

ME 104
Sensors and Actuators
Fall 2003

Laboratory 3
Strain Gage Sensors

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Fall 2003 Revision

Introduction

In this laboratory, you will build an analog circuit that will enable you to use a strain gage* to measure the deflection of a metal ruler. You will then add a noninverting op-amp to amplify the voltage output from your circuit and an analog low-pass filter to remove voltage fluctuations caused by high-frequency noise. As an extra credit exercise, you will write a LabVIEW program to compute the Power Spectrum of the output from your strain gage circuit before and after the low-pass filter.

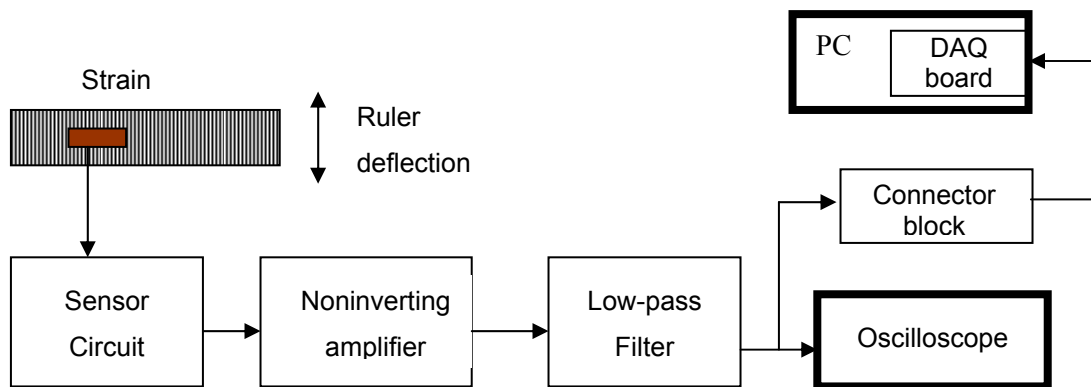


Figure 1. Strain Gage sensor system

Background Reading

Please read the following material prior to this lab:

1. Histan and Alciatore, **Introduction to Mechatronics**, Pages 330-331 and Section 9.3.2.
2. **Data Sheet**, *LMC6484 CMOS Quad Rail-to-Rail Input and Output Operational Amplifier*, National Semiconductor Corporation. Available online at <http://www.national.com/ds/LM/LMC6484.pdf>.

* Also spelled strain *gauge*.

Experiment #1: Build an Analog Circuit for Obtaining Deflection Measurements Using a Strain Gage

In this experiment, you will build an analog circuit for using a 350- Ω strain gage to measure the deflection of a metal ruler. You will then observe the voltage output from your deflection sensor circuit using an oscilloscope. The strain gage, which includes two wire leads, has already been attached (glued) to a bendable ruler.

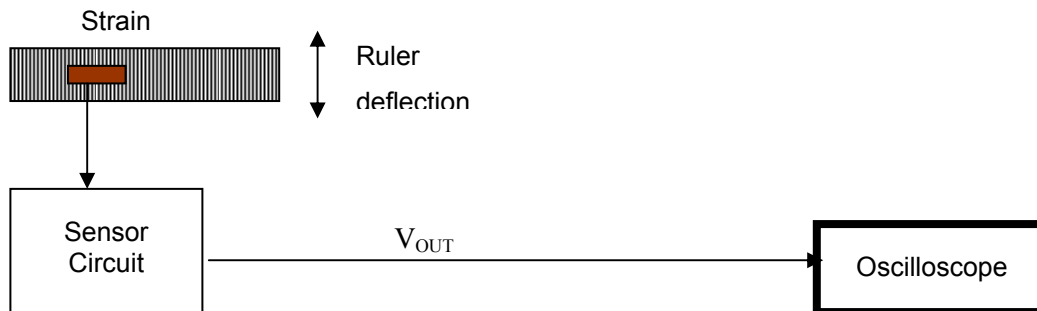


Figure 2. Strain gage sensor

1. Build the analog circuit shown in Figure 3 on an electronic breadboard. Remember to use red wire for positive power connections and black wire for ground connections. Since the strain gage has a resistance of (approximately) $R_{SG} = 350\Omega$, the resistors* on the remaining three arms of the Wheatstone bridge should be matched such that

$$R_{B1} = R_{B2} = R_{B3} = 350\Omega.$$

For this lab, you will actually use

$$R_{B1} = R_{B2} = R_{B3} = 348\Omega$$

or

$$R_{B1} = R_{B2} = R_{B3} = 357\Omega.$$

* The R_B resistors are known as “bridge completion resistors”.

