NAME 1: SID:

NAME 2: SID:

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 crashes. In fact, similar circuits to the one we build are used in all these applications, albeit using technologies that allow much smaller size.

For 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.

How can we do this with an electronic device? It 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 ΔL and ΔR 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 ΔR we can calculate ΔL, 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.

[ ] 1 pt. 0

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 ΔR for one, three, and six weights. Report your results in the table below:

R_o		1 pt. 1
ΔR, 1 weight		1 pt. 1
ΔR, 3 weights		1 pt. 1
ΔR, 6 weights		1 pt. 1

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 of 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 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.

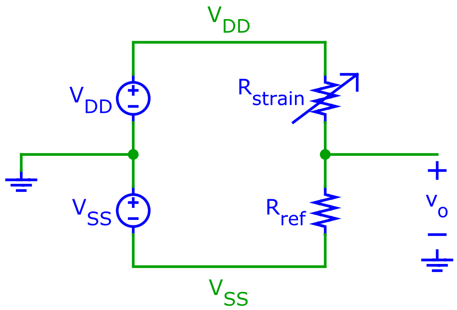


Figure 1 Strain gage in a half bridge circuit configuration.

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_o 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_o of the strain gage resistor and the supply voltages V_{dd} and V_{ss} are equal.

Under these conditions, and for $V_{dd} = V_{ss} = 4\,\mathrm{V}$, what is the value of V_o if R_{strain} increases by 1 % from its nominal value?

1 pt.
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. Set up the laboratory supply for $V_{dd} = V_{ss} = 5$ V. Then take the following measurements of v_o:

no weights — 1 pt. 2

-- Now adjust V_{ss} such that $v_o = 0\,\mathrm{V}$ --

no weights — 1 pt. 2
1 weight — 1 pt. 2
6 weights — 1 pt. 2

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.

The full bridge configuration, shown in Figure 2 on the next 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. $v_o = 0\,\mathrm{V}$. Now let's say the supply voltage is initially $V_s = 4.1\,\mathrm{V}$, but then drops suddenly by 10 %. Calculate the resulting change of v_o.

1 pt.
2

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

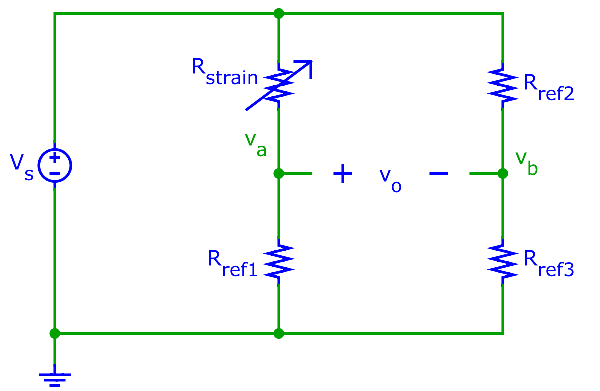


Figure 2 Full bridge configuration.

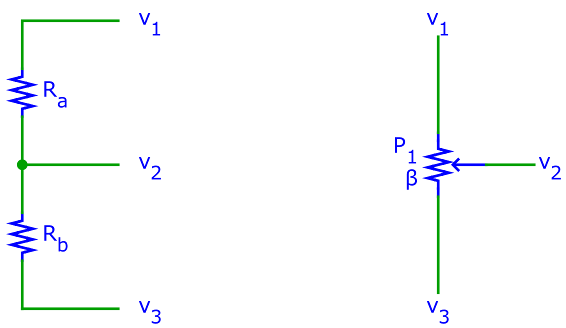


Figure 3 Potentiometer: Equivalent circuit diagram (left) and symbol (right).

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

$R_a =$ ☐ 1 pt. 3

$R_b =$ ☐ 1 pt. 4

$R_a + R_b =$ ☐ 1 pt. 5

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 the bridge simply by turning the adjustment knob.

