Thermo-Fluid Sensors:

Common thermos-fluid sensors include:

- Measuring pressure,
- Fluid flow rate,
- Temperature and
- Heat transfer rate.

Pressure Sensors:

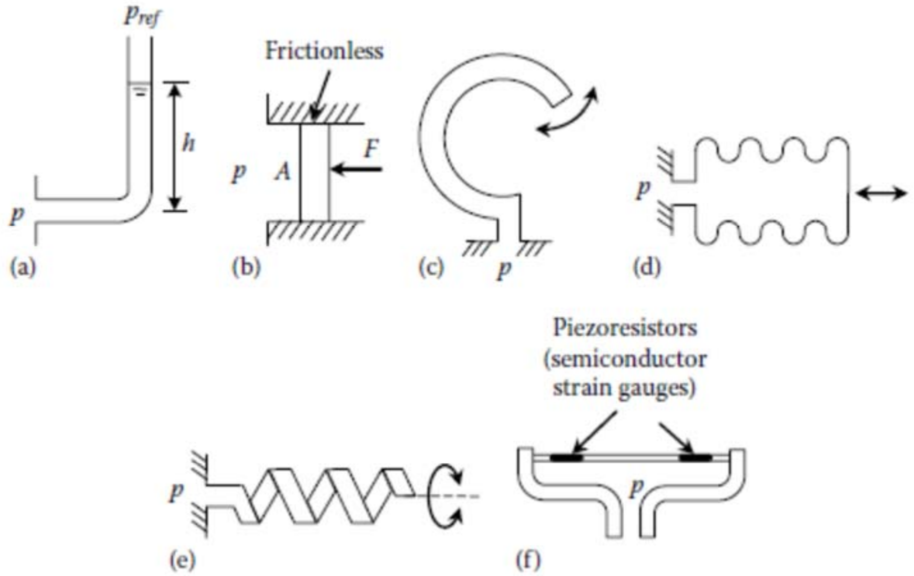


FIGURE 5.59 Typical pressure sensors. (a) Manometer, (b) counterbalance piston, (c) bourdon tube, (d) bellows, (e) helical tube, and (f) diaphragm.

Flow Sensors:

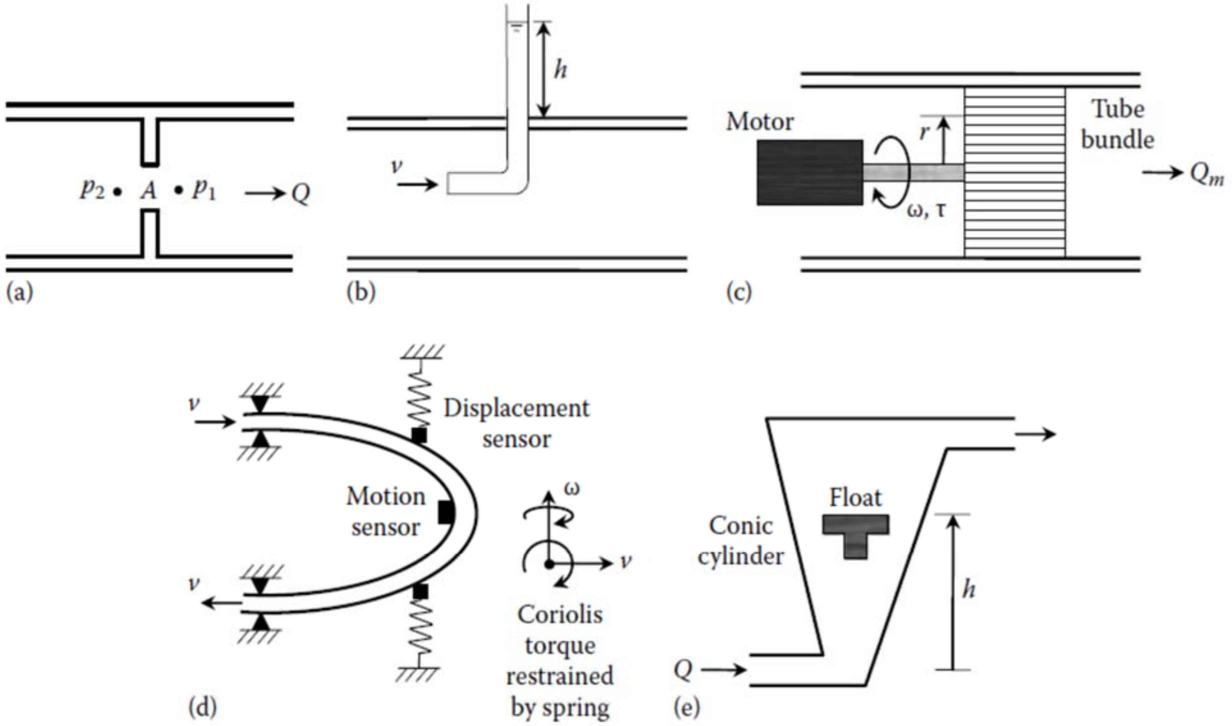
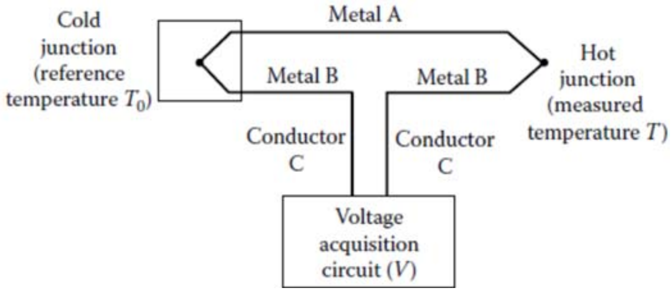


FIGURE 5.60 Several flowmeters. (a) Orifice flowmeter, (b) pitot tube, (c) angular-momentum flowmeter, (d) coriolis velocity meter, and (e) rotameter.

