

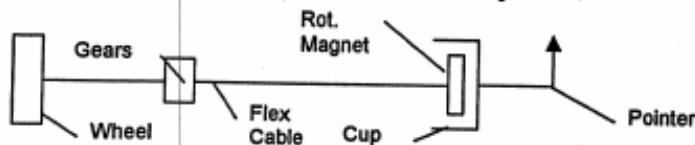
## Assignment # 1

**Problem #1:** Identify the sensing elements, signal-modification element, and indicator or recorder element in the following measurement devices.

- (a) A mechanical automobile speedometer
- (b) An automobile fuel gage
- (c) A human body thermometer with a liquid crystal display

### Solution

**2.1 (a)** The mechanical speedometer measures vehicle speed by measuring the angular velocity of the wheels. The angular velocity of the wheels (through some gears) causes a flexible cable to rotate. This cable causes a magnet to rotate inside a metal cup creating a circumferential drag on the cup (a torque). The drag is sensed by allowing the cup to rotate less than a complete turn against the resistance of a torsional spring. The cup is connected to a pointer which can be compared to a stationary scale.



The sensing element is the magnet rotating inside the metal cup creating drag. The signal modification system is the system that allows the cup to rotate against a torsional spring. The indicator is the comparison of the pointer to a stationary scale.

**(b)** The fuel level inside a fuel tank is measured with a mechanical float which follows the surface of the fuel (see Ch. 10). The position of the float is sensed with a connected arm which rotates a rotary variable resistor (angular potentiometer, see Ch. 8). The resistance of the variable resistor is sensed by passing applying a voltage to the resistor and measuring the current with an electromechanical gage. The sensing element is the float. The signal modification system consists of the angular potentiometer and the indicator is the electromechanical gage.

**(c)** Most of these devices use a variable resistance device called a thermistor. The resistance of the thermistor is a strong function of its temperature. The resistance is sensed by passing applying a voltage to the device and sensing the current, which will be a function of temperature. The current is then converted to a digital form which is then output to the display. In this case, the thermistor is the sensing device. The signal modification system is quite complicated including the creation of the current and the conversion to digital form. Finally, the indicator is the liquid crystal display.

**Problem #2:** Select three different types of measurement systems with which you have experience and identify the sensing elements, signal-modification element, and indicator or recorder element associated with those measurement systems

### Solution

This problem is open-ended and has no unique solution. You have search yourself.

**Problem #3:** Identify which of the following measurement are intrusive and which are non-intrusive. Justify your answer.

- (a) Measuring a person's oral temperature with a thermometer
- (b) Measuring the speed of a bullet using high-speed photography
- (c) Determining the temperature of a furnace by an optical thermal radiation device
- (d) Measuring the speed of an automobile with a radar gun

Solution

- 2.4 (a)** Intrusive; The thermometer causes a loading error.  
**(b)** Non-intrusive; The photography does not affect the speed of the bullet at any time.  
**(c)** Non-intrusive; Optical thermal radiation device would yield a non-intrusive measurement as long as it is insulated from the furnace.  
**(d)** Non-intrusive; The speed of the car is unaffected by waves measured by the radar gun.

**Problem #4:** You find a micrometer (a thickness measuring device) of unknown origin and use it to measure the diameter of a steel rod that is known to have a diameter of 0.5000 in. You use the micrometer to make 10 independent measurements of the rod diameter, and the results are 0.4821, 0.4824, 0.4821, 0.4821, 0.4820, 0.4822, 0.4821, 0.4822, 0.4820 and 0.4822. Estimate the systematic error and the maximum random error in these measurements.

Solution

True Value = 0.5000 inches  
Determination of Bias Error.  
First, the average of readings must be calculated:  
Average of Readings =  
$$\frac{(0.4821 + 0.4824 + 0.4821 + 0.4821 + 0.4820 + 0.4822 + 0.4821 + 0.4822 + 0.4820 + 0.4822)}{10}$$
$$= 0.48214$$
$$= 0.4821 \text{ in}$$
  
Bias Error = Average of Readings - True Value  
$$= 0.4821 - 0.5000$$
$$= -0.01786$$
$$= -0.0179 \text{ in}$$
  
Determination of Maximum Precision Error:  
Maximum Precision Error = (Largest difference between a single reading and the Average of Readings)  
$$= 0.4824 - 0.4821$$
$$= 0.0003 \text{ in}$$

**Problem #5:** You need to measure a pressure, which has a value between 60 kPa and 100 kPa. Four pressure measuring devices of comparable quality are available:

- Device A, range 0-100 kPa
- Device B, range 0-150 kPa
- Device C, range 50-100 kPa
- Device D, range 50-150 kPa

Which device would you choose? Explain your answer.

Solution

**2.11** Device (D) would be the best. Device (C) is really the closest in its range. However, measurement errors might cause device (C) to be over range for some measurements producing meaningless results.

