ME 646 – Lab # 3
Strain Gauges and Vibration

There are three parts to this lab:

1. Use of strain gauges in a Wheatstone bridge mounted on a cantilever beam so that the beam can be used as a load or a displacement sensor.
2. Determining the natural frequency and damping ratio for the cantilever beam using the strain gauge output and comparing the observed behavior to the prediction of the behavior using a spring-mass-damper model of the beam.
3. String Vibration: Use a strain gauge load cell and a piezoelectric force sensor mounted under the vibrating string to investigate the frequency content of a vibrating string.

Your report will consist of answers to specific questions. You do not need to provide a cover letter, executive summary, or integrate the information into a formal report.

Part 1: Strain gauges in a Wheatstone bridge

In Part 1 of the lab, you will calibrate strain gauges and a Wheatstone bridge circuit. We have attached two strain gauges to opposing sides of a cantilevered steel beam so that one is in tension when the other is in compression (or vice versa). You will record bridge output voltage as a function of load placed on the beam and as a function of beam displacement.

Your setup consists of a steel beam with two strain gauges mounted near the clamped end of the beam: one on top and one on bottom. The leads of the two strain gauges are arranged in a Wheatstone bridge as shown in Fig. 1, such that bridge output voltage (ΔE_o between +Eo - Eo) is proportional to strain, and hence load on the beam. Since the bridge output voltage is very small, a differential amplifier is used to filter noise and amplify the output voltage. You will assume the gain is 100.

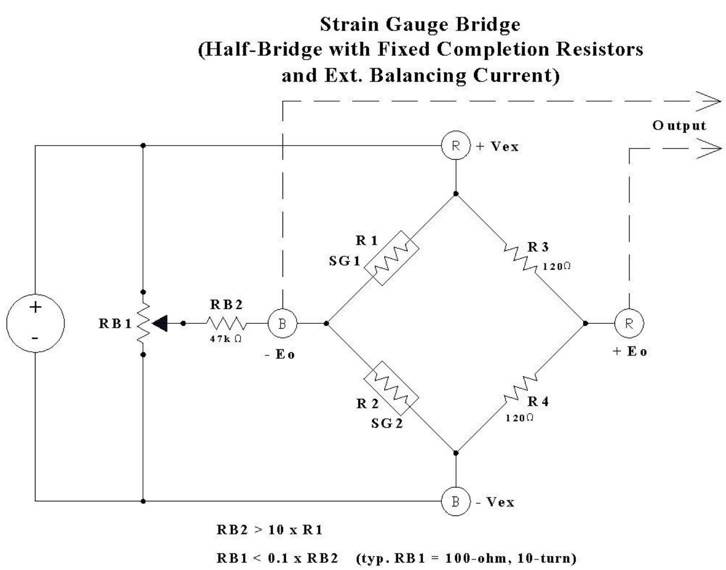

Figure 1 - Schematic of strain gauges in Wheatstone bridge experimental setup. R1 SG1 and R2 SG2 are the strain gauges that have a resistance of 120 Ω (±0.15%) R3 and R4 are 120 Ω (±0.1%) bridge completion resistors. RB1 and RB2 are bridge balancing resistors.

In-lab tasks:

1) Clearly sketch in your lab journal the schematic of the strain gauges in the Wheatstone bridge experimental setup.
2) Use the vernier calipers and micrometers to measure the beam dimensions (length, width, thickness) and the distance "x" between the beam support and the center of strain gauges to allow theoretical calculations of stress at the gauges.
3) Attach the wires for the strain gauges to the setup at the appropriate posts. The white wire is the common lead for the strain gauges. The black wire goes to the $-V_{ex}$ post (marked as ground in the setup) and the red wire goes to the $+V_{ex}$ post (marked as $+V_s$).
4) Connect 5V from Channel 0 of the NI power supply to the excitation connections on the setup (V_s and ground). Make sure the current limit is 0.2 A or the power supply will load down.
5) Connect the + 15 V and – 15 V from the NI power supply to the amplifier using banana plug cables. Connect the output of the bridge ($+E_o$ and $-E_o$) to the input of the amplifier and set the amplifier gain to 100. Connect the output of the amplifier to the input of the oscilloscope. You should be able to flick the cantilever beam and see it oscillate on the oscilloscope trace.
6) Balance the bridge using the potentiometer such that zero load on the beam produces nearly "zero" output voltage. Record the "zero" output voltage with no load. (This ignores the weight of the beam.)
7) Obtain data to calibrate the bridge sensitivity, $\Delta e/\Delta R$. Use the five shunt resistors, R_{shunt}, (between 50 kΩ and 150 kΩ) that were supplied to you. Measure the resistance using the DMM. Place each shunt resistor across one of the strain gauges in the bridge and measure and record the change in the output voltage Δe for each shunt resistor. The resistance due to placement of the shunt resistor in the circuit is computed from

$$\Delta R = R_{strain-gage} - \frac{R_{strain-gage} R_{shunt}}{R_{strain-gage} + R_{shunt}}$$

   You must to derive this equation which is merely the parallel resistor formula reorganized.