Temperature Sensors:

In most (if not all) temperature measuring devices, the temperature is sensed through heat transfer *from the source to the measuring device*. The physical (or chemical) change in the device that is caused by this heat transfer is the transducer stage of the sensing device.

Thermocouple:



When the temperature changes at the junction formed by joining two unlike conductors, its electron configuration changes due to the resulting heat transfer.

- This electron reconfiguration produces a voltage (emf), and is known as the ***Seebeck effect*** or ***thermoelectric effect***. Two junctions (or more) of a thermocouple are made with two unlike conductors such as iron and constantan, copper and constantan, chrome and alumel, and so on.
- One junction is placed in a reference source (cold junction) with temperature T_0 and the other in the temperature source (hot junction) of temperature T, as shown in Figure. The voltage V across the two junctions is measured to give the temperature of the hot junction with respect to the cold junction.
- The associated relationship (approximately) is:

Resistance Temperature Detector (RTD):

A RTD is a *thermos-resistive* temperature sensor. It is a metal element (in a ceramic tube) whose resistance typically increases with temperature, according to a known function. A linear approximation is given by

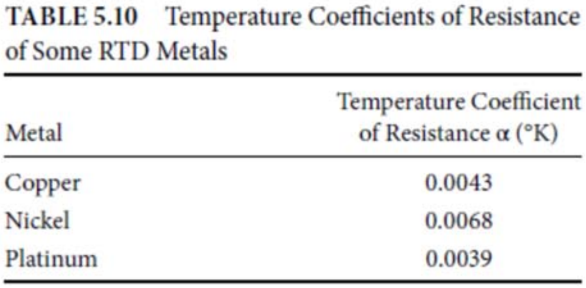


TABLE 5.10 Temperature Coefficients of Resistance of Some RTD Metals

Metal	Temperature Coefficient of Resistance α (°K)
Copper	0.0043
Nickel	0.0068
Platinum	0.0039

Digital and Innovative Sensing:

So far we studied analog sensors and transducers. Let's look at digital transducers and some other innovative sensing methodologies. Our primary focus here is on transducers in mechatronic systems including motion sensors.

- Force, torque, temperature, and pressure, may be converted into a motion and subsequently measured using a motion transducer.

- Bimetallic element may be used to convert temperature into a displacement, which may be measured using a displacement sensor.

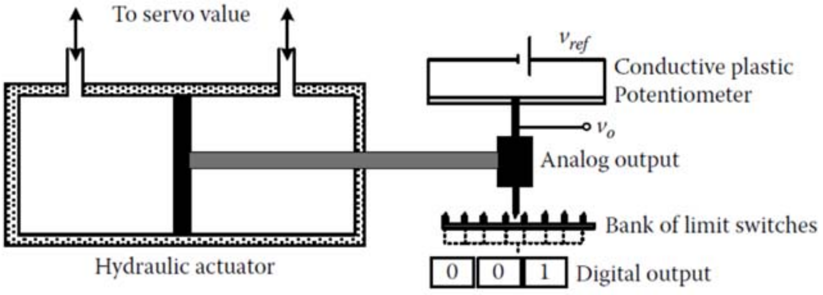
- It is acceptable to call an analog sensor as an analog transducer, because both the sensor stage and the transducer stage of it are analog.

- Typically, the *sensor stage of a digital transducer is typically analog* as well motion, since it is continuous in time and therefore, we cannot *generally speak of digital motion sensors*.

- It is the *transducer stage that generates a discrete output* signal (e.g., pulse train, count, frequency, encoded data) in a digital measuring device. Hence, digital sensing devices may be termed digital transducers rather than digital sensors.

- Other important sensor technologies that are microelectromechanical systems MEMS) sensors, multisensory data fusion, and wireless sensor networks (WSNs).

Analog versus Digital Sensing



Analog and digital methods for displacement sensing.

Analog Sensing Method **Potentiometer with 3-bit ADC**	**Digital Sensing Method** **Eight Limit Switches**
1. An ADC is required to acquire the data by a computer.	1. Easier to acquire data into a computer (e.g., the 1-bit output of a limit switch is typically TTL compatible and can be directly acquired by a microcontroller).
2. Data accuracy is lost in sampling (i.e., aliasing error), and cannot be recovered; signal/sensor noise directly enters into the reading.	2. The 3-bit accuracy is precisely retained even if the limit switch signal has high noise (because only a 1-bit information—triggered or not—is needed from a limit switch).
3. It can sense continuous signals with fine resolution. Resolution of the digitized signal can be improved by using an ADC of larger bit size (say, 4-bit).	3. The resolution is fixed by the number of limit switches.
4. Less robust due to reasons 2, 6, and 7.	4. More robust due to reasons 2 and 6.
5. Direct and simple sensing; data acquisition into a computer is more complex and costly (e.g., filter and amplifier, sample-and-hold, ADC).	5. More components (potentially less reliable) but operates even if a limit switch fails and provides perfect accuracy with respect to the remaining limit switches.
6. Entirely fails if the sensor (potentiometer) fails.	6. There is no issue of quantization error. The actual positions of the limit switches are determined precisely.
7. Quantization error is introduced when a sampled data value is digitized (represented in 3-bit form).	7. Relatively fast (a limit switch is binary). No further signal processing, sampling, and digitizing are needed.
8. Relatively slow (sensor time constant, signal conditioning, sampling, digitizing, and registering).	

