7 **1.** A straight calibration line was fit to temperature sensor data. <u>The slope of the calibration line was found to be 0.04 V/°C. The standard deviation of the sensor output was not affected by the input, and equalled 0.024 V.</u> 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.

Given: $A = 0.04\ V/°C$ & $\sigma_Y = \pm 0.024\ V$

Test number	Temperature Input (°C)	Mean Calibrated Output (°C)	
1	0	0	0
2	2	0	2
3	4	0	4
4	6	0	6
5	8	0	8
6	10	9	1
7	25	23.5	1.5
8	50	48.5	1.5
9	75	73	2
10	100	98	2
11	75	78	-3
12	50	52.5	-2.5
13	25	27	-2
14	10	10.5	-0.5
15	0	0	0

a) repeatability $= \pm 3\sigma_Y$

$$= \pm 3 \left(\frac{0.024\ V}{0.04\ V/°C} \right)$$

$$\boxed{= \pm 1.8\ °C}$$

b) Hysteresis = Max difference at same input

$$= 78 - 73$$

$$= \boxed{5\ °C}$$

c) dead band $= \boxed{8\ °C}$

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

$$= \pm(|8 - 0|) = \boxed{\pm 8\ °C}$$

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

$$= \pm(8 + 1.8)\ °C = \boxed{\pm 9.8\ °C}$$

Note:
These answers to (d) and (e) assume the sensor's range is specified as 0 to 100 °C.

If the range is assumed to be 10 to 100 °C, then the answers are:
d) ± 3 °C and e) $\pm$ 4.8 °C

8 **2.** A force sensor has a sensitivity of 20 mV/N, a range of 100 N to 500 N and an accuracy of ±0.3% 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 9.1 effective bits. Its input range is ±10 V. Repeat part (b) including this source of error.

$F_{in} = 300\ N$, $A = \text{sensitivity} = 20\ mV/N$, range 100 N to 500 N

a) Full scale $= 500 - 100 = 400\ N$

$$\alpha_{sen} = \pm\left[\frac{0.3}{100} \times 400\right] = \boxed{\pm 1.2\ N}$$

b) $V_{in} = V_s\left(\frac{R_{in}}{R_{in}+R_s}\right)$, $V_s = F_{in} \times A = 300\ \cancel{N} \times 20\frac{mV}{\cancel{N}} = 6000\ mV$

$$V_{in} = 6000\ mV\left(\frac{50\ k\cancel{\Omega}}{(50+1)\ k\cancel{\Omega}}\right)$$

$= 58812.35\ mV$

$\Delta V_s = V_s - V_{in} = (6000 - 5882.35)\ mV = 117.65\ mV$

$$\Delta F_{out} = F_{in}\left[\left|\frac{\alpha_{sen}}{F_{in}}\right| + \left|\frac{\Delta V_s}{V_s}\right|\right] = 300\left[\left|\frac{\pm 1.2\ \cancel{N}}{300\ \cancel{N}}\right| + \left|\frac{117.65\ mV}{6000\ mV}\right|\right]$$

$$= \boxed{\pm 7.08\ N}$$

c) $ENOB = 9.1$, full scale $= 20\ V$

$$\alpha_{ADC} = \pm\frac{20V}{2^{9.1}} = \pm 0.0364\ V$$

$$\Delta F_{out} = F_{in}\left[\left|\frac{\alpha_{sen}}{F_{in}}\right| + \left|\frac{\Delta V_s}{V_s}\right| + \left|\frac{\alpha_{ADC}}{V_s}\right|\right] = 300\left[\left|\frac{\pm 1.2\ \cancel{N}}{300\ \cancel{N}}\right| + \left|\frac{\pm 117.65\ mV}{6000\ mV}\right| + \left|\frac{\pm 0.0364\ \cancel{V}}{6\ \cancel{V}}\right|\right]$$

$$= \boxed{\pm 8.9\ N}$$

6 **3.** A measurement system consisting of an accelerometer and signal conditioner has a range of ±100 m/s^2, an accuracy of ±0.5 m/s^2 and a bandwidth of 3000 Hz.

