7 **1.** A straight calibration line was fit to temperature sensor data. The slope of the calibration line was found to be 0.05 V/°C. The standard deviation of the sensor output was not affected by the input, and equalled 0.065 V. The input and the mean values of the calibrated sensor output for a series of tests are listed in the table below. Using the given information, determine values for the following performance specifications:
a) repeatability, b) hysteresis, c) deadband, d) linearity, and e) accuracy.

$A = 0.05\,V/°C$

$\sigma_y = 0.065V = \frac{0.065V}{0.05V/°C} = 1.3°C$

a) Repeatability $= \pm 3\sigma_y = \pm 3(1.3°C) = \pm 3.9°C$

b) Hysteresis: Maximum difference output between increasing & decreasing Input

$= |146 - 155| = 9°C$

c) deadband $= 3°C$

d) linearity $= \pm(\max(\text{abs}(Y_{actual} - Y_{sensor})))$

$= \pm 5°C$

e) accuracy $= \pm(\max(\text{abs}(Y_{actual} - Y_{sensor})) + 3\sigma_y)$

$= \pm(\max(\text{abs}(155°C - 150°C)) + 3(1.3°C))$

$= \pm 8.9°C$

Test number	Temperature Input (°C)		Mean Calibrated Output (°C)	Difference
1	0		0	0
2	3		0	3
3	7		6	1
4	10		9	1
5	20		18	2
6	50		47	3
7	100		97	3
8	150		146	4
9	200		196	4
10	150	↑	155	5 ← max
11	100	8	105	5 ←
12	50	7	54	4
13	20	4	22	2
14	10	0.5	9.5	0.5
15	7	1	7	0
16	3		0	3
17	0		0	0

Hysteresis diff

0
0
1
0.5
4
7
8
9

2. A force sensor has a sensitivity of 15 mV/N, a range of 100 N to 600 N and an accuracy of ±0.25% of full scale.

a) Assuming other sources of error in the measurement system are insignificant, if the input is 300 N, what is the worst case measurement error?

b) The sensor's output impedance is 1 kΩ. It is connected to an ADC with a 50 kΩ input impedance. Repeat part (a) including the effect of these impedances.

c) The ADC has a 10-bit resolution with 8.9 effective bits. Its input range is ±10 V. Repeat part (b) including this source of error.

$A = 15\ mV/N$, range $= [100, 600]N$, accuracy $= 0.25\%\ FS$

a) $\Delta F = \text{accuracy} = 0.0025 \cdot [600 - 100] = \pm 1.25 N$

b) $R_S = 1 k\Omega$, $R_{in,ADC} = 50 k\Omega$

$V_{in} = V_s \left(\frac{R_{in}}{R_{in} + R_s}\right)$ $\quad V_s = 300 N \cdot 15 mV/N = 4500 mV$

$= 4500 \left(\frac{50}{51}\right) = 4411.76 mV$

$\Delta V_s = 4500 - 4411.76 = 88.24 mV$

$\Delta F_{out} = |F_{in}| \left(\frac{a}{F_{in}} + \frac{\Delta V_s}{V_s}\right)$

$= 300 \left(\frac{1.25}{300} + \frac{88.24}{4500}\right) = \pm 7.13 N$

c) $a_{ADC} = \pm \frac{V_{FS}}{2^{ENOB}} = \frac{10 - (-10)}{2^{8.9}} = \frac{20}{2^{8.9}} = 0.0419 V$

$\Delta F_{out} = |F_{in}| \left(\frac{a}{F_{in}} + \frac{\Delta V_s}{V_s} + \frac{a_{ADC}}{V_s}\right)$

$= |300| \left(\frac{1.25}{300} + \frac{88.24}{4500} + \frac{0.0419}{4.5V}\right)$

$= \pm 9.926 N$

6 **3.** A measurement system consisting of an accelerometer and signal conditioner has a range of ±200 m/s², an accuracy of ±1.2 m/s² and a bandwidth of 6000 Hz.

a) If the current output is 60 m/s² and the true acceleration suddenly changes to a new value, how long should the mechatronic system wait before taking its next reading?

b) If the measured acceleration is a 700 Hz sinusoid with a 90 m/s² amplitude, what is the worst case error in the measured amplitude?

a) $\tau_s = \frac{1}{2\pi f_b} = \frac{1}{2\pi(6000 Hz)} = 2.653 \times 10^{-5}$ s.