9) Calibrate the strain gauge-beam system by placing weights (in 5 increments to 250 g) on the bucket attached to the hook at the end of the beam and measuring output voltage. You need to record the weight of the bucket. Do this for increasing load only. Record zero load voltage for each measurement (i.e., record the voltage each time the bucket is off the hook). **Apply and release the loads carefully so that no overshoot of the beam occurs**.
10) Rotate the micrometer over the beam and measure the bridge output for known displacements of the beam. The micrometer moves 0.025 inches per full revolution of the spindle. Apply 10 evenly spaced displacements to a maximum displacement of ~0.25 inches and **<u>record bridge output for both increasing and decreasing displacement.</u>** You will use these data to determine the calibration curve for the beam as a displacement indicator and to estimate hysteresis.

II. <u>Cantilever Beam Vibration</u>

1) Using the same setup as in part I, set the scope triggering so that about 20-40 cycles of the beam output are captured when the beam is deflected and released. Make sure that you do not deflect the beam too much. Save the output data and repeat the measurement a minimum of three times. You will use these data to calculate the damped natural frequency, damping ratio, and natural frequency of the beam.

Part 2: Strain Gauge Load Cell and String Vibration

You will use a strain gauge load cell and a piezoelectric load cell to investigate the frequency content of a vibrating guitar string. You will use the FFT (Fast Fourier Transform) algorithm on the oscilloscope and in Matlab to transform the time data to the frequency domain.

1) Connect the function generator to the oscilloscope and input a sine wave of approximately 500 Hz. Adjust the time base so that 20 to 30 cycles are displayed on the screen. Click on the Frequency icon so that you see a plot of amplitude vs. frequency. Use the cursor to locate the position of the peaks in the FFT. You can adjust the x scale by adjusting FFT settings. Acquire a frozen frame using the Run/Stop button. Save a screenshot for your report and for your lab notebook. Save the data in an lvm file<u>. Do the same for a triangle waveform.</u>
2) Connect the signal leads (green and white) from the strain gauge load cell to the input of the differential amplifier. Connect the amplifier output to the oscilloscope (it should already be connected). Connect the voltage excitation leads of the transducer to +5 volts and ground of Channel 0 of the NI power supply. Assume the sensitivity of the load cell is 3.4 mV output for 1 V of excitation e.g. 3.4 mV/V for full scale output (100 lbf in this case). You will use this to calculate the string tension from the output of the load cell.
3) Measure the length of the vibrating portion of the string in your setup using a tape measure.
4) Connect the output of the charge amplifier for the piezoelectric load cell to the second channel of the oscilloscope. Set both channels to AC coupling. Adjust the V/div (start at 50 mV/div) so that the signal fills the window but is not saturated. You may need to increase the gain on the strain gauge amplifier to 1000 and may need to increase or decrease the V/div.
5) Use the DMM to measure and record the voltage that you will use to convert to the string tension. Adjust the string tension so that the amplified output of the force transducer is close to 0.3V when the gain is 100 or 3V if the gain is 1000.
6) Pluck the string in the center and obtain a waveform from both force transducers. Adjust the time-base settings on the scope to obtain ~10-20 cycles of the low frequency sine wave. Capture a trace using triggering and store the waveform. Repeat for a string tension around 0.6V. You will perform FFT's on these files using Matlab in your report.

Lab Report Deliverables: The information you obtained with your experiments is not organized to answer a specific research question. Rather, it is intended to expose you to several different experimental methods and analysis techniques. Therefore, we are only asking you to provide written descriptions as responses to the various sections to explain how you performed the calculations and analysis. Please be complete and clear in your responses.

The report should be submitted as a ***<u>single</u>*** Word document or pdf. *Do not submit a published Matlab document but you should include the code as an appendix.* In both cases, use Edit, Copy Figure to insert the figures into the report. All figures must have informative comments.