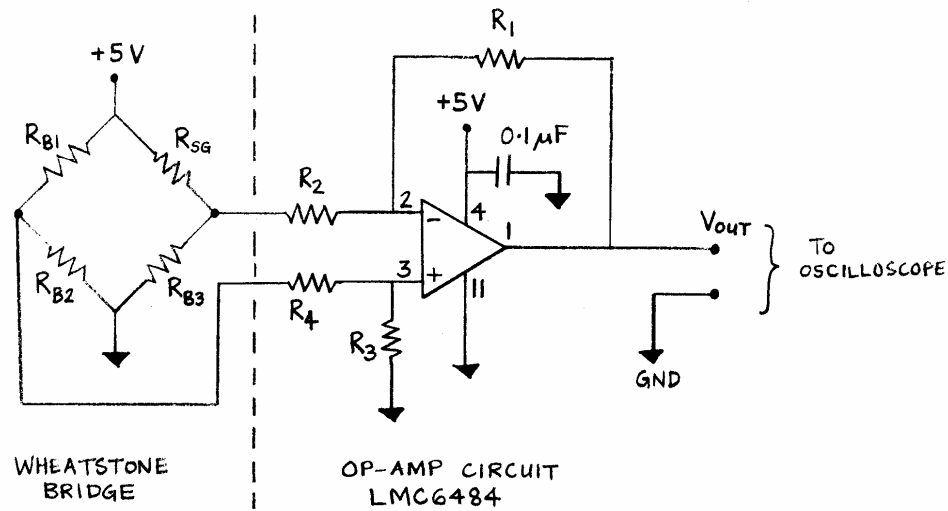


Figure 3. Analog sensor circuit for using a strain gage as a deflection sensor

The voltage output from the Wheatstone bridge is amplified by the LMC6484 operational amplifier, shown on the right side of the dotted line in Figure 3. Although the LMC6484 chip contains four op-amps with identical capabilities (see Figure 4), you will use only op-amp number one at this time (LMC6484 pins 1, 2, and 3).

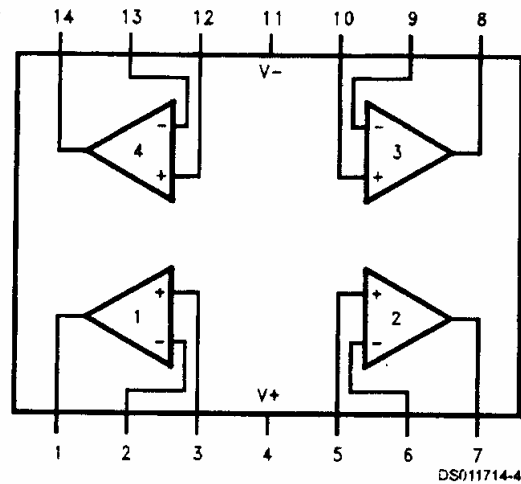


Figure 4. LMC6484 op-amp connection diagram

Choose the op-amp resistors such that

$$R_1 = R_3 = 1 \text{ M}\Omega$$

$$R_2 = R_4 = 100 \text{ k}\Omega.$$

Then, the voltage gain A_V of your op-amp circuit will be

$$A_V = \frac{R_1}{R_2} = 10.$$

Provide power ($V_{CC} = +5$ volts) and ground (GND) to your circuit board using the “5 V FIXED 3 A” output from your Tektronix PS280 DC Power Supply.

- Place the ruler flat on your table so that it is straight (not deflected). Turn on your oscilloscope and set its vertical scale to 50 millivolts/division and its horizontal scale to 400 milliseconds/division. Connect the voltage output V_{OUT} and ground (GND) from your circuit to the oscilloscope.
- Take the ruler in your hand and deflect it upward and downward. Observe the resulting voltage output V_{OUT} on the oscilloscope. If you cannot see a clear deflection voltage (when you bend your ruler), adjust the vertical scale on your oscilloscope until you can see a clear deflection.

V_{OUT} is the sum of two voltage components given by

$$V_{OUT} = V_{DC} + V_{defl}$$

where V_{DC} is a roughly constant DC bias voltage and V_{defl} is a voltage that depends on the deflection of the metal ruler. For the resistor values you have used, your deflection voltage V_{defl} should have a magnitude of 50 mV or less*, while the positive DC bias V_{DC} should be on the order of 150 mV or less (Figure 5).

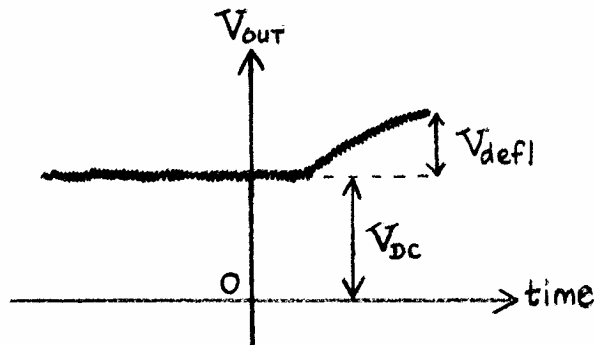


Figure 5. Voltage output from strain gage circuit

- Make a table to record the DC bias for each of the circuits in this lab.** Record the DC bias produced by this circuit.

In theory, when the ruler is not deflected, and if all four resistors in the Wheatstone bridge are perfectly matched (equal to one another), the DC bias V_{DC} should be zero. In practice, however, the resistors are not exactly matched, so the circuit may have a nonzero DC bias even when the ruler is not

deflected[†]. For the purposes of this experiment, we want the DC bias to be approximately 150 mV. If your DC bias is not approximately 150 mV, you can drive it towards 150 mV by adding an appropriate resistor in parallel with one of the resistors in the Wheatstone bridge. Recall that the equivalent resistance R_E across two parallel resistors R_α and R_β is given by

$$\frac{1}{R_E} = \frac{1}{R_\alpha} + \frac{1}{R_\beta}.$$

5. If the DC bias V_{DC} in your circuit is between 125 to 175 mV, you **do not** need to adjust V_{DC} so you can skip the next three steps and proceed directly to Experiment #2.
6. If the DC bias V_{DC} in your circuit is **outside** of the range 125-175 mV, proceed as follows. Place the ruler flat on your table. Connect a 100 k Ω resistor in parallel with R_{B1} as shown in Figure 6(a). The DC bias should move either closer to or further away from the 150 mV mark. If the DC bias moves away from 150 mV, switch the 100 k Ω resistor so that it is connected in parallel with the strain gage R_{SG} as shown in figure 6(b). If adding a 100 k Ω resistor does not improve your DC bias, try using a 200 k Ω resistor instead. **Record the DC bias produced by this circuit.**

