Chapter 5

Lab 4: A Variety of Sensors for the Measurement of Temperature, Strain, Pressure, and Displacement

Objectives:
- Understand and build Wheatstone Bridges
- Use strain gauges to measure the deformation of a beam under load, and to measure the pressure in a cannister
- Use a thermocouple to measure temperature
- Use a thermistor to measure temperature
- Use a Linear Variable Differential Transformer (LVDT) to measure displacement

Introduction

One of the main motivations for teaching electronics and data acquisition in this lab is to help you understand the data acquisition and processing that will occur in the thermodynamics labs that will follow. The final link is the sensors. This lab introduces strain gauges, thermocouples, thermistors, and LVDT's.

Reference:

Dally, James W., Riley, William F., and McConnell, Kenneth G., Instrumentation for Engineering Measurements, 2nd Ed., John Wiley & Sons, 1993.

Instrumentation using Low Output Signal Sensors

Objectives:
- Understanding Strain Gauges.
- Understanding Thermocouples.
- Analysis of a common Instrumentation Amplifier.
- Use these devices to construct and calibrate the following:
  - Pressure Transducer using a Strain Gauge in a ¼ Whetstone Bridge.
  - Thermometer using a type "T" Thermocouple.

5.1 Introduction

This lab will combine what you have learned in Chapters 2 and 3, resistors in series parallel networks and operational amplifiers to analyze the behavior of a mechanical device. You will be introduced to Strain Gauges and Thermocouples as low output signal sensors and the Instrumentation Amplifier (AD623) used to increase the amplitude of their analog signals.

5.2 Sensors

5.2.1 Strain Gauge

The strain gauge is the most common device for the electrical measurement of static deformation. They rely on a proportional linear variance of resistance (ΔR) due to variance in gauge length (ΔL) along its longitudinal axis referred to as Gauge Facture (GF) and is typically no greater than 2.   Gage Factor is expressed in equation form as:

$$GF = \frac{\Delta R / R}{\Delta L / L}$$

A strain gauge is made of a continuous electrical conductor (bonded metallic or foil) called the grid, deposited on a very thin flexible insulating material carrier. **Figure 5.2.1.1** shows a magnified strain gauge.
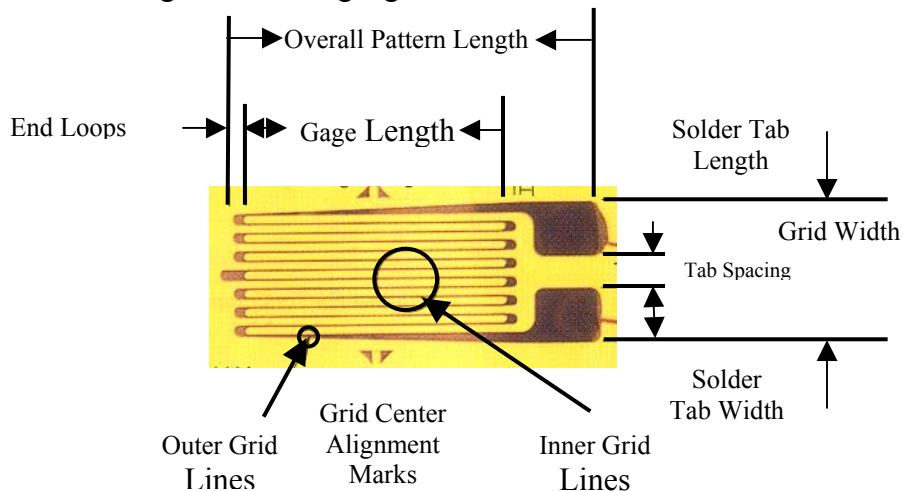
Figure 5.2.1.1

Typical gauge resistance (unstrained) is 120, 350, 600 and 700 ohms. But if attached to an object such as a metal beam, and if the beam is under strain, that is, if a load is applied to the beam, the beam will deform (bend, elongate or compress) carrying with it the gauge. We define Strain (ε) as a deformation per unit length. **Figure 5.2.1.2** shows a beam under load with attached gauge. In this case, the top surface of the beam and the attached gauge is in tension and has become elongated increasing the resistance of the gauge.
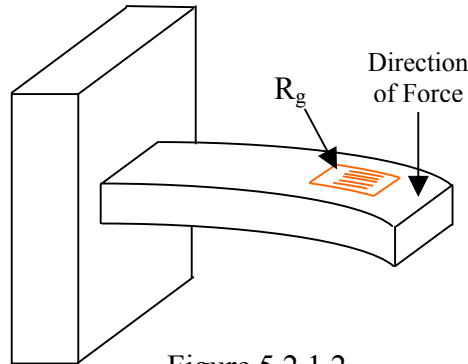

Figure 5.2.1.2

In section 2.3.3 of Chapter 2 in your Lab Manual you demonstrated how a resistor converts voltage to current and visa versa. A strain gauge is nothing more than a variable resistor. **Figure 5.2.1.3** shows an unbalanced ¼ Wheatstone Bridge electrical circuit where R_g is the Strain Gauge and R1, R2 and R3 are fixed resistors referred to as Bridge completion resistors.