$|a_y| = 1.2\ m/s^2$.

$y_{max} - y_{out}(0) = 200\ m/s^2 - 60\ m/s^2 = 140\ m/s^2$

$y_{out}(0) - y_{min} = 60\ m/s^2 - (-200\ m/s^2) = 260\ m/s^2$.

$$t \geq -\tau_s \ln\left(\frac{0.1\,|a_y|}{\max(y_{max} - y_{out}(0),\ y_{out}(0) - y_{min})}\right)$$

$$\geq -2.653 \times 10^{-5} \ln\left(\frac{0.1\,(1.2\ m/s^2)}{260\ m/s^2}\right)$$

$$\geq 2.037 \times 10^{-4}\ s.$$

∴ The wait time should be $\geq 2.037 \times 10^{-4}$ s.

b) $$\Delta A\,(700\ Hz) = |a_y| + \left(\sqrt{1 + \omega^2 \tau_s^2} - 1\right)(90\ m/s^2).$$

$$= 1.2\ m/s^2 + \left(\sqrt{1 + (2\pi(700))^2 (2.653 \times 10^{-5} s)} - 1\right)(90\ m/s^2)$$

$$= \boxed{\pm 1.81\ m/s^2}$$

4. An encoder is attached directly to the shaft of a motor. The maximum torque produced by the motor is 6 Nm. All other torques are negligible. The moment of inertia of the motor plus load varies from 4 x 10^{-3} kgm^2 to 2 x 10^{-2} kgm^2. The encoder produces 500 pulses per revolution. The controller estimates velocity by backward differencing position measurements taken every 0.002 s. <u>The controller uses quadrature counting</u>. Calculate the worst case velocity error in <u>rpm.</u>

$$\alpha = \frac{\tau}{J} \qquad \alpha_{max} = \frac{6\ \text{Nm}}{4 \times 10^{-3}\ \text{kgm}^2} = 1500\ \text{rad/s}^2.$$

$$\text{encoder's position resolution} = \frac{2\pi\ \text{rad}}{500 \times 4} = 3.142 \times 10^{-3}\ \text{rad}$$

$$\Delta V_{est} = \frac{T}{2} \max(|\alpha_{mvel}|) + \frac{\text{encoder's position resolution}}{T}$$

$$= \frac{0.002\ \text{s}}{2}(1500\ \text{rad/s}^2) + \frac{3.142 \times 10^{-3}\ \text{rad}}{0.002\ \text{s}}$$

$$= 3.07\ \text{rad/s}.$$

Rad/s to RPM :

$$3.07\ \text{rad/s} \times \frac{1\ \text{rev}}{2\pi\ \text{rad}} \times \frac{60\ \text{s}}{1\ \text{min}} = \boxed{29.3\ \text{RPM}}$$

9 **5. <u>Based on the material covered in this course</u>**, answer the following questions in the spaces provided:

a) Which two methods can be used for sensing the level of a corrosive clear liquid in a tank?

Answer 1: Measure weight of tank + liquid using force sensor under tank.

Answer 2: Measure distance to top of liquid using ultrasonic sensor

b) Define the sensor specification termed *stability*:

Answer: The ability of a sensor's output to remain constant when its input is constant

c) What advantage do strain gauge-based displacement sensors have over potentiometers?

Answer: They don't wear

d) If the seismic mass used with an accelerometer is decreased then its bandwidth specification will improve and its sensitivity specification will worsen.

e) Other than cost, give one advantage and one disadvantage of an optical encoder compared with a potentiometer.

Advantage: Digital output → less sensitive to noise

Disadvantage: Limited resolution

f) The four common types of temperature sensors are: thermocouples, thermistors, bimetallic strip and resistance temperature detector (RTD)

g) A common design for a force sensor sensor is shaped like an S.