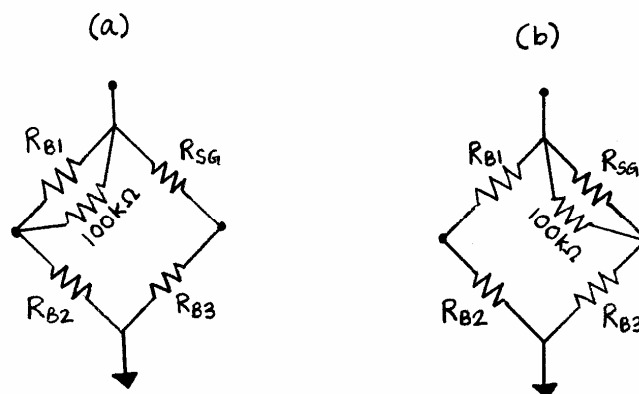


Figure 6. Addition of a parallel resistor to alter DC bias

7. Ultimately, you want the DC bias V_{DC} to be as close to 150 mV as possible, but for the purposes of this experiment, restricting V_{DC} to within 150 ± 25 mV will suffice. Place the ruler flat on your table. Keep adding more 100 k Ω resistors in parallel to either R_{B1} or R_{SG} until V_{DC} (as viewed on the

* If your deflection voltage magnitude is larger than 50 mV, you are bending your ruler too much.

[†] Since you have powered the LMC6484 with a high voltage of $V_+ = 5$ V (pin 4) and a low voltage of $V_- = 0$ V (pin 11), the output from your op-amp is physically restricted to the range 0-5 V.

oscilloscope) drops to within ± 25 mV of 150 mV. If you cannot restrict V_{DC} to 150 ± 25 mV using only $100\text{k}\Omega$ resistors, try adding higher value resistors (for example, $200\text{ k}\Omega$) in parallel for better voltage resolution. **Record the DC bias produced by this circuit.**

8. Take the ruler in your hand and deflect it upward and downward. Verify that the resulting voltage output V_{OUT} on the oscilloscope is similar to what you observed in step 3 (above), but with a DC bias of approximately 150 mV.

Experiment #2: Amplify Voltage Output from Strain Gage Circuit

In this experiment, you will amplify the voltage output from your strain gage circuit using a noninverting operational amplifier.

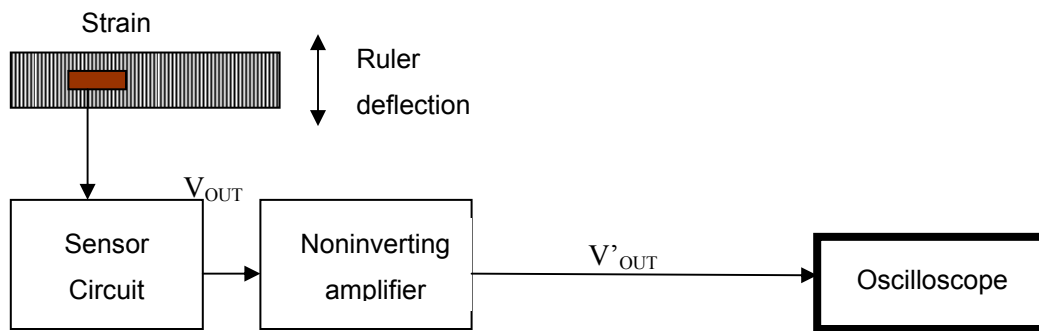


Figure 7. Strain gage sensor with voltage amplification

This amplification is necessary to increase the percentage accuracy of the voltage measurements made by the DAQ (data acquisition) board*. One way to amplify the voltage output is to increase the resistance of both R_1 and R_3 or to decrease the resistance of both R_2 and R_4 . We will assume that the circuit you built in Experiment #2 cannot be modified, which is usually the case with many circuit boards you may encounter in industrial applications. Instead, amplification of the existing voltage output V_{OUT} could be done quite easily using a noninverting op-amp.

* Since the DAQ board has been configured to accept voltages in the range -10 V to $+10$ V, it has an absolute accuracy of approximately 10 mV.