1. Beam/strain gauge response
    a. Provide diagram of physical setup. Include beam dimensions, amplifier, etc.
    b. Determine bridge sensitivity using shunt resistor data
        i. Plot the bridge (not the amplifier) output, Δe_o vs. ΔR using symbols to show the data. On the same plot, show the fit to a linear relationship taking the gain of the amplifier into account (i.e. divide your output by the gain so we can compare to the expected bridge sensitivity). Also on the same plot, show the 95% confidence interval for both the measurement and of the fit. Include the $t_{\nu,P}$ and ν values you used on the plot. List the equation on or below the plot showing the units of the fit constants.

ii. Provide a short section, with equations and complete sentences, describing how you compared your measurement of the bridge sensitivity to the expected bridge sensitivity. You must present a derivation of the bridge equation that includes the effect of shunt resistors on the bridge output. It would make this easier if you used an effective resistance for the parallel combination of the bridge (or strain gauge) resistor and the shunt resistor. This would require you to derive the equation in part 7 for ΔR.

c. Using the above data, provide a short section, with equations and complete sentences, showing how you convert the output of the amplifier to strain using a gauge factor of GF=2 for the strain gauges. Remember to multiply your answer for part 1.a.i. by 2 because both gauge resistances will change when the beam is deflected and section b only changed the resistance of one leg of the bridge.

d. Convert your measurements of amplifier output vs. load and amplifier output vs. displacement to strain vs. load and strain vs. displacement.

i. Use cantilever beam equations that have stress (and therefore strain) as a function of position along the beam to predict the output of the beam for a given force and a given displacement. This will require sentences and equations. The equations should include the position of the strain gauges.

ii. Plot the data, the best fit line, and the theoretical displacement-strain or force-strain relationships for the cantilever beam on two separate plots. (They should fit pretty well but not perfectly if you measured the thickness correctly.)

iii. Provide a separate plot that shows the 95% confidence interval for fit and measurement without the theoretical prediction. List the $t_{\nu,P}$ and ν values you used on the plot.

iv. Determine the hysteresis for the displacement measurement and report it as a single number. Provide a short description of the definition and how you determined this number. Provide a table that shows the upward and downward values and the difference between the two.

2. Cantilever beam vibration

a. Use a peak detection routine to analyze the strain vs. time of the vibrating beam response to get the damped natural frequency, damping ratio and natural frequency. Use both the least squares method described in the problem solution problem to 3.43 and using

$$\zeta = \frac{\frac{1}{n-1}\ln\left(\frac{y_1}{y_n}\right)}{\sqrt{4\pi^2 + \left[\frac{1}{n-1}\ln\left(\frac{y_1}{y_n}\right)\right]^2}}$$

for each peak. Provide a table of the ζ values for each peak for the second method and compute the average and standard deviation for ζ. Compare the results.

b. Use the equations for a cantilever beam and words to explain how you calculate the beam stiffness from the data and compare it to the theoretical prediction. Include or refer to the relevant plot. Remember K=F/δ and you have equations relating the two.

c. Provide a short section using equations and complete sentences to describe how you compare the measured natural frequency to the theoretical value, i.e. $\omega_n = \sqrt{K/m_{eff}}$, where m_{eff} is ¼ of the mass of beam + the mass of hook (*Analysis and Design of Dynamic Systems*, Cochin and Plass, Second Ed, Harper and Row, 1990, pgs.683, 686), and K is the beam stiffness. Be sure to check the units of the calculation. The mass of the hook is 7.4g $\pm$ 0.05g and the mass of the beam can be determined from its volume assuming it is made of steel.

d. Propose a physical origin for the observed damping.

3. Demonstrate understanding of FFT using function generator
    a. Use Matlab to run a FFT of sine wave and triangle wave and compare to screen shots. Adjust both axes so that the comparison is straightforward. Are the peaks at the same frequencies?
    b. The section on the Discrete Fourier Transform in chapter 2 of your book will help on this question. State the frequency resolution, minimum detectable frequency, and maximum detectable frequency as a function of sampling period and the number of points. State the time per division you used when obtaining your measurements and list how many points were obtained. Provide all equations you used to obtain this information.
    c. Explain what parameter you would adjust to improve your frequency resolution.
4. String vibration
    a. Use equations and words to show how you predict the resonant frequency of the string using the mass per unit length, the string tension, and the string length. Use the load cell data to determine tension in the string. The mass per unit length is 6.805g/m. Provide a table that summarizes the values you used.
    b. Use Matlab to perform an FFT and determine the amplitude vs. frequency response for each string tension based on both the strain gauge load cell and the piezoelectric load cell.
    c. Use a table to compare the first four observed resonant frequencies for the two string tensions to predictions for vibrating string. Provide the equations you used to predict the resonant frequencies.
    d. Do both load cells give the same response? If not, propose an explanation. This may take some diagrams, equations, and explanations.