Advantages of Digital Transducers:

1. They do not introduce quantization error.
2. Digital signals are less susceptible to noise, disturbances, or parameter variation in instruments because data can be generated, represented, transmitted, and processed as binary words consisting of bits, which possess two identifiable states (the noise threshold is half a bit).
3. Complex signal processing with very high accuracy and speed is possible through digital means (hardware implementation is faster than software implementation).
4. High reliability in a system can be achieved by minimizing analog hardware components.
5. Large amounts of data can be stored using compact, high-density data storage methods.
6. Data can be stored or maintained for very long periods of time without any drift or disruption by adverse environmental conditions.
7. Fast data transmission is possible through existing communication means over long distances with no attenuation and with less dynamic delays, compared to analog signals.
8. Digital signals use low voltages (e.g., 0–12 V dc) and low power.
9. Digital devices typically have low overall cost.

Shaft Encoders:

Shaft encoders are digital transducers that are used for measuring angular displacements and angular velocities.

Encoder Types:

Shaft encoders can be classified into two categories depending on the nature and the method of interpretation of the transducer output:

1. Incremental encoders and
2. Absolute encoders.

Incremental Decoders:

- The output of an incremental encoder is a pulse signal, which is generated when the transducer disk rotates as a result of the motion that is measured.

- By counting the pulses or by timing the pulse width using a clock signal, both angular displacement and angular velocity can be determined.

- With an incremental encoder, displacement is obtained with respect to some reference point which can be the home position of the moving component.

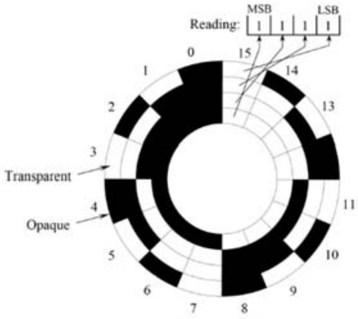
- The index pulse count determines the number of full revolutions.

Absolute Decoders:

- An absolute encoder (or whole-word encoder) has many pulse tracks on its transducer disk. When the disk of an absolute encoder rotates, several pulse trains—equal in number to the tracks on the disk—are generated simultaneously.

- At a given instant, the magnitude of each pulse signal will have one of two signal levels (i.e., a binary state), as determined by a level detector (or edge detector). This signal level corresponds to a binary digit (0 or 1). Hence, the set of pulse trains gives an encoded binary number at any instant.

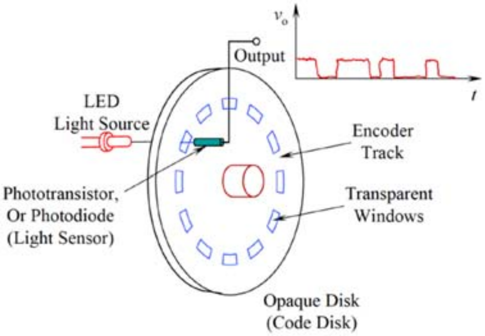
- The windows in a track are not equally spaced but are arranged in a specific pattern to obtain coded output data from the transducer. The pulse windows on the tracks can be organized into some pattern (code) so that the generated binary number at a particular instant corresponds to the specific angular position of the encoder disk at that time.



Binary Code

Four techniques of transducer signal generation may be identified for shaft encoders:

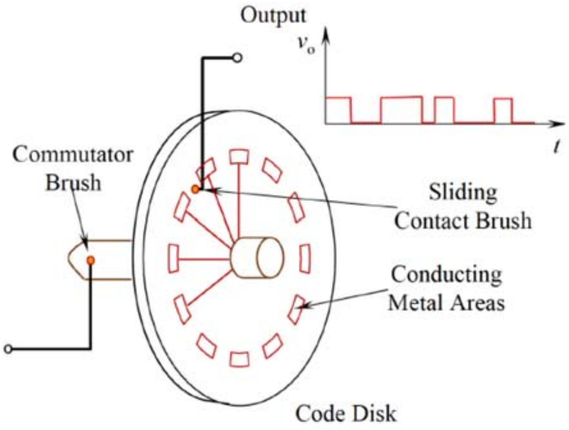
1. Optical (photosensor) method
2. Sliding contact (electrical conducting) method
3. Magnetic saturation (reluctance) method
4. Proximity sensor method



Optical method:

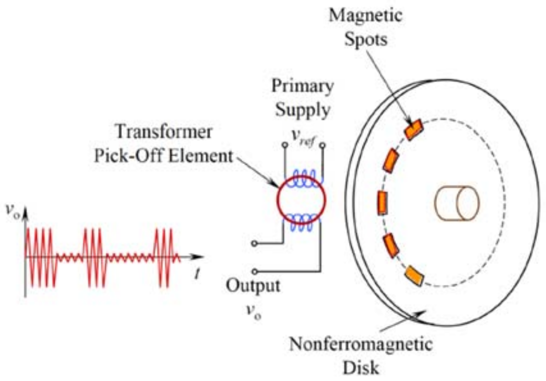
- Since the light from the source is interrupted by the opaque regions of the track, the output signal from the photosensor is a series of voltage pulses.
- This signal can be interpreted (e.g., through edge detection or level detection) to obtain the increments in the angular position and also the angular velocity of the disk.