1. Add the circuit shown in Figure 8 to the circuit you built in Experiment #1. Use op-amp number three (pin numbers 8, 9, and 10) on the LMC6484 chip (Figure 4). Choose the source resistor R_S and the feedback resistor R_F such that

$$R_S = 10 \text{ k}\Omega \quad R_F = 150 \text{ k}\Omega.$$

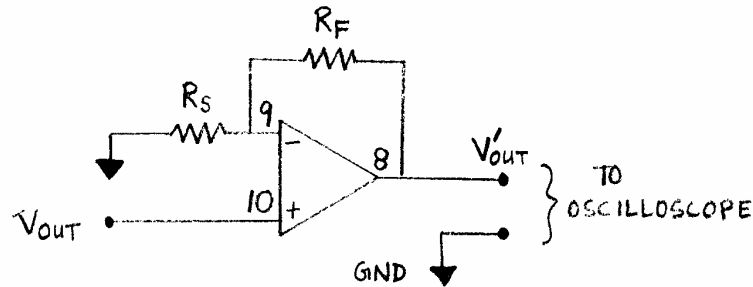


Figure 8. Noninverting operational amplifier circuit diagram

Then, the voltage gain A_V from the noninverting op-amp is given by

$$A_V = \frac{V'_{OUT}}{V_{OUT}} = 1 + \frac{R_F}{R_S} = 16.$$

The amplified voltage should be 16 times greater than what you viewed in Experiment #1.

2. Place the ruler flat on your table so that it is straight (not deflected). Increase the vertical scale on your oscilloscope to 1 volt/division. Connect the amplified voltage output V'_{OUT} and ground (GND) from your circuit to the oscilloscope.
3. Take the ruler in your hand and deflect it upward and downward. Verify that the amplified voltage output V'_{OUT} on the oscilloscope is similar to what you observed at the end of Experiment #1, but with a DC bias of approximately 2 V. **Record the DC bias produced by this circuit.**

Experiment #3: View Strain Gage Output on Computer Screen

In this experiment, you will build a *LabVIEW* VI to measure and display the voltage output from the strain gage sensor circuit you built in Experiment #2.

1. Open `yourname_lab1_ex2b.vi`.
2. Click on **Windows>>Show Diagram** to display your block diagram.

3. Using the *Labeling tool*, change the millisecond multiple control from 250 to 50. This will speed-up your display rate from 4 Hz to 20 Hz.*
4. To view the analog voltage signal from the strain gage circuit, connect the amplified voltage output V'_{OUT} (LMC6484 pin 8) from your sensor circuit to the CB-68LP connector block as shown in Table 1. Do not remove the connections to the oscilloscope.

Table 1. CB-68LP connector block pin assignment for measuring a voltage signal using Analog Input Channel 0.

External Signal	Connect to:
Amplified strain gage voltage output (LMC6484 pin 8)	Pin 68 (ACH0)
Analog ground	Pin 67 (AIGND)

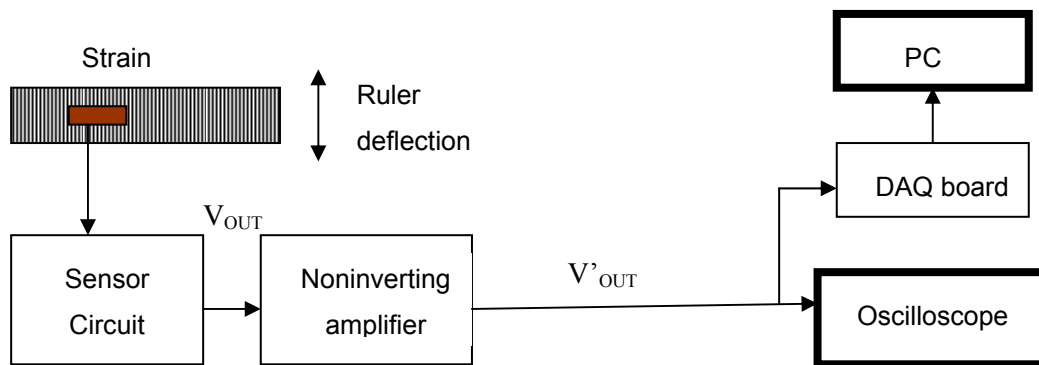


Figure 9. Strain gage sensor with voltage amplification and computer interface

5. Click the **Run** button to see the output from the strain gage circuit. Verify that the deflection voltage viewed on your computer screen corresponds to the deflection voltage (simultaneously) viewed on your oscilloscope.

Although you have displayed the voltage from your strain gage circuit on the computer screen, reading the measured voltage values would be much easier if the values were also displayed digitally. To this end, you can add one or more digital indicators to your front panel.

6. Go to the front panel. Select **Digital Indicator** from the **Controls>>Numeric** subpalette.

* Due to limitations of the Windows operating system, your program may not execute properly if you attempt to sample at faster than 20 Hz using this particular VI. Therefore, reducing the millisecond multiple control below 50 is strongly discouraged for this particular VI.

7. Place the Digital Indicator to the right of your Analog Input Chart.
8. Using the *Labeling tool* from the Tools palette, highlight the Digital Indicator label and change the label to Analog Input Value.
9. Using the *Labeling tool* from the Tools palette, highlight the Waveform Chart label and change the label to Analog Input Chart.
10. Pop up (right click) on the Digital Indicator and choose **Format and Precision**. Enter 3 for the Digits of Precision. The indicator should show three decimal places.
11. Go to the block diagram. Using the *Positioning tool* from the Tools palette, select the Analog Input Value indicator and drag it into the While loop.
12. Using the *Wiring tool* from the Tools palette, wire the sample terminal (output) from the AI Sample Channel.vi to the Analog Input Value indicator.

You are now ready to run your VI.