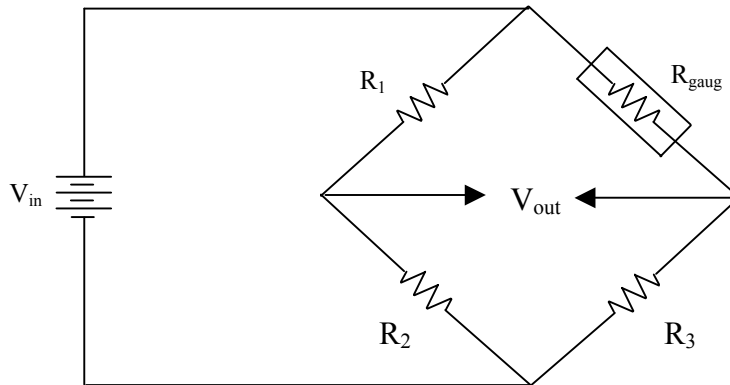**Figure 5.2.1.3**

V_{out} is a function of V_{in}, R_1, R_2, R_3 and R_g. This relationship is:

$$V_{out} = V_{in}\left[\frac{R_3}{R_3 + R_{gauge}} - \frac{R_2}{R_1 + R_2}\right]$$

This equation is not as complicated as it may seem. Note that the left and right sides of the bridge are just voltage dividers and the term in the bracket is proportional to the output voltage of each divider.

If all the Resistance's are equal the bridge is referred to as balanced and $V_{out} = 0$.

5.2.2 Thermocouple

A thermocouple is a temperature measurement sensor consisting of two dissimilar metals joined together at one end (junction) that produces a small thermoelectric voltage. A change in that voltage is interpreted as a change in temperature. The thermocouple is not a linear sensor, but instead a Direct Polynomial when converting µV to Deg C and Inverse Polynomial converting Deg C to µV.
 There are many types of thermocouples such as J, K, T, and E to name a few. They all have different and sometimes overlapping temperature ranges. For the exercises that follow we will be using Type T, copper for one wire, an alloy consisting of copper, and nickel (constantan) for the second wire.
The open-ended voltage is not only a function of the closed-ended (Junction) temperature but also the open-ended temperature. For that reason the open-ended temperature must be known to correct for the error or forced to some level. This adjustment is known as Cold Junction Compensation (CJC). The industry standard for the open-ended temperature is 0 Deg C. **Figure 5.2.2.1** shows a Type T thermocouple with its open-ended temperature forced to 0 Deg C using an ice bath.
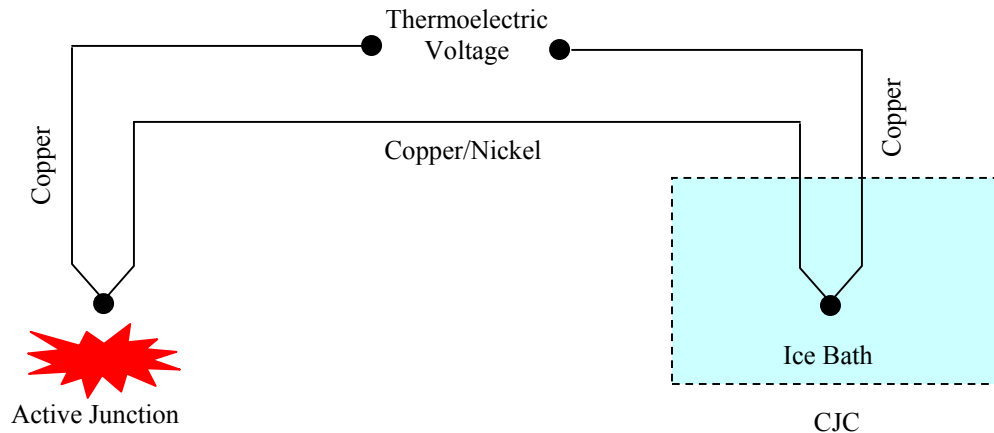

Figure 5.2.2.1

5.3 Instrumentation Amplifier (AD623)

The Instrumentation Amplifier offers high gain for low output signal sensors. The differential input measures the inverting and non-inverting input with respect to each other and amplifies the difference. The single ended output provides an amplified signal with respect to reference.   A resistor between pins 1 and 8 determines gain. A data sheet for the AD623 should be in the reference Manual.