Sliding Contact Encoder



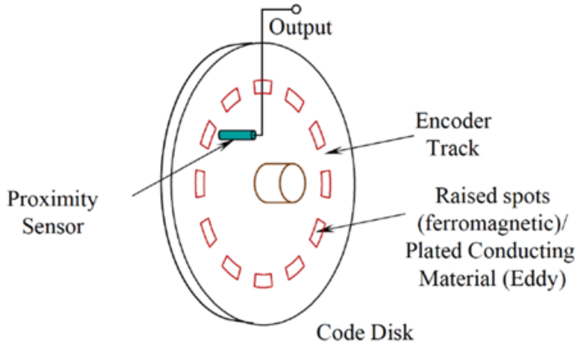
- In a sliding contact encoder, the transducer disk is made of an electrically insulating material.
- Circular tracks on the disk are formed by implanting a pattern of conducting areas.
- These conducting regions correspond to the transparent windows on an optical encoder disk.
- All conducting areas are connected to a common slip ring on the encoder shaft.
- A constant voltage v_{ref} is applied to the slip ring using a brush mechanism. A sliding contact such as a brush touches each track, and as the disk rotates, a voltage pulse signal is picked off by it.
- The pulse pattern depends on the *conducting & non-conducting* pattern on each track, as well as the nature of rotation of the disk. The signal interpretation is done as it is for optical encoders.
- *The advantages:* high sensitivity (depending on the supply voltage) and simplicity of construction (low cost).
- *The disadvantages:* drawbacks of contacting and commutating devices (e.g., friction, wear, brush bounce due to vibration, and signal glitches and metal oxidation due to electrical arcing).
- A transducer’s accuracy is very much dependent on the precision of the conducting patterns of the encoder disk.

Magnetic Saturation Method:



- A magnetic *encoder has high-strength magnetic regions imprinted* on the encoder disk using techniques such as etching, stamping, or recording (similar to magnetic data recording).
- These *magnetic regions correspond to the transparent windows* on an optical encoder disk.
- The signal pick-off device is a micro-transformer, which has primary and secondary windings on a circular ferromagnetic core.
- This pick-off sensor resembles a core storage element in a historical mainframe computer.
- A high-frequency (typically 100 kHz) primary voltage induces a voltage in the secondary windings of the sensing element at the same frequency, operating as a transformer.
- A magnetic field of sufficient strength can saturate the core, however, thereby significantly increasing the reluctance and dropping the induced voltage.
- By *demodulating the induced voltage, a pulse signal is obtained*.
- *Advantage:* non-contacting pick-off sensors.
- *Disadvantage:* more costly than the contacting devices, however, primarily because of the cost of the transformer elements and the demodulating circuitry for generating the output signal.

Proximity Sensor Method:

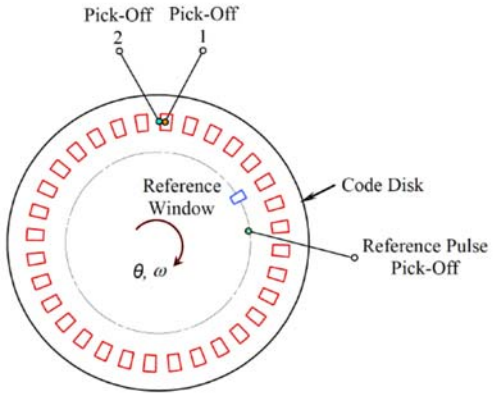


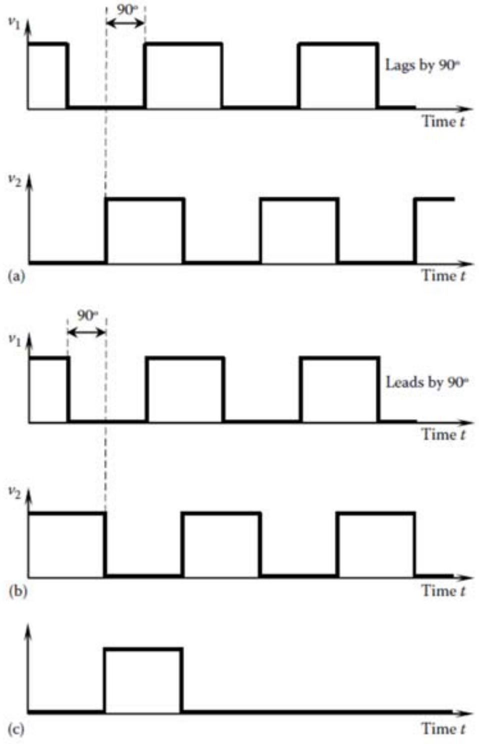
- A proximity *sensor encoder uses a proximity sensor* as the signal pick-off element. for example, a magnetic induction probe or an eddy current probe (recall chapter 5)
- In the *magnetic induction probe*, for example, the disk is made of ferromagnetic material.
- The encoder tracks have raised spots of the same material. *As a raised spot approaches the probe the flux linkage increases due to the associated decrease in reluctance. This raises the induced voltage level.*
- The *output voltage is a pulse-modulated signal, which is then demodulated*, and the resulting pulse signal is interpreted.
- Instead of a *disk with a track of raised regions, a ferromagnetic toothed wheel may be used along with a proximity sensor placed in a radial orientation.* In principle, this device operates like a conventional digital tachometer.
- If an eddy current probe is used, the pulse areas in the track have to be plated with a conducting material.

Incremental Optical Encoder:

There are two possible configurations for an incremental encoder disk with the direction sensing capability:

1. *Offset probe configuration (two probes and one track)*
2. *Offset track configuration (two probes and two tracks)*





- The *first configuration* is schematically shown in figure which shows disk has a single circular track with identical and equally spaced transparent windows.
- The area of the opaque region between adjacent windows is equal to the window area. Note: An output pulse is on for half the period and off for the other half, giving a 50% duty cycle.
- Two photodiode sensors probes 1 and 2 are positioned facing the track at a quarterpitch (half the window length) apart. The forms of their output signals (v_1 *and* v_2), after passing them through pulse-shaping circuitry (idealized), are shown in *figure a and b* for the two directions of rotation.
- The delay between the two signals will change by an integer multiple of 360° (assume constant speed over the delay), that is, no change.