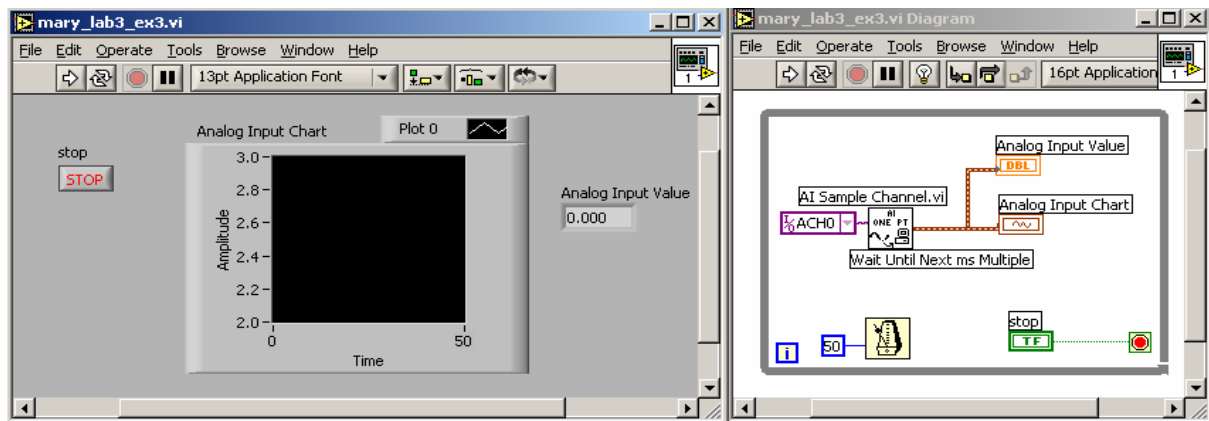


Figure 10. Front panel and block diagram for `yourname_lab3_ex3.vi`.

13. Click the **Run** button to see the output from the strain gage circuit. Verify that the deflection voltage shown by the Analog Voltage Value indicator corresponds to the deflection voltage shown by the Analog Voltage Chart.
14. Save this VI as `yourname_lab3_ex3.vi`.

For higher resolution readings, you can increase the digits of precision on your Analog Voltage Value indicator. Alternatively, you can add another digital indicator to your front panel and assign it a higher value for digits of precision.

Experiment #4: Add an Analog Low-Pass Filter to the Strain Gage Circuit

In this experiment, you will add an analog low-pass filter to your circuit to reduce the voltage fluctuations caused by high-frequency noise.

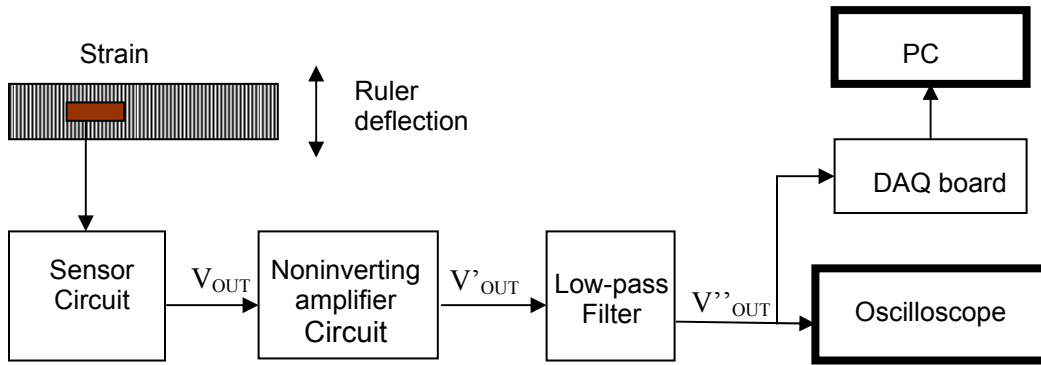


Figure 11. Strain gage sensor with voltage amplification and filter

1. Add the RC low-pass filter shown in Figure 12 to the circuit you built in Experiment #2.

Choose the resistor R_{LP} and the capacitor C_{LP} such that

$$R_{LP} = 100 \text{ k}\Omega$$

$$C_{LP} = 0.1 \text{ }\mu\text{F}.$$

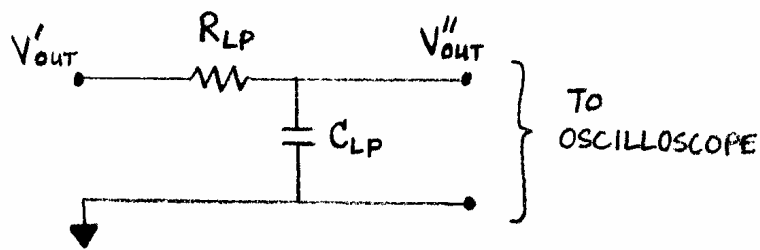


Figure 12. RC Low-pass filter

Then, the cutoff frequency ω_0 of the filter is given by

$$\omega_0 = \frac{1}{RC} = 100 \text{ rad/s}$$

or

$$f_0 = \frac{\omega_0}{2\pi} = 15.9 \text{ Hz.}$$

2. Connect the filtered voltage output V''_{OUT} and ground (GND) from your circuit to the oscilloscope.
3. Take the ruler in your hand and deflect it upward and downward. Verify that the amplified voltage output V'_{OUT} on the oscilloscope is similar to what you observed at the end of Experiment #2.
4. To view the filtered voltage signal on your computer screen, connect the filtered voltage output V''_{OUT} from your sensor circuit to the CB-68LP connector block as shown in Table 2. **Do not** remove the connections to the oscilloscope (step 2 above) and **do not** remove the connections you made to the CB-68LP in Experiment #3 (Table 1).