Recall from section 3.5.3 Chapter 3 of your Lab Manual on converting small analog signals to their digital representation for a computer using an A/D. Simply stated, it is usually necessary to amplify small analog signals to take advantage of as much dynamic range of the A/D as possible. The AD623 is a circuit based on three Op amps. The first two are non-inverting amplifiers with degenerative feedback and the third is differential. **Figure 5.3.1** shows a simplified schematic.
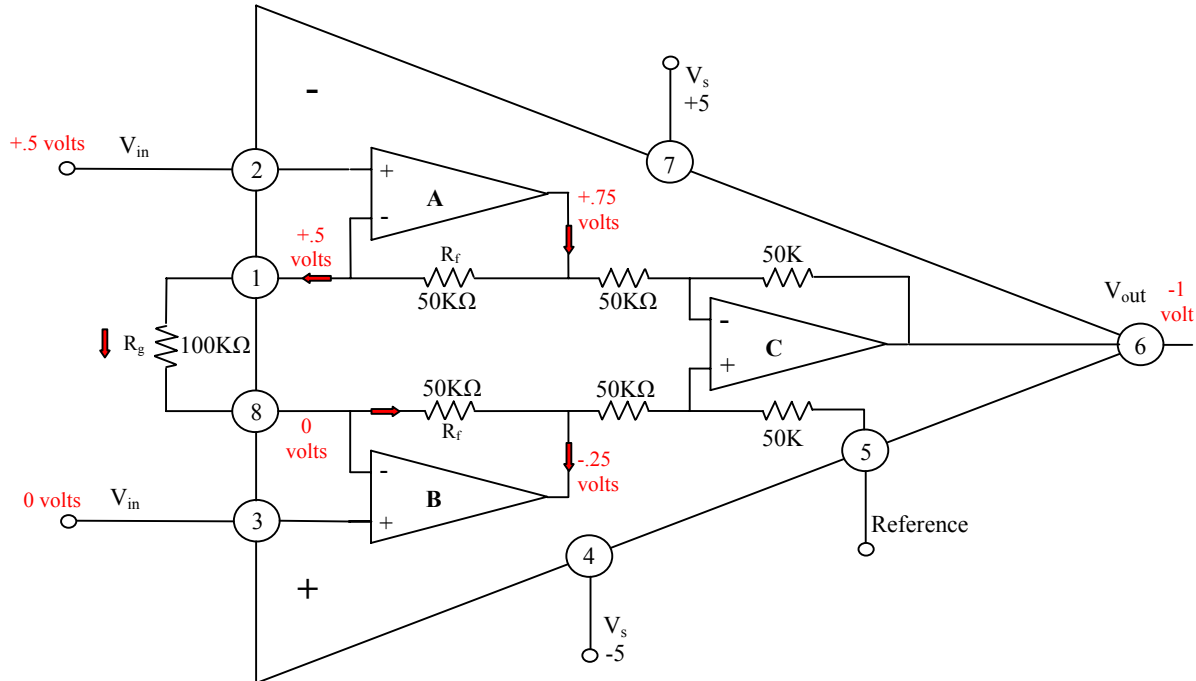
Figure 5.3.1 AD623

Review what we have learned about op-amps.

- Op-amp **A** and **B** are non-inverting amplifiers.
- The output of an op-amp will attempt to whatever is necessary to make the voltage difference between its inputs 0.
- Gain is determined by the relationship between R_f an R_g.
- Op-amp **C** is a differential amplifier used as a difference amplifier with unity gain (gain = 1).
- The idealized op-amp has an input impedance of infinity ($Z_{input} = \alpha$) and output impedance of 0 ($Z_{output} = 0$).

Analyze the circuit using +.5 volts on the inverting and 0 volts on the non-inverting inputs.

The transfer function for the AD623 is:

$$Vo = \left[1 + \frac{100K\Omega}{Rg}\right]Vi$$

5.4 Laboratory Activities

5.4.1 Measure the change in resistance of a strain gauge.

Attach a 350Ω strain gauge to a 2" diameter brass disc using a drop of super glue. Press the gauge on using a strip of Teflon tape so you don't become stuck as well and wait until the glue hardens. Connect the assembly to your Keithley DVM as shown in Figure 5.4.1.1 and record the resistance with the disc relaxed and slightly flexed. Record your measurements in your lab notebook.
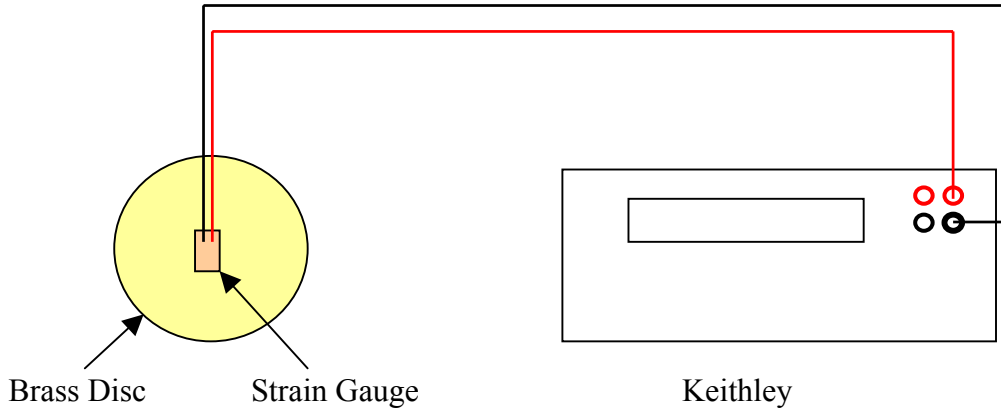

