Enter the names and SIDs for you and your lab partner into the boxes below.

Name 1	SID 1	
Name 2	SID 2	

#### **Strain Gages**

In this lab we design an electronic scale. The device could equally well be used as an orientation sensor for an electronic camera or display, or as an acceleration sensor e.g. to detect car crashed. In fact, similar circuits to the one we build are used in all these applications, albeit using technologies that result in much smaller size.

In our scale we use the fact that metal bends if subjected to a force. In the lab we use an aluminum band with one end attached to the lab bench. If we load the other side, the band bends down. As a result, one side of the band gets slightly longer and the other one correspondingly shorter. All we need to do to build a scale is measure this length change.

### Attention: The setup and gage are fragile. Load it only with the supplied brass weights and do not manually force or bend the aluminum band.

How can we do this with an electronic device? Turns out we need to look no farther than to simple resistors. A resistor is similar to a road constriction, such as a bridge or tunnel. The longer the constriction, the higher the "resistance". Cars (or electrons) will back up. Increasing the width on the other hand reduces the resistance.

If we glue a resistor to our metal band its value will increase and decrease proportional to the length change. The percent change is called the "gage factor" *GF* and is approximately two (since an increase in length is accompanied by a corresponding decrease in width due to conservation of volume): a 1% change in length results in a 2% change in resistance. Mathematically we can express this relationship as

$$\frac{\Delta R}{R_o} = GF \, \frac{\Delta L}{L_o} \tag{1}$$

where  $L_o$  and  $R_o$  are the nominal length and resistance, respectively, and  $\Delta L$  and  $\Delta R$  are the changes due to applied force. The nominal length and value of the resistor,  $L_o$  and  $R_o$ , can be measured. If we further determine  $\Delta R$  we can calculate  $\Delta L$ , and, with a bit of physics, determine the applied force.

Assuming you can measure resistance with a resolution of  $0.1 \Omega$ , what is the minimum length change that you can detect for  $R_o = 218 \Omega$  and  $L_o = 82 \text{ mm}$ ? Use GF = 2 for this and all subsequent calculations.

In the laboratory, attach the metal band with attached strain gage to the bench. Measure the the nominal resistance  $R_o$  without any extra weight applied to the band. Then determine  $\Delta R$  for one, three, and six weights. Report your results in the table below:



The small changes may be difficult to resolve if the display of the meter flickers. Use the bench top meter (not handheld device), and make sure the connections are reliable. Poor connections can contribute several Ohms resistance, and small changes in the setup (e.g. a wire moved) can result in big resistance changes. Also, as for all measurements, keep wires short.

#### Half Bridge Circuit

Using an Ohm-meter to evaluate the output of our scale is not very practical. Typically we prefer a voltage output for sensors. Voltages can easily be interfaced for example to microcontrollers (small computers), which in turn can



 $\mathsf{R}_{\mathsf{ref1}}$ 

Figure 1 Strain gage in a half bridge circuit configuration.

Figure 2 Full bridge configuration.

be connected to a display or other appropriate device. In this lab we focus on getting a voltage out of our sensor and leave the microcontroller interface for later.

R<sub>ref3</sub>

Resistors, in combination with a voltage source, come to the rescue here also. Figure 1 shows a so-called half bridge configuration where the strain gage resistor  $R_{strain}$  is connected to a reference resistor  $R_{ref}$  and a balanced supply. An important objective is to achieve nominally zero output voltage  $v_0$  when no strain (weights) are applied to the scale. This is achieved in the circuit when  $R_{ref}$  is set equal to the nominal value  $R_0$  of the strain gage resistor and the supply voltages  $V_{dd}$  and  $V_{ss}$  are equal.

Under these conditions, and for  $V_{dd} = V_{ss} = 4$  V, what is the value of  $V_0$  for a 1% increase of  $R_{strain}$  from its nominal value?

1

Build the circuit in the laboratory using a solderless breadboard (download the guide from the manual section of the website). Choose  $R_{ref}$  as close as possible to  $R_o$ . Do not just rely on the color code but measure the actual resistor values. Use more than one resistor to synthesize the value to within a few percent of the correct value. Set up the laboratory supply for  $V_{dd} = V_{ss} = 5$  V. Then take the following measurements of  $v_o$ :



Ask the teaching assistant to verify the circuit operation.