Table 2. CB-68LP connector block pin assignment for measuring a voltage signal using Analog Input Channel 1.

External Signal	Connect to:
Filtered strain gage voltage output	Pin 33 (ACH1)
Analog ground	Pin 67 (AIGND)

5. Open **yourname_lab3_ex3.vi**.

To simultaneously view both the non-filtered and filtered output from your circuit, you will add another Analog Sample Channel to this VI.

6. Go to the block diagram. Use the *Positioning* tool from the Tools palette to create some space inside your While loop so that you can add more components.
7. To create a copy of the existing chart, indicator, and Analog Sample Channel VI, select the *Positioning* tool from the Tools palette. Draw a box enclosing the Analog Input Chart, the Analog Sample Channel VI, and the Analog Input Value Indicator. You can do this by clicking down and dragging.
8. To make a copy of all the objects enclosed by your box, select **Edit>>Copy**.
9. Click on the block diagram inside the While loop and select **Edit>>Paste** to paste a copy of your previous setup. Feel free to re-position as necessary.
10. Using the *Labeling (Edit Text)* tool from the Tools palette, highlight the Analog Input Chart 2 label and change it to Filtered Analog Input Chart.
11. Similarly, highlight the Analog Input Value 2 indicator label and change it to Filtered Analog Input Value.

12. Also, highlight ACH0 in the Create Constant control and change it to ACH1. This indicates that the data on the Filtered Analog Input Chart will be obtained from **Analog Input Channel 1** (Pin 33 on the CB-68LP).
13. Using the *Labeling tool*, change the millisecond multiple control from 50 to 100. This will slow-down your display rate from 20 Hz to 10 Hz.*

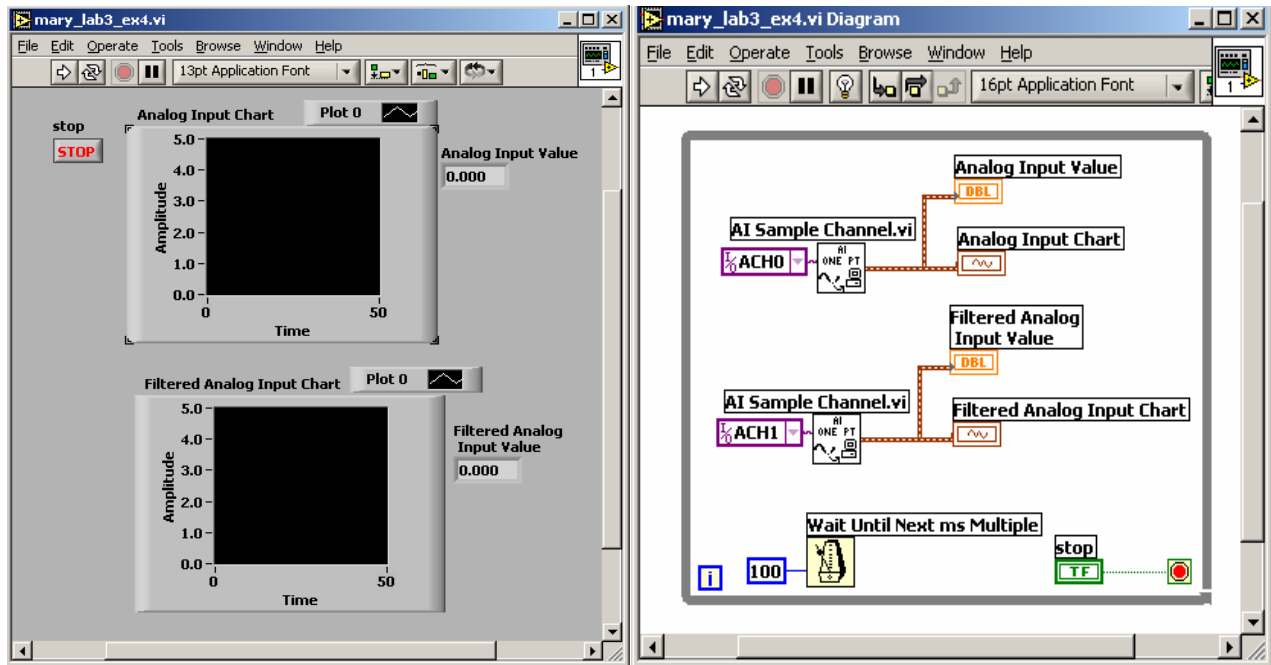


Figure 13. Front panel and block diagram for `yourname_lab3_ex4.vi`

You are now ready to run your VI.

14. Click the **Run** button to see the output from the strain gage circuit. Verify that the deflection voltage viewed on the Filtered Analog Input Chart is similar to the deflection voltage (simultaneously) viewed on your oscilloscope.

The effect of the low-pass filter should be clear. The voltage fluctuations due to noise should be significantly less after filtering.

15. Place the ruler flat on the table. Write down what the DC bias is for the filtered voltage. It should be slightly less than what you observed in Experiment #3.

*Because you are using two input channels, your maximum sampling rate (per channel) will be halved.