a) If the current output is 40 m/s^2 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 900 Hz sinusoid with a 70 m/s^2 amplitude, what is the worst case error in the measured amplitude?

a) $$\tau_s = \frac{1}{2\pi f_b} = \frac{1}{2\pi(3000\text{ Hz})} = 5.31 \times 10^{-5}\text{ s}$$

$$\max(Y_{max} - Y_{out}(0),\ Y_{out}(0) - Y_{min}) = \max(100-40,\ 40-(-100))$$
$$= \max(60,\ 140)$$
$$= 140\ m/s^2$$

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

$$t \geq -5.31\times10^{-5}\text{ s} \cdot \ln\left[\frac{0.1\,(0.5\ m/s^2)}{140\ m/s^2}\right]$$

$$t \geq \boxed{4.211 \times 10^{-4}\text{ s}}$$

∴ The mechatronic system should wait 4.211×10^{-4} s before taking its next reading

b) $A_{out}(\omega) = 70\ m/s^2$, $\omega = 2\pi f = 2\pi(900\text{ Hz}) = 5654.87$ rad/s

$$\Delta A_{out}(\omega) = |a_y| + \left(\sqrt{1+\omega^2\tau_s^2} - 1\right) A_{out}(\omega)$$

$$\Delta A_{out}(5654.87) = 0.5\ m/s^2 + \left[\sqrt{1+(5654.87\text{ rad/s})^2(5.31\times10^{-5}\text{ s})^2} - 1\right] 70\ m/s^2$$

$$= 0.5\ m/s^2 + 3.08\ m/s^2$$

$$= \boxed{\pm 3.58\ m/s^2}$$

4. A force control system will estimate the derivative by computing the backward difference of the measured force. The force measurement has a repeatability of ±0.75 N. The maximum second derivative equals 35 N/s^2.

a) What is the standard deviation of the force measurement?

b) The worst case error of the estimated derivative must be less than or equal to 20 N/s. Determine the smallest and largest values of sampling period that can be used.

<u>Hints:</u> 1) The answer uses the Δv_{est} equation.

2) The answer does not involve the optimal sampling period.

(a) Repeatability $= \pm 3\sigma_y \longrightarrow \sigma_y = \dfrac{0.75\text{ N}}{3} = 0.25\text{ N}$

(b) $\Delta V_{est} \geq \dfrac{T}{2}\max|a_{true}| + \dfrac{6\sigma_p}{T}$

$$20\text{ N/s} \geq \frac{T}{2}(35\text{ N/s}^2) + \frac{6(0.25\text{ N})}{T}$$

$$20\text{ N/s} \geq 17.5\,T + \frac{1.5}{T}$$

$$20\,T \geq 17.5\,T^2 + 1.5$$

$$0 \geq 17.5\,T^2 - 20\,T + 1.5$$

$$T = 1.06\text{ s}, \quad T = 0.08\text{ s}$$

Sampling period: $0.08\text{ s} \leq T \leq 1.06\text{ s}$

Please note: 1) The answers to this question can be found in Chapters 1 and 2.

2) None of these questions will appear again on the final exam.

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

a) For safety-critical applications, ___________________ control is always preferable to ___________________ control.

b) Give one non-financial reason why computer simulations are very important in mechatronics engineering.
Reason: ____

____

c) What did the artificial hand described in Chapter 1 use to extend its battery life?

Answer: ____

d) Other than cost, list one advantage and one disadvantage of a thermistor:

Advantage: ____

Disadvantage: ____

e) List two types of displacement sensors:
Answer 1: ____

Answer 2: ____

f) A ________________________________ sensor uses the time-of-flight method.

g) Other than being more compact, what advantage does a retro-reflective proximity sensor have over a thru-beam proximity sensor?
Answer: ____