- In the *second configuration* *of an incremental encoder, two identical tracks are used, one offset from the other by a quarter-pitch*.
- Each track has its own probe (light sensor), oriented facing the corresponding track.
- The two probes are positioned along a radial line of the disk, without any circumferential offset unlike the previous configuration. The output signals from the two sensors are the same as before, however.
- In both configurations, an additional track with a lone window and associated probe is also usually available. This track generates a reference pulse (index pulse) per revolution of the disk (*see figure 6.4c*).
- This pulse is used to initiate the counting operation and also to count complete revolutions, which is required in measuring absolute angular rotations.

Note: When the disk rotates at a constant angular speed, the pulse width and pulse-to-pulse period (encoder cycle) are constant (with respect to time) in each sensor output. When the disk accelerates, the pulse width decreases continuously; when the disk decelerates, the pulse width increases.

Method 1: It is clear from Figure 6.4a and b that in the cw rotation, v_1 lags v_2 by a quarter of a cycle (i.e., a phase lag of 90°) and in the ccw rotation, v_1 leads v_2 by a quarter of a cycle. Hence, the direction of rotation may be obtained by determining the phase difference of the two output signals, using phase-detecting circuitry.

Method 2: A rising edge of a pulse can be determined by comparing successive signal levels at fixed time periods (can be done in both hardware and software). Rising-edge time can be measured using pulse counts of a high-frequency clock. Suppose that the counting (timing) begins when the v_1 signal begins to rise (i.e., when a rising edge is detected). Let n_1 = number of clock cycles (time) up to the time when v_2 begins to rise; and n_2 = number of clock cycles up to the time when v_1 begins to rise again. Then, the following logic applies:

$$\text{If } n_1 > n_2 - n_1 \Rightarrow \text{cw rotation}$$

$$\text{If } n_1 < n_2 - n_1 \Rightarrow \text{ccw rotation}$$

This logic for direction detection should be clear from Figure 6.4a and b.

Method 3: In this case, we first detect a high level (logic high or binary 1) in signal v_2 and then check whether the edge in signal v_1 rises or falls during this *high* period of v_2. It is clear from Figure 6.4a and b that the following logic applies:

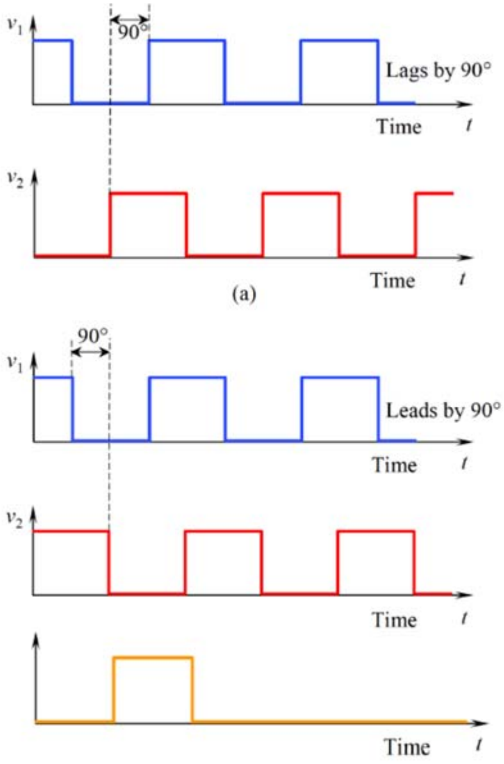
$$\text{If edge is rising in } v_1 \text{ when } v_2 \text{ is at logic high} \Rightarrow \text{cw rotation}$$

$$\text{If edge is falling in } v_1 \text{ when } v_2 \text{ is at logic high} \Rightarrow \text{ccw rotation}$$

Method 4: Detect a high to low transition in signal v_1.

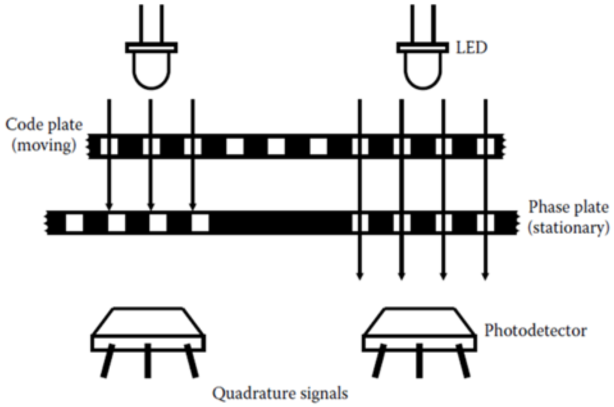
If the next transition in signal v_2 is Low to High → cw rotation

If the next transition in signal v_2 is High to Low → ccw rotation



Linear Encoders:

- An arrangement is shown in figure where the code plate is attached to the *moving object whose rectilinear motion* is to be measured.
- An LED light source and a phototransistor light sensor are used to detect the motion pulses, which can be interpreted just like the way it is done for a rotatory encoder.
- The phase plate is used, as with a shaft encoder, to enhance the intensity and the discrimination of the detected signal.



- *Two tracks of windows* in quadrature (i.e., quarter-pitch offset) would be needed to *determine the direction of motion*, as shown in figure.
- Another track of windows at half-pitch offset with the main track (not shown in figure) *may be used as well on the phase plate, to further enhance the discrimination of the detected pulses*.
- Specifically, *when the sensor at the main track reads a high intensity (i.e., when the windows on the code plate and the phase plate are aligned)* the sensor at the *track that is half pitch away will read a low intensity (because the corresponding windows of the phase plate are blocked by the solid regions* of the code plate).

Motion sensing by encoder:

- An optical encoder can measure both displacement and velocity.
- Depending on the encoder design (linearly moving code plate or rotating code disk) rectilinear motions or angular motions can be measured.
- An incremental encoder measures displacement as a pulse count and it measures velocity as a pulse frequency.