16. Save this VI as **yourname_lab3_ex4.vi**.

Saving Files

Before you leave, remember to save all of your files to your **ECI account** (for later use and backup purposes). For this laboratory, you should save the following files:

yourname_lab3_ex3.vi

yourname_lab3_ex4.vi

Laboratory Report

1. For the VI's you wrote in this laboratory (listed in the preceding section), provide a printout that shows the front panel and block diagram, similar to Figure 10 above.
2. Provide (draw) a **complete** circuit diagram for the strain gage circuit you built in Experiments 1 through 4.
3. In Experiment #1, you made sure that your DC bias was approximately 150 mV. If you had chosen a smaller DC bias, such as 10 mV, what would happen if you bent your ruler by a large amount in (a) the positive direction and (b) the negative direction? Illustrate your answer with a picture similar to Figure 5 above.
4. In Experiment #1, explain why connecting a parallel resistor as shown in Figure 6 allows you to move your DC bias.
5. In Experiment #2, you used a noninverting amplifier to amplify the voltage output. Explain why an inverting amplifier would not have worked in this situation. (Assume that you are not concerned whether the amplified output is positive or negative).
6. Create a table to list your DC bias values from Experiments 1-4. Compare the values and explain how they are related. In Experiment #4, explain why the filtered DC bias value is less than the non-filtered DC bias. If you used $R_{LP} = 10 \text{ k}\Omega$ instead of $R_{LP} = 100 \text{ k}\Omega$, would you expect a different value for the filtered DC bias? Explain.

Your Lab Report should clearly state your name, Lab Report number, Lab date, and your laboratory partner's name (if any). Your lab report should be thorough, but concise. You will be graded on quality, not quantity. **Lab Report #3 is due at the beginning of Laboratory #4.**

Additional Reading and Practice

1. *LabVIEW Data Acquisition Basics Manual*, Pages 5-1 to 5-8, Pages 6-1 to 6-2, and Pages 7-1 to 7-3. Available online at www.ni.com/pdf/manuals/320997e.pdf.
2. *LabVIEW User Manual, Power Spectrum*, Page 13-14. Available online at www.ni.com/pdf/manuals/320999b.pdf.

Extra Credit Experiment: Obtain Power Spectrum of the Voltage Output

In this experiment, you will use a built-in *LabVIEW* VI to quantify the frequency characteristics of the output voltage from your strain gage circuit. This can be done by computing the *power spectrum* of the output voltage. The power spectrum is a plot that shows the power in each of the frequency components of the output voltage.* The x-axis of the power spectrum will be in units of frequency given by

$$\Delta f = \frac{f_s}{N}$$

where Δf is the frequency spacing between tick marks, f_s is the sampling frequency, and N is the number of samples.

Until now, you have used the **AI Sample Channel** VI to sample external voltages. This VI provides a non-buffered input, which means the software reads one value from an input channel and immediately returns the value to you. This process cannot be done very quickly, so for applications that require very fast sampling rates, the **AI Acquire Waveform** VI should be used.

1. Create a new VI by selecting **New VI** in the LabVIEW dialog box.
2. From the **Controls** palette, click on the **Options** navigation button. From the **Function Browser Options** pop-up window, select the **default** palette set. Click on the **OK** button. This will allow you to view all the functions in LabVIEW. (The **basic** palette set that you were using up to now contained only a small subset of the LabVIEW libraries).
3. Go to the block diagram. Select **AI Acquire Waveform.vi** from the **Functions>>Data Acquisition>>Analog Input** subpalette.

* *LabVIEW* User Manual, page 13-14.

4. Place that VI on your block diagram. Pop up (right click) on it and select the **Visible Items>>Label** option.
5. Using the **Wiring** tool, pop-up on the **channel (0)** terminal of the AI Acquire Waveform VI and select **Create Constant**. Using the *Operating tool* to select `ACH0` from the pull-down menu. This indicates that you will sample using Analog Input Channel 0.
6. Pop-up on the **number of samples** terminal of the AI Acquire Waveform VI and select **Create Constant**. Type `65536` to indicate that you will acquire 2^{16} samples*.
7. Pop-up on the **sample rate (1000 samples/sec)** terminal of the AI Acquire Waveform VI and select **Create Constant**. Type `65536` to indicate that you will acquire 2^{16} samples per second.
8. If your constants are on top of one another, feel free to use the **Positioning** tool to move them apart.
9. Select **Power Spectrum.vi** from the **Functions>>Analysis>>Signal Processing>>Frequency Domain** subpalette. Place the Power Spectrum VI to the right of your AI Acquire Waveform VI. Pop-up on it and select the **Visible Items>>Label** option.
10. Using the **Wiring** tool, wire the **waveform** (upper output) terminal of the AI Acquire Waveform VI to the **X** (input) terminal of the Power Spectrum VI.
11. Go to the front panel. Select **Waveform Graph** from the **Controls>>Graph** subpalette.
12. Place this graph on the front panel and modify its label to read `Voltage Vs Time Graph`. Pop-up on the graph and select **X Scale>>AutoScale X**. Do the same for the **Y Scale**.
13. Place another Waveform Graph below your `Voltage Vs Time Graph` and label it `Voltage Power Spectrum`. Pop-up on the graph and select **Y Scale>>Formatting**. Select a **Linear** Mapping mode with **1** Digit of Precision and **Engineering Notation**. Before you click on **OK**, select a fine grid by clicking on the Y Axis/Grid Options icon and then selecting the rightmost choice. You may also change the colors for better viewing. Click **OK** to implement your choices.
14. Pop-up on the `Voltage Power Spectrum` graph and select **X Scale>>Formatting**. Select a **Log** Mapping mode with **2** Digit of Precision and **Engineering Notation**. Before you click on **OK**, select a fine grid by clicking on the X Axis/Grid Options icon and then selecting the rightmost choice. You may also change the colors for better viewing. Click **OK** to implement your choices.
15. Pop-up on the graph and select **X Scale>>AutoScale X**. Repeat this for the **Y Scale** as well.
16. Go to the block diagram. Wire the `Voltage Vs Time Graph` to the **waveform** (output) terminal of the AI Acquire Waveform VI.

