ME220 Introduction to Sensors Homework #3, due 5:00 pm, **Wednesday** 5/7/08

1. Force Sensor + Circuit Calculations

A resistive contact force sensor has a response given by:

$$R = R_0\left(1 + \frac{F}{\beta}\right)$$

where R_0 = 1000 Ω, β = 200N, F is the applied force (in Newtons), and R is the resistance of the sensor.

This sensor is to be used for measuring forces ranging from 0 to 50N.

Please design a measuring circuit that will produce an output voltage that ranges from 0V to 4V as the applied force ranges from 0 to 50N. Please design this circuit so that the nonlinearity in the relationship between force and voltage is less than 1% of the full scale output.

You are allowed to use operational amplifiers, resistors, and circuit examples from the lectures, handouts, and reading from the book.

Solution (20 points): For this problem, I'm hoping to see a wheatstone bridge circuit with a set of load resistors that are bigger than the sense resistor by about 20X – this is necessary to eliminate the nonlinearity. After that, a differential amplifier with a lot of gain is necessary. There should be calculations to show that their design is correct.

2. Smart Home Thermostat

A. Amount of Expansion and Hysteresis

Solution: (10 points)

Copper and Iron have thermal Expansion coefficients of 16.6 ppm/degree and 12.0 ppm/degree, respectively (from the book). For a 5 degree temperature change and a 1 meter strip, the change in length is 80 microns and 60 microns, respectively.

The deflection can be calculated using the approximations given in the book

$$r = \frac{2j}{3(\alpha_x - \alpha_y)(\Delta T)} = \frac{2(2x10^{-3}m)}{3(4.6x10^{-6})(10)} = 28m$$

$$Deflection = r[1 - Cos(180L/\pi r)] = 28[1 - Cos(180/\pi 28)] = 17.8mm$$

B. RTD

It is possible to replace this with a Resistance Temperature Detectors (RTD). Calculate and plot as a function of temperature the resistance for room temperatures from 15°C to 30°C for Copper, Nickel, and Platinum.

Solution (5 points): The temperature coefficients of resistance for Cu, Ni and Pt are : 3.9, 6.9, 3.7 (all in units of 10-3/degree). All have approximate resistance(T) of R=Ro(1+alpha(delta T)).

Chose a material for your design and explain why it was selected. Using this material design a circuit to that gives a 0-5V output over the aforementioned range.

Solution (5 points): Here, any would do, but Pt is usually the best choice because it is less reactive and therefore more stable. It is also the most expensive. If students talk about selecting Ni because it is cheaper, that would be OK. For the circuit, any approach that works is acceptable. One likely solution is a wheatstone bridge with a difference or instrumentation amplifier.

C. Thermocouple

Solution (10 points): for this, the students need to look online or elsewhere for information. There are lots of places to get approximate thermocouple sensitivities for the J and K thermocouples. In the book, there is a table with J sensitivity of 51.7 µV/degree, and K sensitivity of 40.6 µV/degree. To get linearity, they would need to find a plot of the thermocouple response. They are reasonably good, and estimates of about 10% of the full-scale would be acceptable.

.

3. You are asked to design a garden hose with an integral flow sensor. Suppose the normal inside diameter of a garden hose was 2 cm, and a special restrictor has been inserted with a diameter of 1 cm. When water flows through this element, there is a pressure difference between the narrow and wide sections of the hose. For normal garden hose applications, there is interest in measuring flow velocities from 1 cm/sec to 1 m/sec through the end of the hose.

A. Calculate the pressure differences for the cases of 1cm/s and 1m/sec.

Solution (10 points): Use Bernoulli's Equation to find that

$$P_1 + \frac{1}{2}\rho V_1^{\,2} = P_2 + \frac{1}{2}\rho V_2^{\,2}$$

$$V_2 = 4V_1$$

$$P_1 - P_2 = 7.5\rho V_1^{\,2}$$

$$\rho = 1000\left\{\frac{kg}{m^3}\right\}$$

at 1 cm/s, we find a pressure difference of 7.5*1000*0.01^2= 0.75 Pa, and at 1 m/s, the pressure difference is 7500 Pa

Note: These numbers are pretty small, so a real product based on this concept would probably use a tighter flow restriction to generate a bigger pressure difference.

B. Select the 4 parameters that you think are the most important to specify for this pressure sensor to guarantee that it will function in this application. State the numerical requirements for these parameters.

Solution (10 points): Given the numbers, the resolution is going to be important, it is necessary to be able to detect pressure changes in the 1 Pa range, and this is hard for many of the products we've seen. Other parameters to be concerned about are temperature coefficients of offset and sensitivity (the water in the hose can be hot or cold), cost (this is a garden hose and the sensor can't be more than a few $$), robustness (it has to survive being dropped, left outdoors, and maybe even frozen).