#### **Full Bridge Circuit**

The half bridge circuits has several drawbacks. While doing the measurements you may have noticed how difficult it is to accurately set the null point and keep it stable. Any change of the supply voltage directly affects the output of the circuit. In practice such changes occur frequently, e.g. as the result of a sudden increased current consumption of a different part of the circuit such as an amplifier or microcontroller. The need for balanced supply  $V_{dd} = V_{ss}$  is a further drawback of the half bridge circuit.



**Figure 3** Potentiometer: Equivalent circuit diagram (left) and symbol (right).

The full bridge configuration, shown in Figure 2 on the previous page, results in significant improvements. Four resistors are used, all with nominally equal value  $R_o$ . The output voltage  $v_o$  is the difference of  $v_a$  and  $v_b$  and only a single supply  $V_s$  is needed.

Let's investigate the full bridge's ability to reject supply voltage variations. For our analysis, let's assume that the bridge is balanced, i.e.  $v_o = 0$  V. Now let's say the supply voltage is initially  $V_s = 4.1$  V, but then drops suddenly by 10%. Calculate the resulting change of  $v_o$ .

This property of the full bridge significantly reduces its offset voltage in practical situations where e.g. supply variations are common.

In practice of course the reference and nominal strain resistance will not be exactly equal. As a consequence,  $v_o$  has an offset, i.e. its value is not zero when no load is applied to the scale. Rather than tweaking the reference resistor values, we use a potentiometer for offset adjustment. Figure 3 shows the circuit diagram and symbol for a potentiometer. The sum  $R_T = R_a + R_b$  of the values of resistors  $R_a$  and  $R_b$  is constant, e.g.  $1 \text{ k}\Omega$ (potentiometers are available with many different values). A knob or screw terminal is used to adjust values of  $R_a$  and  $R_b$  such that

$$R_a = \beta R_T \tag{2}$$
$$R_b = (1 - \beta) R_T \tag{3}$$

with  $0 \le \beta \le 1$ , depending on the setting of the adjustment knob. Calculate the values of  $R_a$  and  $R_b$  for a potentiometer with  $R_T = 9.2 \text{ k}\Omega$  and its adjustment knob set such that  $\beta = 3.4/10$ :



If we add a potentiometer in parallel with  $R_{ref2}$  and  $R_{ref3}$  as shown in Figure 4 on page 5, we can adjust  $v_b$  and hence the offset of the bridge simply by turning the adjustment knob.

This circuit has a very frustrating problem: rather than adjusting the value of  $v_b$  by a few percent of its nominal value,  $V_s/2$ , turning the potentiometer adjustment knob changes  $v_b$  all the way from 0 V to  $V_s$ . As a consequence, only small adjustments change the output drastically, and nulling  $v_o$  precisely is infuriatingly difficult.

Figure 5 on page 5 adds resistor  $R_x$  to solve this problem. Derive an expression for  $v_b$  as a function of  $V_s$ ,  $\beta$ , and resistor values (show the derivation).

On the graph paper below or on a separate sheet accurately plot  $v_b/V_s$  as a function of  $\beta$  (2 points) for  $R_{ref2} = R_{ref3} = R_T = R_o = 6 \text{ k}\Omega$  and  $R_x = 2.4R_o$  and calculate the values for  $\beta = 0$ ,  $\beta = 0.5$ , and  $\beta = 1$ . The plot is best done with a program such as Excel, Matlab, or the free version, Octave.



From this analysis we conclude that the minimum ( $\beta = 1$ ) and maximum ( $\beta = 0$ ) values of  $v_b$  can be set by appropriately choosing  $R_x$ . We exploit this to set the overall adjustment range to a reasonable value, in our case about 10% of the supply, i.e.

$$0.45 V_s \le v_b \le 0.55 V_s \tag{4}$$

Calculate the value of  $R_x$  for  $R_{ref2} = R_{ref3} = R_T = R_o = 9 \text{ k}\Omega$ .