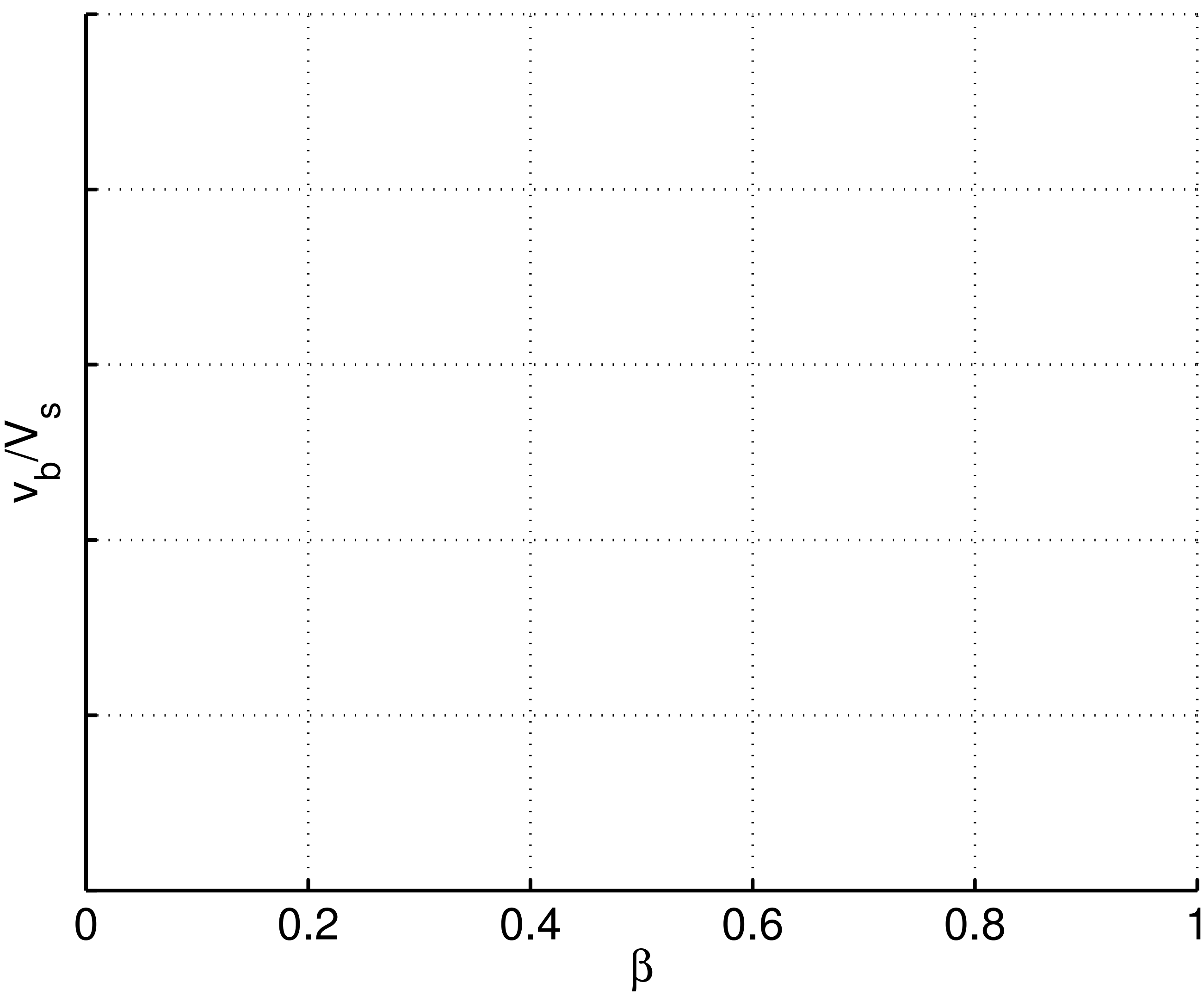
This circuit has a very frustrating problem: rather than adjusting the value of v_b by a few percent of its nominal value, $V_s/2$, turning the potentiometer adjustment knob changes v_b all the way from 0 V to V_s. As a consequence, only small adjustments change the output drastically, and nulling v_o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

Figure 5 on page 5 adds resistor R_x to solve this problem. An expression for v_b as a function of V_s, β, and resistor values can be derived using y-delta transformation:

$$\frac{v_b}{V_s} = \frac{(1-\beta)R_{ref} + \beta(1-\beta)R_T + R_x}{R_{ref} + 2\beta(1-\beta)R_T + 2R_x}$$

On the graph paper below or on a separate sheet accurately plot v_b/V_s as a function of β 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 $\beta = 1$. Plot at least 5 points. The plot is best done with a program such as Excel, Matlab, or the free version, Octave.