Displacement Measurement:

Digital Resolution:

Physical Resolution:

Step-Up Gearing:

The physical resolution of an encoder can be improved by using step-up gearing so that one rotation of the moving object that is monitored corresponds to several rotations of the code disk of the encoder. This improvement is directly proportional to the step-up gear ratio (p).

- Equation to show p can be written as: $\Delta\theta_p = \frac{360^0}{4pN}$;
- Gear ration may introduce backlash error which is significanly smaller than the resolution.
- Gear ratio improvement leads to further enhancement to the digital resolution as: $\Delta\theta_d = \frac{180^0}{p2^{r-1}} = \frac{360^0}{p2^r}$

Velocity Measurement:

Two methods are available for determining velocities using an incremental encoder are: *Pulse-counting method* and *Pulse-timing method*

In the first method:

- the pulse count over a fixed time period (the successive time period at which the data register is read) is used to calculate the angular velocity.
- For a given period of data reading, *there is a lower speed limit below which this method is not very accurate*.
- To compute the angular velocity ω using this method, suppose that the count during a time period T is n pulses. Hence, *the average time for one pulse cycle (i.e., window-to-window pitch angle) is T/n*. If there are N windows on the disk, assuming that quadrature signals are not used, the angle moved during one pulse period is 2π/N radians.

$$\text{for pulse-counting method, Speed } \omega = \frac{2\pi/N}{T/n} = \frac{2\pi n}{NT}$$

In the second method:

- The time for one encoder pulse cycle (i.e., window-to-window pitch angle) is measured using a high-frequency clock signal.
- This method is *particularly suitable for accurately measuring low speeds*.
- In this method, suppose that the clock frequency is f Hz. If m cycles of the clock signal are counted during an encoder pulse period (i.e., window pitch, which is the interval between two adjacent windows, assuming that quadrature signals are not used), the time for that encoder cycle (i.e., the time to rotate through one encoder pitch) is given by m/f.
- With a total of N windows on the track, the angle of rotation during this period is 2π/N radians as before.

$$\text{for pulse timing method, Speed } \omega = \frac{2\pi/N}{m/f} = \frac{2\pi f}{Nm}$$

Velocity Resolution:

- Depends on the method that is employed to determine velocity.
- Both the pulse-counting method and the pulse-timing method are based on counting, the velocity resolution is given by the change in angular velocity that corresponds to a change (increment or decrement) in the count by one.
- For the pulse-counting method:

Velocity Resolution with Step-Up Gearing:

As before, the speed resolution is given by the change in speed corresponding to a unity change in the count. Hence, for the pulse-counting method

$$\text{for the pulse-counting method: } \Delta\omega_c = \frac{2\pi(n+1)}{pNT} - \frac{2\pi n}{pNT} = \frac{2\pi}{pNT}$$

It follows that in the pulse-counting method, step-up gearing causes an improvement in the resolution. For the pulse-timing method:

$$\Delta\omega_t = \frac{2\pi f}{pNm} - \frac{2\pi f}{pN(m+1)} = \frac{2\pi f}{pNm(m+1)} \cong \frac{pN}{2\pi f}\omega^2$$

Note: In the pulse-timing approach, for a given speed, the resolution degrades with increasing *p*.

In summary, the speed resolution of an incremental encoder depends on the following factors:

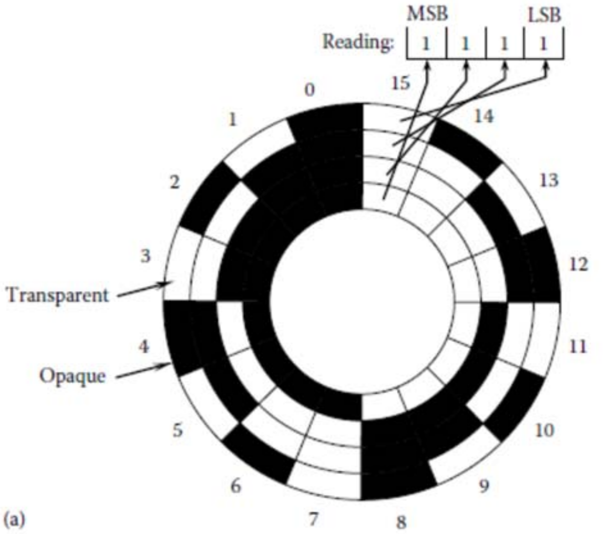
1. Number of windows **N**
2. Count reading (sampling) period **T**
3. Clock frequency **f**
4. Speed **ω**
5. Gear ratio **p**

In particular, gearing-up has a detrimental effect on the speed resolution in the pulse-timing method, but it has a favorable effect in the pulse-counting method.

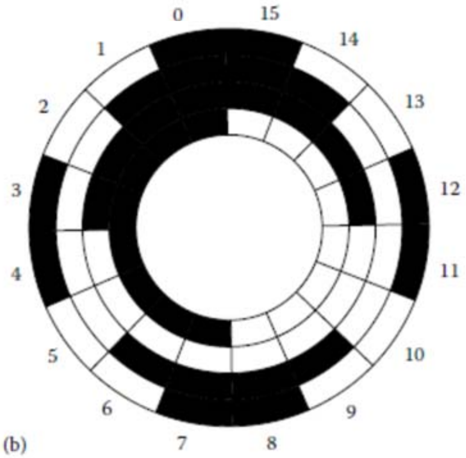
Gray Coding:

In an absolute encoder, there is a data interpretation problem associated with the straight binary code.