**Problem #6:** Digital voltmeters often have a choice of ranges. The ranges indicated on a typical voltmeter are 0-3, 0-30, 0-300, 0-3000 AC volts. The output is represented with four significant digits. Determine the following:

- (a) Resolution uncertainty for each range (in V)
- (b) If it has an accuracy of  $\pm 2\%$  of full range for each range, determine the absolute uncertainty of measurement in each case.
- (c) Determine the relative (percentage of reading) uncertainty if, for a measurement of 25 volts, the ranges 30, 300, or 3000 were used.

Solution

**2.13 (a)** The maximum reading for each range will be 2.999, 29.99, 299.9 and 2999. and the resolution uncertainty will be 1 in the least significant digit. So the resolution uncertainty will be 0.001V, 0.01V, 0.1V and 1V for the three ranges. This could also be viewed as  $\pm 0.0005V$ ,  $\pm 0.005V$ ,  $\pm 0.05V$  and  $\pm 0.5V$

**(b)** The uncertainties will be 2% of full scale. This is  $.02 \times 3$  for the lowest scale or  $\pm 0.06V$ . Similarly for the higher ranges, the uncertainties will be  $\pm 0.6V$ ,  $\pm 6V$  and  $\pm 60V$ .

**(c)** The resolution uncertainty is negligible compared to the accuracy. Hence we can use the results of part (b). For the 30 V range the relative uncertainty will be  $0.06/25 = \pm 2.4\%$ . For the higher ranges, the uncertainties are  $\pm 24\%$  and  $\pm 240\%$ .

**Problem #7:** A bourdon tube (a mechanical device to measure gage pressure, the pressure relative to atmospheric pressure), which has a range of 0 to 50 psi, reads +0.5 psi when measuring atmospheric pressure. It is claimed to have an accuracy of  $\pm 0.2\%$  of full-scale reading. What is the expected error in measurement of 20 psi in psi and in percentage of reading? How can you reduce the error produced by this gage?

Solution

**2.14** Since the device reads 0.5 psi when it should read zero, it has a zero offset of 0.5 psi which will affect all readings. Zero offset is not a component of accuracy. The accuracy specification of 0.2% of full scale gives an uncertainty of  $\pm 0.002 \times 50 = \pm 0.1$  psi. This means that we can have an expected error in any reading of  $0.5 \pm 0.1$  psi. For an applied pressure of 20 psi, the reading would be expected to be in the range 20.4 to 20.6 psi.

We can reduce the expected error by either adjusting the zero (if possible) or by subtracting 0.5 psi from each reading. It may be possible to reduce the error due to the accuracy specification by a calibration of the gage.

**Problem #8:** A static calibration is performed on a bourdon gage pressure measuring device with a nominal range of 0 to 1 MPa. The results of this calibration are shown in the following table.

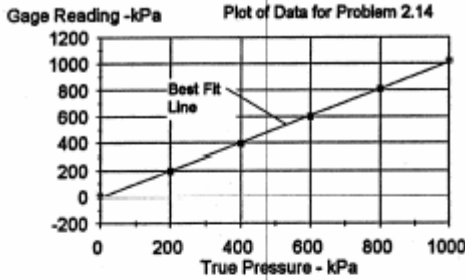
- (a) Plot the data and fit a straight line through them.
- (b) Using deviation plots, estimate the accuracy and repeatability errors, both as a percentage of the putout span.

TABLE P2.24

True pressure (kPa)	Measured pressures					(max. – min.)
	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	
200	192	191	194	193	192	3
400	391	389	391	392	393	4
600	596	597	597	593	596	4
800	807	806	805	803	805	4
1000	1022	1022	1021	1022	1020	3
800	816	814	816	816	817	3
600	606	603	603	603	604	3
400	399	403	402	401	403	4
200	203	201	202	200	205	5
0	10	12	9	11	10	3

Solution

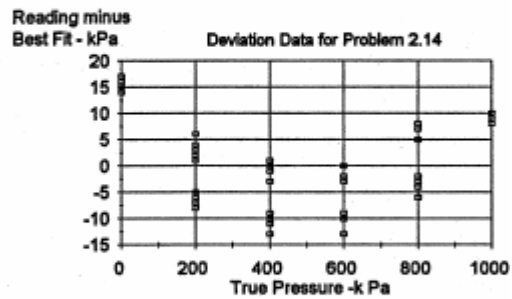
**2.24**



Best Fit Line:  
 $Reading = -4.5 + 1.017 (\text{True Pressure})$

Deviations based on difference between readings and best fit line.