$\beta = 0$	$v_b/V_s =$		1 pt. 6
$\beta = 0.5$	$v_b/V_s =$		1 pt. 7
$\beta = 1$	$v_b/V_s =$		1 pt. 8



2 pt. 8

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.

$$0.45\,V_s \leq v_b \leq 0.55\,V_s \tag{4}$$

Calculate the value of R_x such that the above voltage range is available for $R_{ref2} = R_{ref3} = R_T = R_o = 9\ \text{k}\Omega$.

$R_x =$		3 pts. 9

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 β for $R_T \gg R_x$.

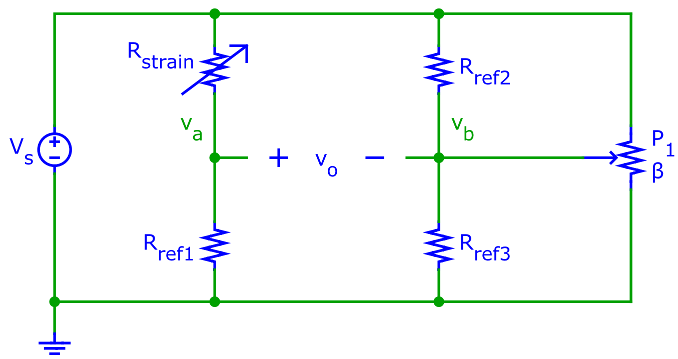


Figure 4 Full bridge circuit with potentiometer for offset adjustment.

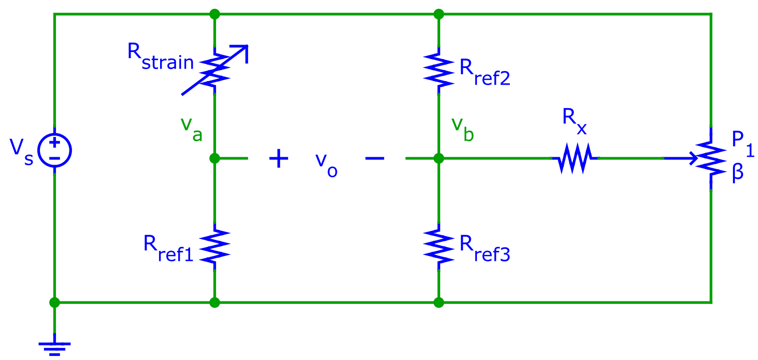


Figure 5 Full bridge circuit for offset adjustment with range control resistor R_x.

2 pts.
10

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 and set the potentiometer adjustment knob such that $v_o = 0\,\text{V}$ when no weights are on the scale. Then perform the following measurements:

v_o	no weights		1 pt. 10
v_o	1 weight		1 pt. 10
v_o	6 weights		1 pt. 10

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 minimizes these undesired dependences.

The full bridge circuit shown in Figure 2 on page 3 still has practical problems. Resistor values generally are a function of temperature. This effect is be modeled to first order by the following equation:

$$R(T) = R(T_o)\left[1 + TC_R\,(T - T_o)\right]. \tag{5}$$

The temperature T_o is a convenient temperature (e.g. 20 $_o$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 3, calculate the value of v_o if the temperature of the strain gage increases by 1 K. Use $TC_R = 389$ ppm/K.

1 pt.
10

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 ΔR, i.e. $R_{strain1} = R_{strain4} = R_o + \Delta R$ and $R_{strain2} = R_{strain3} = R_o - \Delta R$. What is the value of $\frac{v_o}{V_s}$ for $R_o = 4.8\,\mathrm{k}\Omega$ and $\Delta R =$ -2.1 Ω?

1 pt.
11

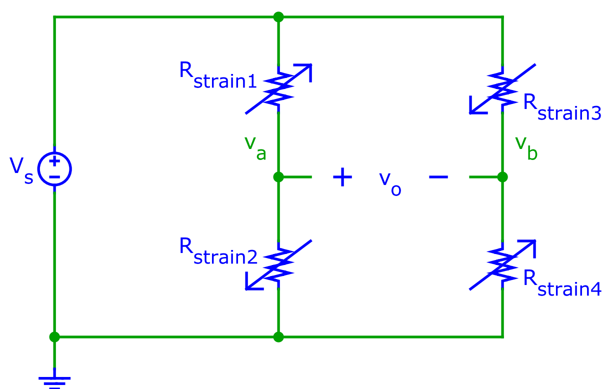


Figure 6 Balanced full bridge circuit with four strain resistors.

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 resistors 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!