Brass Disc   Strain Gauge   Keithley

Figure 5.4.1.1

5.4.2 Constructing a Balanced ¼ Wheatstone Strain Gauge Bridge

Wire up the circuit shown in **Figure 5.4.2.1** on your trainer board. Use the strain gauge you attached to the brass disc for R_g. Measure V_{out} on the o-scope. Adjust R_2 so that V_{out} is approximately equal to 0. Flex the disc and record the change in V_{out} due to changes in the resistance of R_g. Leave the circuit assembled for an upcoming exercise.
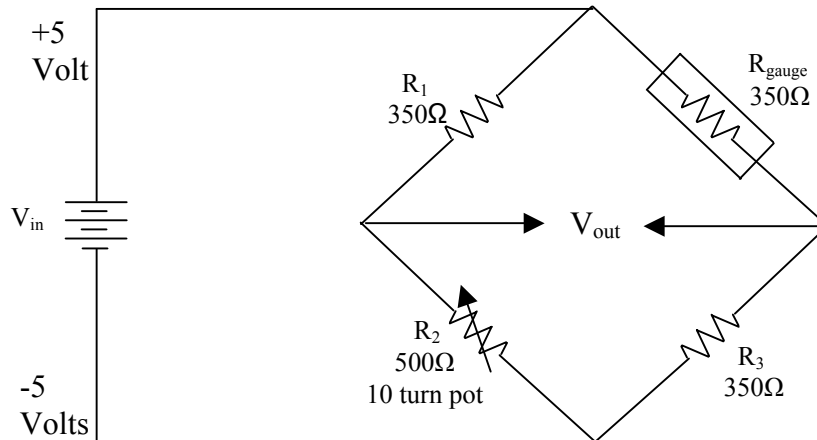

Figure 5.4.1.2

5.4.3 Constructing a Pressure Transducer

Wire the AD623 to your strain gauge assembly on the trainer board as shown in Figure 5.4.4.1. Measure the output of the amplifier using the o-scope. Adjust R2 so that V_{out} is as close to zero as possible.
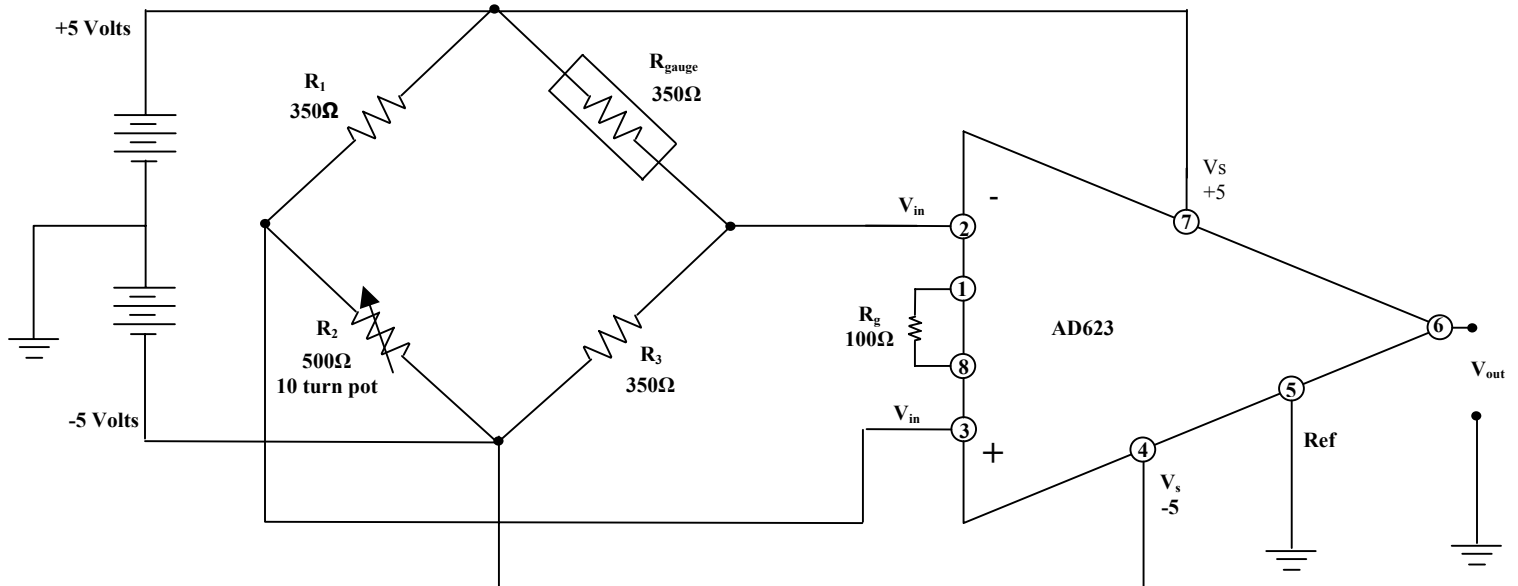

Figure 5.4.3.1

Flex the disc and record the data in your lab notebook. Notice that the V_{out} values from the AD623 is approximately 1000 times greater then V_{in} due to the value of R_g.