- Note in Table that with the straight binary code, the transition from one sector to an adjacent sector may require more than one switching of bits in the binary data.
- For example, transition from *0011 to 0100 or from 1011 to 1100 requires three bit* switching, and the transition from *0111 to 1000 or from 1111 to 0000 requires four bit switching.*
- If the light probes are not properly aligned along a radius of the encoder disk, or if the manufacturing error tolerances for imprinting the code pattern on the disk were high, or if environmental effects have resulted in large irregularities in the sector matrix, then the bit switching from one reading to the next may not take place simultaneously.
- This will result in ambiguous readings during the transition period. For example, in changing from *0011 to 0100, if the LSB switches first, the reading becomes 0010*. In decimal form, this incorrectly indicates that the rotation was from angle 3 to angle 2, whereas, it was actually a rotation from angle 3 to angle 4.
- Such *ambiguities in data interpretation can be avoided by using a gray code*, as shown in figure for this example.
- The coded representation of the sectors is given in Table 6.2.
- Note that in the case of gray code, each adjacent transition involves only one bit switching.



(a)



(b)

TABLE 6.2 Sector Coding for a 4-Bit Absolute Encoder

Sector Number	Straight Binary Code (MSB → LSB)	A Gray Co (MSB → L
0	0 0 0 0	0 0 0 0
1	0 0 0 1	0 0 0 1
2	0 0 1 0	0 0 1 1
3	0 0 1 1	0 0 1 0
4	0 1 0 0	0 1 1 0
5	0 1 0 1	0 1 1 1
6	0 1 1 0	0 1 0 1
7	0 1 1 1	0 1 0 0
8	1 0 0 0	1 1 0 0
9	1 0 0 1	1 1 0 1
10	1 0 1 0	1 1 1 1
11	1 0 1 1	1 1 1 0
12	1 1 0 0	1 0 1 0
13	1 1 0 1	1 0 1 1
14	1 1 1 0	1 0 0 1
15	1 1 1 1	1 0 0 0

Encoder Error:

The primary sources of errors in shaft encoder readings can come from:

1. *Quantization error (due to digital word size limitations)*
2. *Assembly error (eccentricity of rotation, etc.)*
3. *Coupling error (gear backlash, belt slippage, loose fit, etc.)*
4. *Structural limitations (disk deformation and shaft deformation due to loading)*
5. *Manufacturing tolerances (errors from inaccurately imprinted code patterns, inexact positioning of the pick-off sensors, limitations and irregularities in signal generation and sensing hardware, etc.)*
6. *Ambient effects (vibration, temperature, light noise, humidity, dirt, smoke, etc.)*
7. *These factors can result in inexact readings of displacement and velocity and erroneous detection of the direction of motion.*

Eccentricity Error:

Eccentricity (denoted by *e*) of an encoder is defined as:

- *The distance between the center of rotation C of the code disk and*
- *The geometric center G of the circular code track.*
- *Nonzero eccentricity causes a measurement error known as the eccentricity error.*

The primary contributions to eccentricity are:

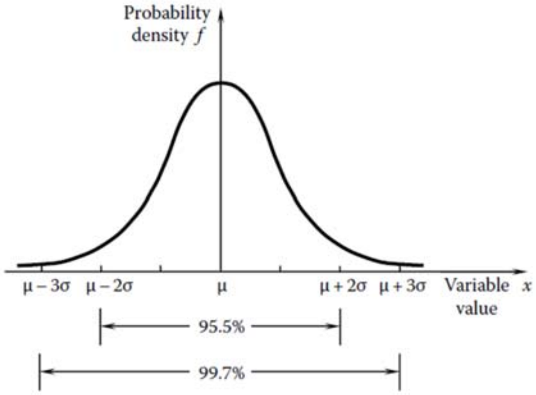
1. Shaft eccentricity (e_s): *axis of rotation is different from geometric axis.*
2. Assembly eccentricity (e_a): *center of code disk is not on the shaft axis.*
3. Track eccentricity (e_t): *center of the track is not the center of the disk.*
4. Radial play (e_p): *looseness in the assembly in radial direction.*

- All four of these parameters are random variables.
- Let their mean values be $\mu_s, \mu_a, \mu_t, \mu_p$, and
- The standard deviations be $\sigma_s, \sigma_a, \sigma_t, and\ \sigma_p$ respectively.
- A very conservative upper bound for the mean value of the overall eccentricity is given by the sum of the individual absolute (i.e., considered positive) mean values. A more reasonable estimate is provided by the root-mean-square (rms) value, as given by:

$$\mu = \sqrt{\mu_s^2 + \mu_a^2 + \mu_t^2 + \mu_p^2}$$

And the standard deviation of the overall eccentricity is given by:

$$\sigma = \sqrt{\sigma_s^2 + \sigma_a^2 + \sigma_t^2 + \sigma_p^2}$$



Probability that eccentricity between:

μ-2σ and μ+2σ : 95.5%
μ-3σ and μ+3σ : 99.7%

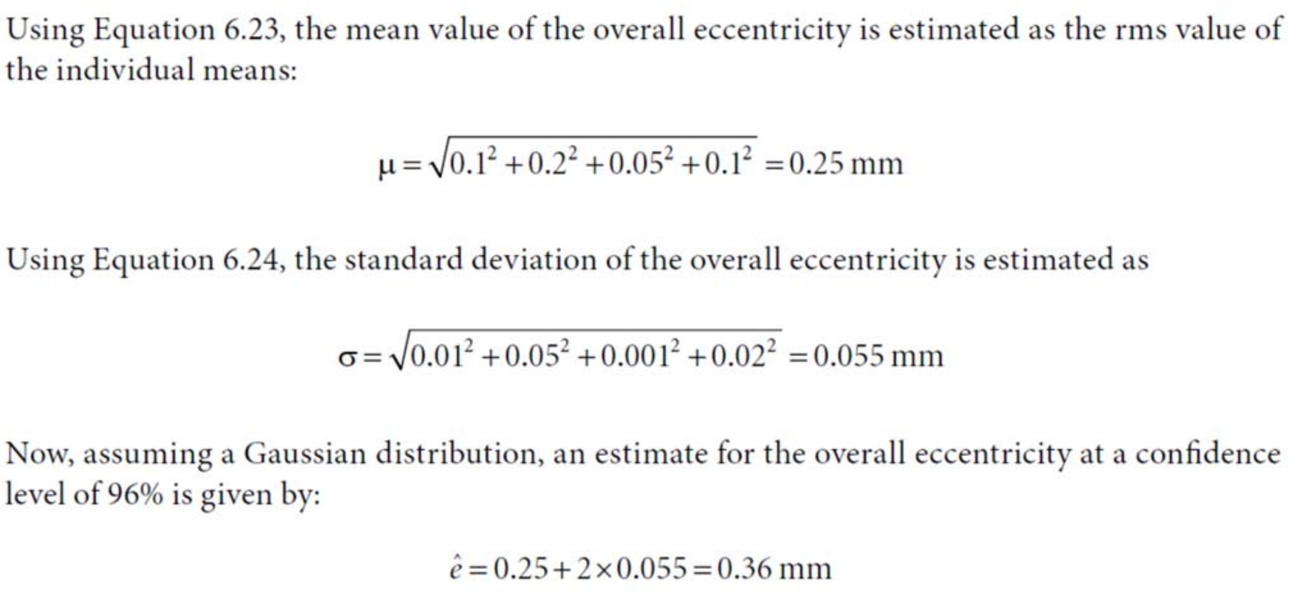
Example:

The mean values and the standard deviations of the four primary contributions to eccentricity in a shaft encoder (in millimeters) are as follows:

- Shaft eccentricity = (0.1, 0.01);
- Assembly eccentricity = (0.2, 0.05);
- Track eccentricity = (0.05, 0.001);
- Radial play = (0.1, 0.02).

Estimate the overall eccentricity at a confidence level of 96%.

Solution:



Using Equation 6.23, the mean value of the overall eccentricity is estimated as the rms value of the individual means:

$$\mu = \sqrt{0.1^2 + 0.2^2 + 0.05^2 + 0.1^2} = 0.25\ \text{mm}$$

Using Equation 6.24, the standard deviation of the overall eccentricity is estimated as

$$\sigma = \sqrt{0.01^2 + 0.05^2 + 0.001^2 + 0.02^2} = 0.055\ \text{mm}$$

Now, assuming a Gaussian distribution, an estimate for the overall eccentricity at a confidence level of 96% is given by:

$$\hat{e} = 0.25 + 2 \times 0.055 = 0.36\ \text{mm}$$

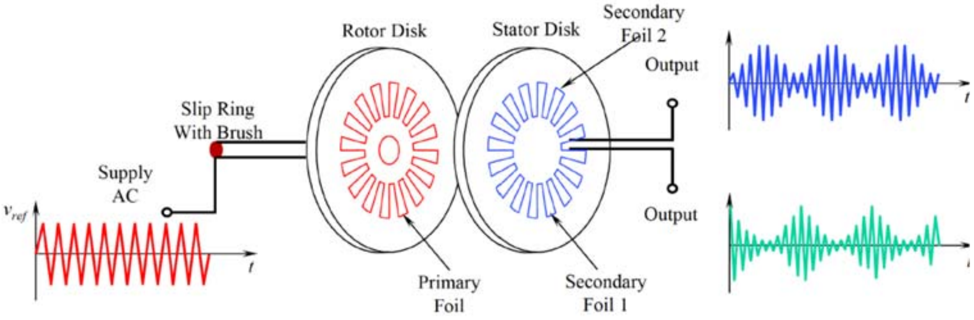
Miscellaneous Digital Transducers:

Binary Transducers:

- Digital binary transducers are two-state sensors. The information provided by such a device takes only two states (on/off, present/absent, go/no-go, high/low, etc.) which can be represented by one bit.
- For example, a limit switch is a sensor that is used in detecting whether an object has reached a particular position (or, limit), and is useful in sensing presence/absence and in object counting.
- In this sense, a limit switch is considered a digital transducer.
- Additional logic is needed *if the direction of contact* is also needed.
- Limit switches are available for both *rectilinear and angular* motions.

Digital Resolvers:

Digital resolvers, or mutual induction encoders, operate somewhat like analog resolvers, using the principle of mutual induction. They are commercially known as Inductosyns.



- A digital resolver has two disks facing each other (but not in contact), one (the stator) stationary and the other (the rotor) coupled to the rotating object whose motion is measured. The *rotor has a fine electric conductor foil imprinted on it, as shown above.*

- The printed pattern is pulse shaped, closely spaced, and connected to a high-frequency ac supply (carrier) of voltage v_{ref}.

- The stator disk has two separate printed patterns that are identical to the rotor pattern, but *one pattern on the stator is shifted by a quarter-pitch from the other pattern* (Note: pitch = spacing between two successive crests of the foil).

- The primary voltage in the rotor circuit induces voltages in the two secondary (stator) foils at the same frequency; that is, the *rotor and the stator are inductively* coupled.

- These induced voltages are quadrature signals (i.e., 90° out of phase). As the rotor turns, the level of the induced voltage changes, depending on the relative position of the foil patterns on the two disks.

- When *the foil pulse patterns coincide, the induced voltage is a maximum* (positive or negative), and when *the rotor foil pattern has a half-pitch offset from the stator foil pattern, the induced voltage in the adjacent segments cancel* each other, producing a zero output.

- Very fine resolutions (e.g., 0.0005°) may be obtained from a digital resolver, and it is usually not necessary to use step-up gearing or other techniques to improve the resolution. These *transducers are usually more expensive than optical encoders. The use of a slip ring and brush to supply the carrier signal may be viewed as a disadvantage*.