4. A hot-wire anemometer consists of a miniature thermistor that is mounted sticking up from a surface as shown in the figure below. This thermistor has resistance of 1000Ω at 20°C (ambient temperature) and a positive Temperature Coefficient of Resistance (TCR) of 0.2%/°C. The thermistor is mounted in an electrical circuit as shown in the figure below with a load resistor of 9 K and a Vin of 10V. The thermal conduction from the thermistor is a function of the airflow velocity according to

$$G = \frac{\alpha(\beta + v)}{\beta}$$

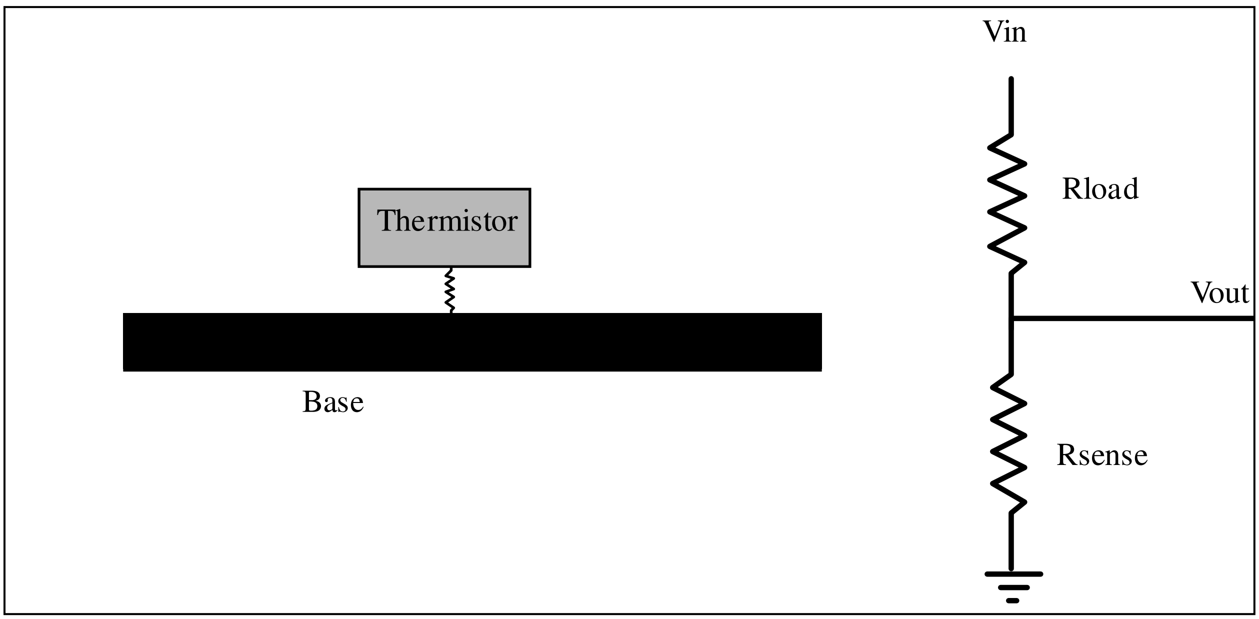
where α = 1 mW/C, β = 1 m/s, and v is velocity {m/s}.

A. If the airflow velocity is 0 m/s, what is the temperature of the thermistor? What is the resistance of the thermistor?

B. What is the output voltage of the circuit in this case? How much does this voltage change if the airflow is increased to 1m/s?

C. Write an algebraic expression for the sensitivity of this flow sensor. (in this expression, use symbols for all the quantities, rather than a numerical expression. This expression should include Vin, Rload, etc as variables)

D. In the expression above, the bias voltage Vin should be present, suggesting that the sensitivity of this system can be improved by increasing the bias voltage. Please comment on how large this voltage can be increased before bad things start to happen.



a) (10 points) If the airflow velocity is 0 m/s, what is the temperature of the thermistor? What is the resistance of the thermistor?

G=1 mW/C in this case, so the temperature is room temperature + some heating offset from the bias current. The heating power associated with the bias current is 1 mW, so there is a temperature rise of 1 degree C to 21 C.

G

Of course, this heating effect leads to a change in the resistance, which may lead to a change in the current. However, since the resistance change for a 1 degree temperature change is 2 Ohms on a 1000 Ohm resistor, the error associated with ignoring this effect is less than 0.2%. That is fine for this class.

b) (5 points) What is the output voltage of the circuit in this case? How much does this voltage change if the airflow is increased to 1m/s?