Demonstrate your results to an instructor before continuing.

Use the LabView Program **Measure Pressure and Temperature.vi** to Calibrate your transducer and measure Pressure.
The program collects 1000 data points at a rate of 10000 points per second and iterates every 200 milli-seconds. Connect the output of the AD623 to the Analog Input Channel 0 of the A/D breakout box.
Calibration
Measure the V_{out} of the AD623 using the o-scope with respect to the pressure reading from the dial on the hand pump. Use Excel and enter these values in columns A & B respectively. Use an XY Scatter Plot, add a Trend Line and Show the Equation. Enter this equation in the Formula Node and run the program.

Demonstrate your results to an instructor before continuing.

5.4.4 Testing a Type T Thermocouple

For this exercise you will need an ice bath, Type T thermocouple, hot plate and beaker. Immerse one end of the thermocouple into the ice bath. Identify the positive and negative wires using your Kethley DVM (your setup should look something like the drawing in section 5.2.2). Refer to the Type T Reference Table, which should be in the three ring binder at your bench. The table converts millivolts to Deg C. Record room temperature in both millivolts and deg C in your notebook, also, measure the temperature of the ice bath and boiling water. Remember to record the data.

5.4.5 Constructing a Thermometer

Wire the AD623 to your Type T thermocouple as shown in Figure **5.4.4.1** on your trainer board.
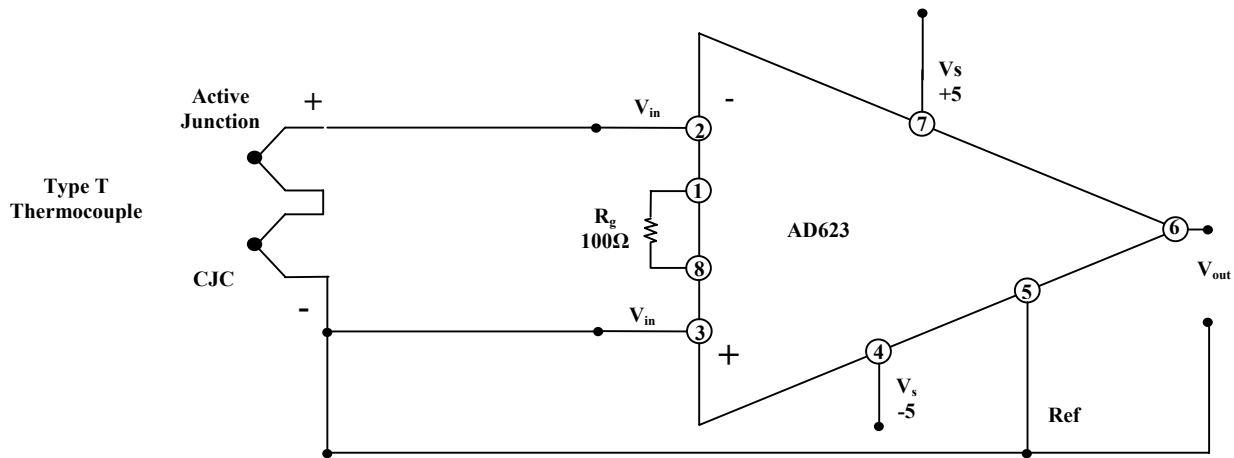

Figure 5.4.4.1

Notice that the V_{out} values from the AD623 is approximately 1000 times greater then V_{in} due to the value of R_g

Demonstrate your results to an instructor before continuing.

Connect the output of the AD623 to the Analog Input Channel 0 of the A/D breakout box. Measure room temperature the temperature of the ice bath and boiling water.

Demonstrate your results to an instructor before continuing.

The Linear Variable Differential Transformer

Introduction

The Linear Variable Differential Transformer (LVDT) is a displacement transducer similar in appearance to a linear potentiometer; however, the mechanism by which it operates is very different. LVDT's tend to be much more expensive than pots and offer significant advantages in longevity, friction, and linearity.