* If the number of samples is a power of 2, the Power Spectrum can be computed very quickly using an algorithm known as the Fast Fourier Transform (FFT). If the number of samples is not a power of 2, calculating the power spectrum could take a long time.

17. Wire the Voltage Power Spectrum graph to the **Power Spectrum** (output) terminal of the Power Spectrum VI.

You are now ready to run your VI.

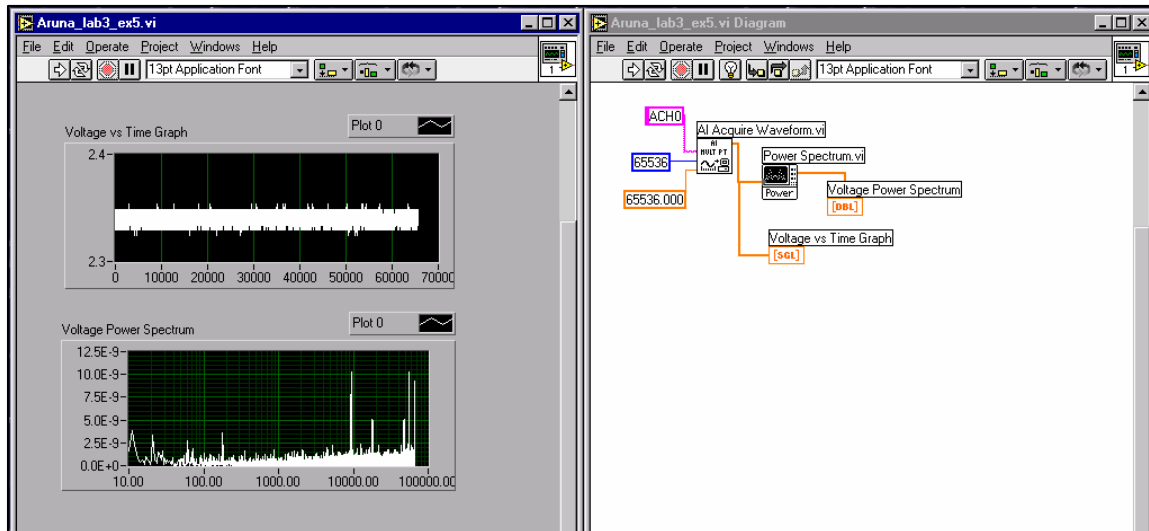


Figure 14: Front panel and block diagram for `yourname_lab3_extra.vi`.

18. Do not modify the connections you made to the CB-68LP during Experiment #4. That is, you will sample the amplified voltage signal (V'_{OUT}) *before* the low-pass filter.
19. Click the **Run** button. The program will take a few seconds to collect the voltage samples and display the time domain graph and also the power spectrum. Verify that the deflection voltage viewed on the Voltage Vs Time Graph is similar to the deflection voltage (simultaneously) viewed on your oscilloscope.

Since you chose $F_S = 2^{16}$ samples/second and $N = 2^{16}$ samples, the x-axis of your power spectrum is in units of $\Delta f = 1$ Hz. The first half of the power spectrum represents positive frequencies, while the second half of the spectrum represents negative frequencies. Therefore, for practical purposes, **do not pay attention to the frequency components greater than $2^{15} = 32,768$ Hz.**

20. Save this VI as `yourname_lab3_extra.vi`.
21. Run this VI a few times and observe the resulting graphs. While oscillating your ruler at 1Hz, run the VI to see what the power spectrum looks like. For your lab report, obtain printouts as shown in Figure 14 above. (The signal displays must be included on your graphs).

22. In the **channel (0)** terminal of the AI Acquire Waveform VI, *replace* ACH0 with ACH1 to indicate that you will sample using Analog Input Channel 1. Run this VI a few times and observe the resulting graphs. While oscillating your ruler at 1Hz, run the VI to see what the power spectrum looks like. For your lab report, obtain printouts as shown in Figure 14 above. (The signal displays must be included on your graphs).

Lab Report (Question 7):

23. For the VI's you wrote in this experiment, provide a printout that shows the front panel and block diagram, similar to Figure 14 above. You should include four such printouts (i.e., non-filtered and stationary, non-filtered and oscillating, filtered and stationary, filtered and oscillating). Describe what you saw on both the *Voltage Vs Time* graph and the *Voltage Power Spectrum* graph. In particular, compare power spectra for the stationary ruler and the oscillating ruler. Also compare power spectra for filtered and unfiltered voltages.