From the voltage divider expression, when the velocity = 0,

$$Vout = \frac{VinR_s}{R_L + R_s} = \frac{Vin(1002\Omega)}{9000\Omega + 1002\Omega} = 1.0018V$$

However, when the velocity = 1 m/s, G=2 mW/C, and the temperature rise is reduced to 0.5C, and so the resistance change is reduced from ΔR=2Ohms to ΔR=1Ohm.

$$Vout = \frac{VinR_s}{R_L + R_s} = \frac{Vin(1001\Omega)}{9000\Omega + 1001\Omega} = 1.0009V$$

c) (10 points) Write an algebraic expression for the sensitivity of this flow sensor. (in this expression, use symbols for all the quantities, rather than a numerical expression. This expression should include Vin, Rload, etc as variables)

Again, we use the chain rule :

$$\frac{dV}{dFlow} = \frac{dV}{dR}\frac{dR}{dT}\frac{dT}{dG}\frac{dG}{dFlow}$$

$$\frac{dV}{dFlow} = \frac{-VinR_L}{(R_S + R_L)^2}\alpha R_S \frac{-P}{G^2}\frac{(1mW/C)}{1m/s}$$

$$\frac{dV}{dFlow} = \frac{-VinR_L}{(R_S + R_L)^2}\alpha R_S \frac{(-VinR_L)^2}{(R_S + R_L)^2 R_S}\frac{1}{[\frac{(1mW/C)(1m/s + Velocity)}{1m/s}]^2}\frac{(1mW/C)}{1m/s}$$

d) (5 points) In the expression above, the bias voltage Vin should be present, suggesting that the sensitivity of this system can be improved by increasing the bias voltage. Please comment on how large this voltage can be increased before bad things start to happen.

We see that the bias voltage appears to the 3rd power in this expression – so the sensitivity is extremely dependent on this choice, and that there is a good opportunity to adjust the performance by increasing the bias. However, increases in bias cause increases in heating of the thermistor, and eventual variations in the linearity of this system. It is probably OK to increase the power by a factor of 5x-10x, thereby increasing the ΔT to 10 degrees C. Outside of that, the the approximations in the expression above will begin to break down, and things will become very complicated.

5. A round steel bar with modulus of elasticity 200 GPa and diameter 1 cm is loaded in tension with an axial load of 50 kN. A strain gauge with a gage factor of 2.5 and resistance of 120 Ω (in the unloaded state) is mounted on the bar in the axial direction

   A. What is the change in resistance of the gauge from the unloaded state to the loaded state?
   B. If the strain gauge is placed in one leg of a Wheatstone bridge, with 120 Ω resistors in the other 3 legs, what is the output voltage of the bridge in the strained state?
   C. What is the stress in the bar?
   D. If we assume that the maximum strain of a Steel beam is 1%, and we were interested in measuring strains all the way to this level, what would the corresponding axial load be?
   E. What changes to the design of the bridge are necessary to allow 0.2% accuracy (as compared to a linear estimate for sensor output) for signals all the way to the 1% strain level?

A round steel bar with modulus of elasticity 200 GPa and diameter 1 cm is loaded in tension with an axial load of 50 kN. A strain gauge with a gage factor of 2.5 and resistance of 120 Ω (in the unloaded state) is mounted on the bar in the axial direction.

a) (5 points) What is the change in resistance of the gauge from the unloaded state to the loaded state?

The stress from the load is $\varepsilon = \frac{F}{EA} = \frac{5e4}{(2e11)(\pi(0.005)^2)} = 3.2e-3$. Since the gage factor is 2.5, and the resistance is 120 Ohms, the change in resistance is about 1 ohm.

b) (5 points) If the strain gauge is placed in one leg of a Wheatstone bridge, with 120 Ohm resistors in the other 3 legs, what is the output voltage of the bridge in the strained state.

For a bridge, $V_{out} = V_{in}\frac{\Delta R}{4Ro} = (5V)\frac{1\Omega}{4(120\Omega)} = 10mV$

c) (5 points) What is the stress in the bar?

From above, the strain was 3.2e-3, so the stress is 640 MPa

d) (5 points) If we assume that the maximum strain of a Steel beam is 1%, and we were interested in measuring strains all the way to this level, what would the corresponding axial load be?

Since a load of 50 kN caused a strain of 3.2e-3, a load of 156 kN would cause a strain of 0.01.

e) (5 points) What changes to the design of the bridge are necessary to allow 0.2% accuracy for signals all the way to the 1% strain level?

Increases in the load resistors in the bridge would be necessary to increase the linearity. To get to 0.2%, the resistors would need to be increased to the point that