Operation

The basic construction of an LVDT is shown in Figure 1. The device consists of a primary coil, two secondary coils, and a moveable magnetic core which is connected to an external device whose position is of interest. A sinusoidal excitation is applied to the primary coil, which couples with the secondary coils through the magnetic core (ie. voltages are induced in the secondary coils). The position of the magnetic core determines the strength of coupling between the primary and each of the secondary cores, and the difference between the voltages generated across each of the secondary cores is proportional to the displacement of the core from the neutral position, or *null* point.
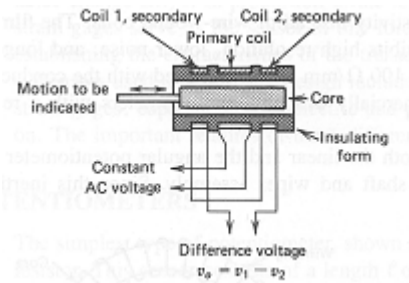

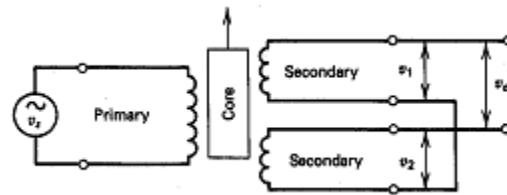**Figure 1: Cross-section (Dally et al.)**   **Figure 2: Electrical connections (Dally et al.)**
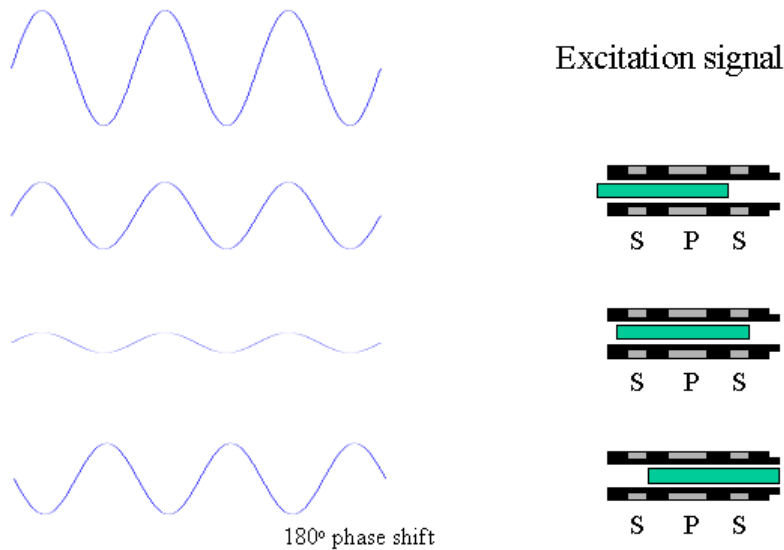

**Figure 3: The effect of core position on amplitude and phase
of the output signal with respect to the excitation signal.**

Figure 2 shows the electrical connections within the LVDT. The primary coil is connected to an AC signal source. The frequency of this source should be much higher than (at least 10 times) the frequency of the motion you wish to record – typical source frequencies are in the kHz range. The secondary coils are connected in series such that the difference between their output voltages can be measured, hence the name *differential* transformer. Therefore the output voltage is a sinusoid with the same frequency as the excitation, and the amplitude of the signal is proportional to the distance of the core from the null point. Because the two secondary signals are opposite in polarity, the ouput undergoes a 180° phase shift as the core passes the null point, and therefore the direction from the null point can also be determined.   These phase and amplitude dependencies are illustrated in Figure 3.

The output signal should be proportional to the position of the core, and Figure 4 shows how this is achieved. As we know, the excitation signal is modulated by the position of the core, resulting in the 'amplitude-modulated signal'. This is then rectified, but attention must be paid to the phase of the signal so that positive or negative displacement can be discerned – displacement in one direction gives a positive output while the other is negative. Then the high-amplitude excitation is filtered out using a low-pass filter, yielding an output voltage that is proportional to position. Figure 5 shows the processed output signal as a function of core position.
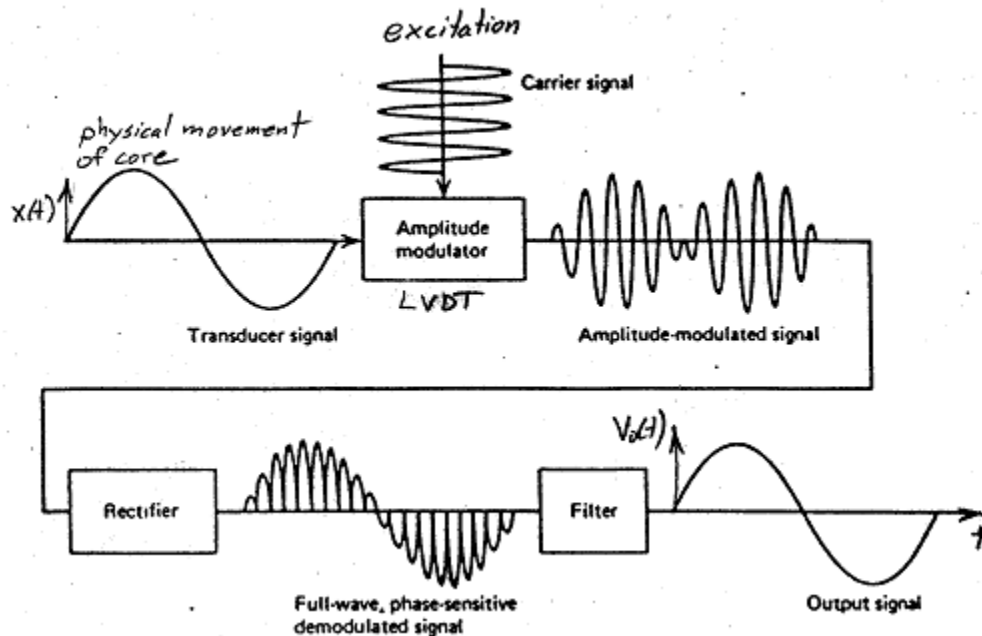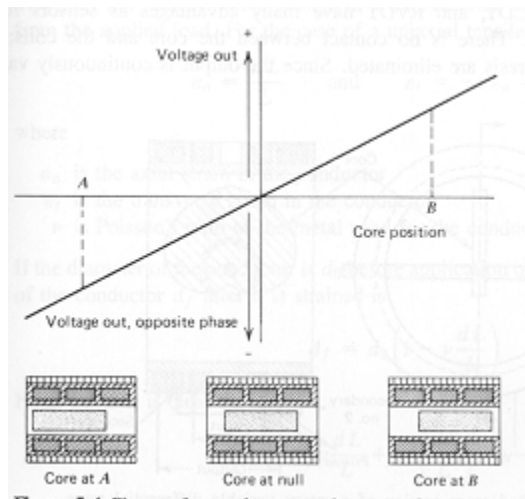

