7 **1.** A straight calibration line was fit to temperature sensor data. 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 0.06 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) linearity, c) accuracy, d) deadband, and e) hysteresis.

Test number	Temp. Input (°C)	Mean Calibrated Output (°C)	Error mag. (°C)
1	0	0	0
2	5	0	5
3	10.5	9	1.5
4	15	13.5	1.5
5	30	27	3
6	75	70.5	4.5
7	150	145	5
8	225	219	6
9	300	294	6
10	225	232.5	7.5
11	150	157	7
12	75	81	6
13	30	33	3
14	15	16	2
15	10.5	9.5	1
16	5	0	5
17	0	0	0

$A = 0.04\,V/°C$

$\sigma_{sensor} = 0.06V \rightarrow \sigma_{temp} = \frac{0.06V}{A} = 1.5°C$

a) repeatability $= \pm 3\sigma_{temp} = \pm 3(1.5°C) = \boxed{\pm 4.5°C}$

b) linearity $= \pm(\max|Y_{true} - Y_{sensor}|)$

$= \pm$ max error $\rightarrow$ test #10

$= \boxed{\pm 7.5°C}$

c) accuracy $= \pm(\max|Y_{true} - Y_{sensor}| + 3\sigma_{temp})$

$= \pm(7.5 + 4.5) = \boxed{\pm 12°C}$

d) deadband $= \boxed{5°C}$ $\rightarrow$ last input where output = 0

e) hysteresis $\rightarrow$ max difference in output for the same input

↳ happens @ 225° C input

$= 232.5°C - 219°C = \boxed{13.5°C}$

8 **2.** A force sensor has a sensitivity of 12 mV/N, a range of 50 N to 750 N and an accuracy of ±0.15% of full scale.

a) Assuming other sources of error in the measurement system are insignificant, if the input is 250 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 60 kΩ input impedance. Repeat part (a) including the effect of these impedances.

c) The ADC has a 12-bit resolution with 9.7 effective bits. Its input range is ±10 V. Repeat part (b) including this source of error.

a). $accuracy = \pm 0.15\% \times (750-50) = \pm 1.05\,N.$

$$\Delta F = F_{in}\left(\left|\frac{a_{sensor}}{F_{in}}\right|\right) = 250\,N \times \frac{1.05}{250N}$$

$$= 1.05N \leftarrow \text{worst case error.}$$

b). $V_s = 250N \times 12mV/N = 3000\,mV.$

$$V_{in} = \frac{R_{in}}{R_s+R_{in}} \times V_s = \frac{60}{1+60} \times 3000 = 2950.82\,mV$$

$$\therefore \Delta V_s = V_s - V_{in} = 3000 - 2950.82 = 49.18\,mV.$$

$$\therefore \Delta F = F_{in}\left(\left|\frac{a_{sensor}}{F_{in}}\right| + \left|\frac{\Delta V_s}{V_s}\right|\right)$$

$$= 250 \times \left(\left|\frac{1.05}{250}\right| + \left|\frac{49.18}{3000}\right|\right)$$

$$= 5.15N.$$

c). $$a_{ADC} = \frac{V_{FS}}{2^{ENOB}} = \frac{(10-(-10))V}{2^{9.7}} = \frac{20V}{2^{9.7}} = \pm 0.024\,V.$$

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

$$= 250 \times \left(\frac{1.05}{250} + \frac{49.18}{3000} + \frac{0.024}{3}\right) = 7.15\,N.$$

6 **3.** A measurement system consisting of an accelerometer and signal conditioner has a range of ±100 m/s², an accuracy of ±2.5 m/s² and a bandwidth of 10 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 400 Hz sinusoid with a 80 m/s² amplitude, what is the worst case error in the measured amplitude?

$a_y = \pm 2.5\,m/s^2$ $\quad T_s = \frac{1}{\omega_b} = \frac{1}{2\pi \times 10} = \frac{1}{20\pi}$

a). $t \geq -T_s \ln\left(\frac{0.1\,|a_y|}{\max(Y_{max} - Y_{out}(0),\ Y_{out}(0) - Y_{min})}\right)$

$\geq -\frac{1}{20\pi} \ln\left(\frac{0.1 \times 2.5}{\max(100-60,\ 60-(-100))}\right)$

$\geq -\frac{1}{20\pi} \ln\left(\frac{0.25}{160}\right)$

$\geq 0.103\ s.$

b). $f = 400\,Hz \quad \omega = 2\pi f = 2\pi \times 400 = 800\pi$

$A_{out} = 80\,m/s^2$

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

$= 2.5 + \left(\sqrt{1 + (800\pi)^2 \times \left(\frac{1}{20\pi}\right)^2} - 1\right) \times 80$

$= 3123.5\ m/s^2$

Please Note: This number is clearly wrong. The problem was caused by a mistake in equation 2.34 that has since been corrected in chapter 2, problem set 1 and the equation list for test 1.

5 **4.** An encoder is attached directly to the shaft of a motor. The maximum torque produced by the motor is 10 Nm. All other torques are negligible. The moment of inertia of the motor plus load varies from 5 x 10^{-3} kgm^2 to 4 x 10^{-2} kgm^2. The encoder produces 1000 pulses per revolution. The controller estimates velocity by backward differencing position measurements taken every 0.005 s. The controller uses quadrature counting. Calculate the worst case velocity error in **rpm**.

$$\alpha = \frac{T}{J} = \frac{10\,Nm}{5\times10^{-3}kgm^2} = 2000\ rad/s^2.$$

$$\text{encoder's position} = \frac{2\pi}{1000\times4} = 0.00157\ rad$$

$$T = 0.005s$$

$$\Delta V_{est} = \frac{T}{2}\max|a_{true}| + \frac{\text{encoder's position resolution}}{T}$$

$$= \frac{0.005}{2}\times 2000 + \frac{0.00157}{0.005}$$

$$= 5.314\ rad/s$$

$$\frac{5.314}{2\pi}\times 60 = 50.74\ rpm.$$

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

a) What is the main difference between the outputs of a typical process control system and a typical sequential control system?

Answer: sequential control system gives digital binary outputs while process control system produce analog outputs.

b) How did the artificial hand for a small child covered in Chapter 1 save electrical power so its batteries would last longer?

Answer: The hand was always in a gripping state via a spring. Power was only used to open the hand momentarily.

c) Define the sensor specification *resolution*.

Answer: the smallest change in quantity being measured that is detectable by the sensor

d) Why aren't acceleration sensors commonly used with integration to measure velocity?

Answer: Integrating the acceleration to produce outputs has very notable drawbacks such as the introduction of bias & a constant drift in the velocity produced.

e) Give one advantage and one disadvantage of a thermistor.

Advantage: The sensor can be very small.

Disadvantage: nonlinear output, special calibrated system required.

f) What advantage and disadvantage does a retro-reflective proximity sensor have when compared with a thru-beam proximity sensor?

Advantage: The transmitter & reciever can be on the same device which removes the need for alignment calibration.

Disadvantage: Very much depends on the optical properties of the measured object.

g) Describe a method for making a displacement sensor employing strain gauges less temperature sensitive?

Answer: To reduce temperature dependence, pair of sensors can be mounted on either face of the mechanical element, on straining, one face will be in tension & the other will be in compression. This results in a pair of voltages with differing signs that can be fed into a differential input

$$V_{output} = (V_{strain} + V_{temp}) - (-V_{strain} + V_{temp}) = \underline{V_{strain}}$$

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