 $R_{\chi} =$ <sup>3 pts.</sup>
<sub>9</sub>

The value of the potentiometer  $R_T$  should be on the order of  $R_x$ , but its exact value (as that of  $R_x$ ) is not critical. Making  $R_T$  very small leads to extra (and unnecessary) power dissipation. What problem arises for  $R_T \gg R_x$ ? Hint: redo the plot  $v_b$  as a function of  $\beta$  for  $R_T \gg R_x$ .



**Figure 4** Full bridge circuit with potentiometer for offset adjustment.

**Figure 5** Full bridge circuit for offset adjustment with range control resistor  $R_x$ .

2 pts. 15

Build the circuit in the laboratory. Choose the reference resistors as close to the measured value of  $R_o$  as possible using available resistors. Recalculate the value of  $R_x$  using actual values in your circuit and round the result to available component values. Power on the circuit with  $V_s = 10$  V and set the potentiometer adjustment knob such that  $v_o = 0$  V when no weights are on the scale. Then perform the following measurements:



Demonstrate your circuit to the lab instructor.

#### Sensitivity to Temperature Variations

All sensor applications are faced with the following problem: We are interested in sensing a particular parameter, in this case strain, but the output of our circuit is invariably also a function of other influences, such as supply voltage or temperature. Good design minimize these undesired dependences

The full bridge circuit shown in Figure 2 on page 2 still has practical problems. Resistor values generally are a function of temperature. This effect is be modeled to first order by the following equation:

$$R(T) = R(T_o) \left[ 1 + TC_R \left( T - T_o \right) \right].$$

(5)

The temperature  $T_o$  is a convenient temperature (e.g.  $20^{\circ}$ C) at which the nominal value of the resistance,  $R(T_o)$ , is measured. The value  $TC_R$  is the temperature coefficient of the resistor. Depending on the material the resistor is made from, it varies from a few ppm up to a fraction of a percent per degree Kelvin. The higher values are exploited in thermistors, special resistors that are used for temperature sensing. Nonidealities such as temperature dependence depend on the point of view: For strain sensors a low temperature coefficient is desired while in a thermometer this same effect is used to advantage! Engineers are often confronted with such tradeoffs.

Let's analyze the effect of the temperature coefficient of resistors on the strain gage. To start, we again assume that the output  $v_o = 0$  V. For the circuit in Figure 2 on page 2, calculate the value of  $v_o$  if now the temperature increases by 1 K. Use  $TC_R = 389$  ppm/K.

In our setup, nothing ensures that the temperatures of  $R_{strain}$  and the reference resistors remain the same. They are in different locations and probably made from different materials and consequently have different temperature coefficients. The first problem is addressed by placing the reference resistors in close proximity to  $R_{strain}$ . The second problem is solved by using strain resistors also for the references, as shown in Figure 6.

To operate, this requires the values of  $R_{strain1}$  and  $R_{strain4}$  to change in opposite direction from those of  $R_{strain2}$  and  $R_{strain3}$ , as indicated by the arrows in the diagram. In our scale this is easily achieved by mounting the resistors on opposite sides of the metal band.

Let's calculate the sensitivity. Model the change of resistance with  $\Delta R$ , i.e.  $R_{strain1} = R_{strain4} = R_0 + \Delta R$  and  $R_{strain2} = R_{strain3} = R_0 - \Delta R$ . What is the value of  $\frac{v_0}{V_s}$  for  $R_0 = 4.8 \text{ k}\Omega$  and  $\Delta R = -2.1 \Omega$ ?



Figure 6 Balanced full bridge circuit with four strain resistors.

In addition to being a much less susceptible to temperature changes, this circuit also has improved sensitivity compared to either the half or full bridge with only one strain sensing resistor. The added cost of four separate strain resistor is usually well worth these benefits. Not doing so in this lab is acceptable since temperature changes over the course of a measurement can be expected to be small. In practical applications however such "shortcuts" often lead to big troubles or even angry customers. Do not ever let this happen to you!

# EE 42/100 Lab 2 Electronic Scale

## **Prelab Summary**

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