Figure 4: Signal Processing

Figure 5: The processed output signal

LVDT's vs. Pots

We've previously used a linear pot as a displacement transducer, so why do we need yet another device? The LVDT and signal conditioner that you will use in the lab costs about $700, compared to perhaps 10's of dollars for a pot, so we really don't want to use an LVDT unless we really need one. We know that the potentiometer consists of a wiper that slides along a conducting surface, and therefore there is necessarily some friction. In the LVDT there is no physical contact between the core and the coils so friction is limited only to that in the linear bearings, and therefore can be made very small. In addition, the physical contact in the pot results in wear, leading to noise. For applications with constant movement over long time periods, the LVDT is superior. The LVDT is also superior to the pot in one other way: linearity. In lab 1 we calibrated the wirewound potentiometer and saw that it had some nonlinearity. A high-quality pot may have a linearity of 1% of full-scale (F.S.), whereas an inexpensive LVDT could have 0.25% F.S. or less. This simply means that if we were to fit a line to the relationship between output voltage and displacement (as we did with the wirewound pot), any measurements could deviate up to 0.25% x (the full-scale displacement range) from that line.

Laboratory Activities

We will use the LD310-50, a relatively inexpensive LVDT manufactured by Omega Engineering Inc. It has a linear range of +/- 50 mm and is driven by a 5 kHz excitation signal. Omega also provides the LDX-3A signal conditioner which generates the excitation and processes the output signal. We will use this; however, we will also explore some more fundamental techniques which employ basic laboratory tools.

You should have two LVDT's at your station. One fitted with a special 5-pin plug, and the other with bare wires exposed at the end of the signal cable. The plug is designed to fit into the Omega signal conditioning unit. When we are not using the conditioning unit, we will use the LVDT with exposed wire ends.

Start by looking at the tags adhered to the cables of each LVDT. Note that each one has a serial number and is individually calibrated. Linearity and sensitivity are reported. The linearity is expressed as a percentage of full scale, or displacement range of the instrument. Sensitivity is a

measure of the change in output (mV) per unit change in displacement (mm). Since the amplitude of the excitation signal is also a variable, this is divided out from the sensitivity so that it is presented in units of mV *output* per Volt *excitation* per mm *displacement* (mV/V/mm).

Excitation is introduced on the blue and red wires, and the output signal is carried by the green and white wires. The yellow wire is used to correct for asymmetry in the LVDT, which is particularly noticeable near the null point. We will not use it right now. Connect the excitation wires to a function generator and set the frequency to 5 kHz (set the amplitude to maximum), and view the excitation and output signals simultaneously with your oscilloscope. Move the shaft back and forth and note the change in amplitude and phase as the null point is traversed.

The oscilloscope shows the unprocessed LVDT output. This is useful for verifying connections and understanding the operation of the LVDT; however, if we need to acquire position data, this is not particularly convenient. We need to process this signal so that we get only a number proportional to the displacement from the null point. Such a signal is much condensed, making storage and further manipulation simpler. The lab computers contain a program called LVDT.vi, that applies appropriate conditioning to the signal. Turn off the function generator and open the program LVDT.vi. LVDT.vi reads the excitation signal on Channel 0, and the LVDT output signal on Channel 1. We will continue to use the function generator to excite the LVDT, so do not disconnect it, but now connect the Channel 0 and Channel 1 inputs to your LVDT. Turn the function generator on again, and push the 'continuous run' button on LVDT.vi to run the program. Now observe the three charts on the screen. The upper left chart shows the excitation signal (white) with the LVDT output signal superimposed (red). Move the shaft in and out and confirm that the signal you see here is the same signal that you previously observed on the oscilloscope screen.

