanced so the potentiometer is included, as shown, to set the output voltage to zero.

The change in resistance of a strain gauge is given by:

$$\frac{\Delta R}{R} = G\varepsilon$$

We already have the equations

$\varepsilon = (1.371\times10^{-3})F$. and:

$$\Delta V_o = \left(\frac{R+\Delta R}{2R} - \frac{1}{2}\right)V_s = \frac{1}{2}\left(\frac{\Delta R}{R}\right)V_s$$

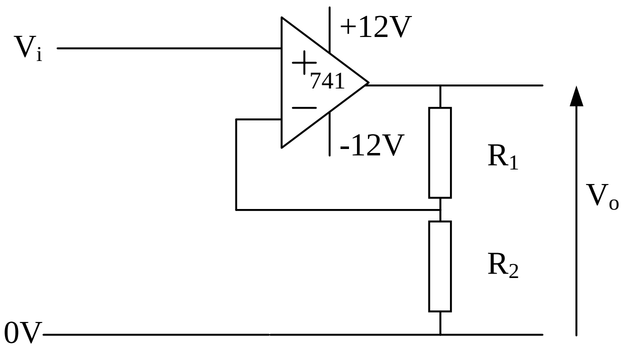
Therefore $\Delta V_o = \frac{1}{2}\left(1.371\times10^{-3}FG\right)V_s \qquad \Delta V_o = \frac{9}{2}\left(1.371\times10^{-3}FG\right)$

G is given as 2.1 therefore the output voltage for the balanced circuit is theoretically:

$$V_o = 1.2956\times10^{-2}F$$

This will not be the exact output due to a variety of reasons. The thermally induced change in the strain gauge is ±2µ strain/ºC. As can be seen this may make a noticeable change if say the gauge is used outdoors.

It can be seen that the output is in the order of 1-2 milivolts per gram loading. This is not a suitable output for measuring and so an amplifier is required to amplify this voltage for easy reading. The amplifier will be based on the 741 operational amplifier. A non-inverting amplifier will be used since investigations with an oscilloscope showed that an increase in loading on the beam produces a positive increase in voltage. The op-amp is powered by a ±15V supply. The circuit for a non inverting amplifier based on the 741 is shown below:



Non Inverting Amplifier:

$$G = \frac{R_1 + R_2}{R_2}$$

The gain of the amplifier should be about 100-1000 to give a voltage in a suitable range. Choosing R_1 = 1M and R_2 = 3.3k gives a gain of 304 which is in the correct range.

The amplifier was built and the noise level was checked on an oscilloscope. This was found to be a few milivolts which would affect the stability of the measurement slightly so a low-pass filter was used across the feedback resistor to attempt to reduce this (RC ≈ 0.1sec).

Results and Analysis

Part 1 - Manual Measurement

The amplifier was connected to the whetstone bridge output and the output voltage was set to zero using the potentiometer. The output was viewed on an oscilloscope and the output change in output voltage was observed when varying load on the beam. The output from the amplifier was then connected to a DVM. Washers weighing 0.25g were used as standard weights. The zero point was set and washers were added one at a time for 0-30 washers. A graph showing the results is shown on the next page.

As can be seen from the graph the increase in voltage becomes non-linear after about 20 washers (5g). The equation gives the voltage increase per washer (¼ increase per gram) The voltage increase per Newton is given as $1.27749\times10^{-2}\div0.25\div9.8\times10^{3}$ = $5.214VN^{-1}$. And the range as 0 to $20/4\times9.8\times10^{-3}$. = 0 - 0.049N.

Therefore the linear range is about 0 - 0.049N and the sensitivity is $5.214VN^{-1}$.

This is relatively close to the predicted sensitivity of approximately $4VN^{-1}$, but as with any real system there are many external factors affecting the sensitivity. These may include temperature changes, errors in measurement of dimensions, component tolerances etc.

Part 2 – Data Acquisition

This section involves using a A/D (Analogue to Digital) card installed in a PC. A 6023E (12-bit A/D) card was used with Labview to log the data. Labview gives an output graphically on the monitor as well as logging the data to disk. The output was connected across pin 68 (Channel 0) and pin 67 (AIGND). The logging settings were set to 1000 data points with a sample interval of 20ms. Only channel 0 was used, as the other channels were not connected. To determine noise levels, data was collected with the beam in an unloaded state. Three sets of data were collected and the data was graphed in Matlab. The 3 graphs produced are shown on the next pages. The sample interval and number of sample points means that a graph corresponds to a time period of 20sec (One graph has 2000 sample points and so represents 40s):

A can be seen from the graphs there is a great deal of noise on the input to the A/D card. This could be due to EM interference due to unscreened circuitry used. The room where the measurements were undertaken contained many PCs and VDUs. These would provide a very harsh EM environment, which would affect the circuit since no screening was used. It may be observed that the ground level is slowly varying sinusoidaly. The cause of this is not known. No difference was noted when a capacitor was placed across the feedback resistor, possibly because the noise level was to great on the signal line to the A/D card. This passed close to the VDU and was an unscreened ribbon cable.

The dynamic behaviour of the cantilever was attempted to be tested. This was performed by tapping the end of the beam lightly. A graph showing this is shown on the next page:

Unfortunately the noise level is so high as to obscure anything other than the first peak so the time needed for the beam to stabilise cannot be calculated. (More graphs are included in appendix A).

Conclusion

A measurement system was constructed using a whetstone bridge and a non-inverting amplifier. The measurement system was calibrated using 'standard' weights and the linear range was found to be about 0 - 0.049N and the sensitivity to be 5.214VN^{-1}.
The overall equation for the output was derived as:

$$\Delta V_o = A\frac{1}{2}\left(\frac{6(l-x)}{wt^2E}FG\right)V_s$$

The sensitivity can therefore be increased by increasing A (Amplifier gain), V_s (Whetstone bridge supply voltage), the distance of the strain gauge from the end, using four strain gauges, or by reducing the thickness, width or Young's Modulus. It may be noted that changing the thickness will have a larger effect on the sensitivity since it is a squared term. Error in measuring the thickness would therefore cause a large error in the predicted sensitivity, possible accounting for the difference between the experimental and calculated sensitivity in this investigation.
Ambient temperature changes will affect the strain on the gauge. The thermal expansion coefficient of steel is given as 11×10^{-6}m/m/ºC. Therefore for a strain gauge measuring 20mm a change of 10ºC would give a change in strain of ε = 2.2μ/20m = 110μ strain resulting in a voltage change after amplification of 0.316V, obviously a appreciable value. However this should have negligible effect since the opposite gauge should compensate for the change in the whetstone bridge as they should both be subjected to the same stress. It may still however be worth recalibrating the system after an appreciable temperature change.
The results from the data capture investigation could be greatly improved by reducing the noise in the system, possibly by switching the monitor off or providing screening for the cables/system. The results in the electronics lab, a much more EM friendly environment, had much less noise and the results taken proved useful for calibrating the system.
Overall a suitable system was produced and proved to work. The system was calibrated and found to be liner up to about 5g (≈0.05N). The system could be further improved by using four strain gauges to increase sensitivity.

Bibliography

Lecture Notes - ES21Q Design of Measurement Systems.
Assignment Sheet - ES21Q Design of Measurement Systems.

Appendices

Appendix A - Data Logging - Extra Graphs

Appendix B - Lab Sheet