True Force (N)	Deviations (Readings - Best Fit) (N)				
	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5
200	-7	-8	-5	-6	-7
400	-11	-13	-11	-10	-9
600	-10	-9	-9	-13	-10
800	-2	-3	-4	-6	-4
1000	10	10	9	10	8
800	7	5	7	7	8
600	0	-3	-3	-3	-2
400	-3	1	0	-1	1
200	4	2	3	1	6
0	15	17	14	16	15



The accuracy can be determined from the deviation data. The maximum positive deviation is 17 Pa and the largest negative deviation is -13 Pa. For a span of 1000 Pa, this translates to an accuracy of +1.7% and -1.3% of full scale. Note: this accuracy only applies when the readings are corrected using the above curve fit to the data.

The repeatability can be evaluated from the deviations given in Table P2.14. This occurs at the 200 Pa "down" reading and has a value of 5 Pa. This translates to  $\pm 0.5\%$  of full scale.

The hysteresis error is given by the maximum deviation between the up and the down readings for any value of the measurand in one cycle. The value is 14 Pa which occurs at 400 Pa in Cycle 2.

**Problem #9:** Explain the usefulness and appropriateness of the concepts of time constant, response time, rise time, and settling time for,

- (a) Zero-order
- (b) First-order
- (c) Overdamped second-order, and
- (d) Underdamped second-order systems.

Solution

**2.29 (a)** The concepts of time constant, response time, rise time, and settling time do not apply to zero order systems due to their instantaneous responses. All of the concepts would have values approaching zero.

**(b)** First order systems as shown in Response A of Figure 2.8 (b) can most effectively be represented by the concept of time constant in Eq. 2.3:

$$\frac{y}{y_s} = 1 - e^{-t/\tau} = 0.632 \text{ at } t = \tau$$

The preceding equation is a numerical specification of the transient response of the first order system. Although the time constant is the most appropriate concept, the response time and rise time concepts can also be used.

**(c)** For overdamped second order systems also shown in Response A of Figure 2.8(b), the time constant concept of Eq. 2.3 is not really applicable. Therefore, use of the response time and rise time terms is more appropriate occurring when  $\frac{y}{y_s}$  values are 0.95 and 0.1 to 0.9, respectively.

**(d)** Underdamped second order systems as in Response B of Figure 2.8(b) are oscillatory responses which can best be represented by the settling time concept. This concept is the time until the amplitude of the oscillations are less than fraction of the equilibrium response.

**Problem #10:** Answer the following questions:

- (a) High-intensity discharge (HID) lamps come to full brightness in about 5-10 minutes. A light meter, which can detect instant light level, is used to record the light output of an HID lamp. Is this a static or dynamic measurement? Explain.
- (b) The pressure inside a car cylinder cycles at 1500 times per minutes at an engine speed of 3000 rpm (revolution per minute). Can a pressure transducer with a response time of 2 seconds resolve the pressure variation? What value response time would you recommend? Explain your answer.
- (c) A utility meter measures the power draw of a plant every 15 minutes. One of the highest consumers of power in the plant is a 100 kW heater that goes on for 4 minutes every other 10-minute period. Will the meter accurately record the variation in power consumption of this plant? Explain.

### Solution

**2.30 (a)** The light intensity is changing slowly relative to the response of the meter. Each time a measurement is made, it is essentially a static measurement. This is not a dynamic measurement.

**(b)** The cycling occurs at  $1500/60 = 25$  times per second. A pressure transducer with a response time of 2 seconds will just measure some kind of average value and will not respond to the pressure variations. The response time must be much shorter than the time for each cycle ( $1/25 = 0.04$  sec) to show the variation in pressure. The response time should probably be less than 1% of 0.04 seconds or 0.0004 seconds.

**(c)** No, it would not measure the power accurately. It is possible to construct a scenario in which the power is off every time the power is measured. It would be necessary to measure the power every minute or more frequently to get a reasonable measurement. There are better ways to measure the power consumption. For example, the on-off time of the heater can be measured over time and separately the power consumption when it is on.

**Problem #11:** A thermometer, initially at a temperature of  $20^\circ\text{C}$ , is suddenly immersed into a tank of water with a temperature of  $80^\circ\text{C}$ . The time constant of the thermometer is 4 s. What are the values of the rise time and the 90% response time?

### Solution

**2.33** Since this is a first order system,

$$\frac{y}{y_0} = 1 - e^{-t/\tau} \quad \text{where } y_0 = 80 - 20 = 60^\circ\text{C}; \text{ and } \tau = 4 \text{ sec.}$$

Since the rise time is the time it takes  $y/y_0$  to increase from 0.1 to 0.9,

$$0.1 = 1 - e^{-t_1/4} \rightarrow t_1 = 0.42 \text{ sec}$$

$$0.9 = 1 - e^{-t_2/4} \rightarrow t_2 = 9.21 \text{ sec}$$

$$\Delta t = t_2 - t_1 = 9.21 - 0.42 = 8.79 \text{ sec}$$

Therefore the rise time is 8.79 seconds and the 90% response time is 9.21 seconds.