In order to detect the phase of the output with respect to the input signal, LVDT.vi multiplies both signals together point by point. If the signals are in phase, the product will be positive. If they are 180 degrees out of phase, the product will be negative. The upper right chart displays the product of the two signals. Again, move the shaft in and out and confirm that the product changes sign as the null point is traversed. Note also that because the excitation amplitude is constant, the product is proportional to amplitude of the output signal, and hence proportional to the distance from the null point. All that is left is to filter the 5 kHz oscillation from the product, and the result is displayed in the bottom chart – a value proportional to the displacement.

The LDX-3A signal conditioner will perform a similar task to the LabVIEW program. Plug the other LVDT into the 5-pin socket on the LDX-3A, and apply power by plugging the line cord into one of the power outlets at your bench. Using your oscilloscope, measure the output voltage from the pair of wires extending out of the LDX-3A and confirm that this is a displacement measurement.

Replace all of the equipment so that it is ready for the next group to use.

The Thermistor

Use of a Standard 47kΩ Resistor as a Temperature Probe
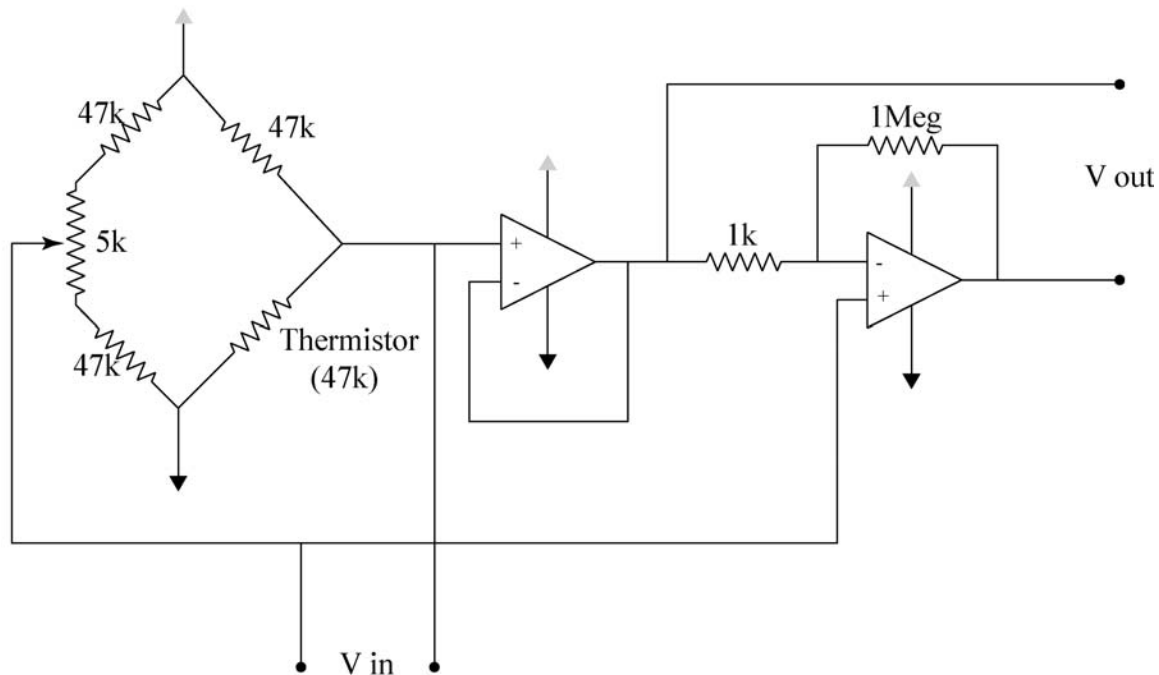
The above circuit is designed to make use of an ordinary 47 k resistor as a temperature probe. You will, no doubt, recognize the circuit as a resistor bridge with a voltage follower and an inverting voltage amplifier. One of the legs of the resistance bridge will be used as a temperature probe. Wire the thermistor 47k resistor some distance from the rest of the circuit as will be (was) explained at the beginning of the lab. Wire up the above circuit as shown. A more precise pin-out diagram will be distributed at the beginning of the lab. Adjust the 5k pot until the bridge is balanced (Vin and Vout go to zero).

Why is the voltage follower necessary? Why the super high input impedance op-amps (> 10^12 Ohms!)?

From the web page http://www.ohmite.com/catalog/little_rebel.html we see a temperature coefficient of –450 ppm/K. How much do you expect Vin to change per Kelvin change of the thermistor? How much gain will be needed to get a respectable change in output voltage of 1 volt per 100 K? Select an appropriate resistor for R2. What is the gain from Vin to Vout?

Now that you've balanced the bridge at room temperature and set the gain, "cook" the thermistor with the heat gun. What would you estimate the temperature of the heat gun exhaust to be?