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:

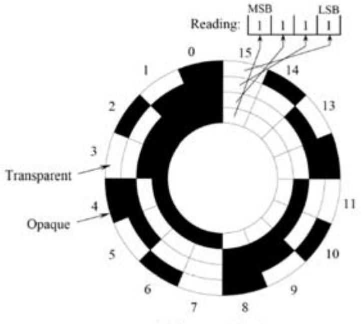
- The output of an incremental encoder is a pulse signal, which is generated when the transducer disk rotates as a result of the motion that is measured.

- 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:



Binary Code

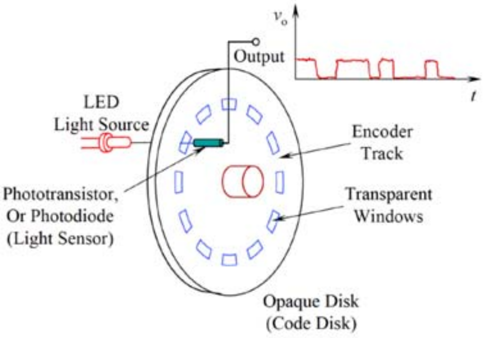
- An absolute encoder (or whole-word encoder) has many pulse tracks on its transducer disk. When the disk of an absolute encoder rotates, several pulse trains—equal in number to the tracks on the disk—are generated simultaneously.

- 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.

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

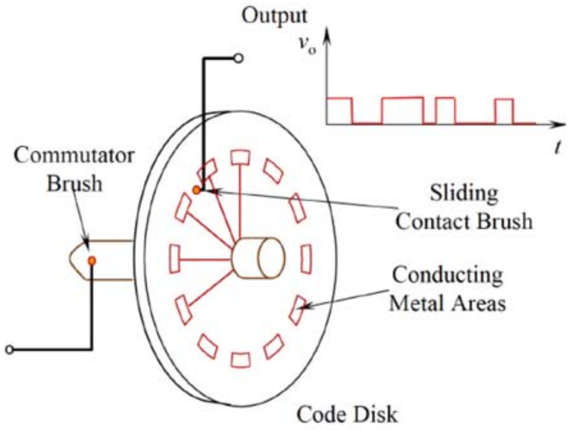
1. Optical (photosensor) method
2. Sliding contact (electrical conducting) method
3. Magnetic saturation (reluctance) method
4. Proximity sensor method



Optical method:

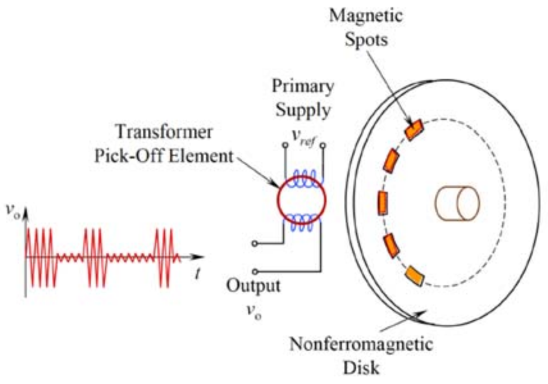
- Since the light from the source is interrupted by the opaque regions of the track, the output signal from the photosensor is a series of voltage pulses.
- This signal can be interpreted (e.g., through edge detection or level detection) to obtain the increments in the angular position and also the angular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

Sliding Contact Encoder



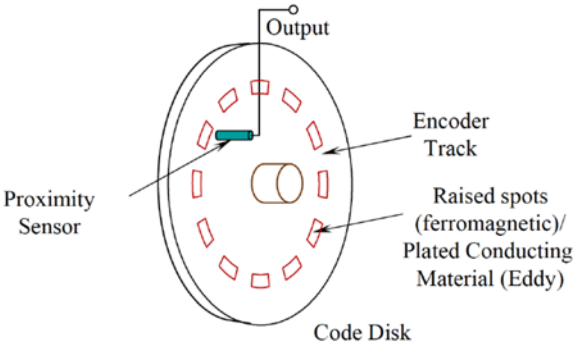
- In a sliding contact encoder, the transducer disk is made of an electrically insulating material.
- Circular tracks on the disk are formed by implanting a pattern of conducting areas.
- These conducting regions correspond to the transparent windows on an optical encoder disk.
- All conducting areas 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.

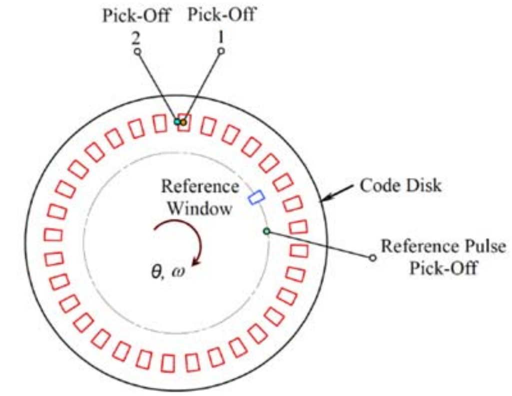
Proximity Sensor Method:

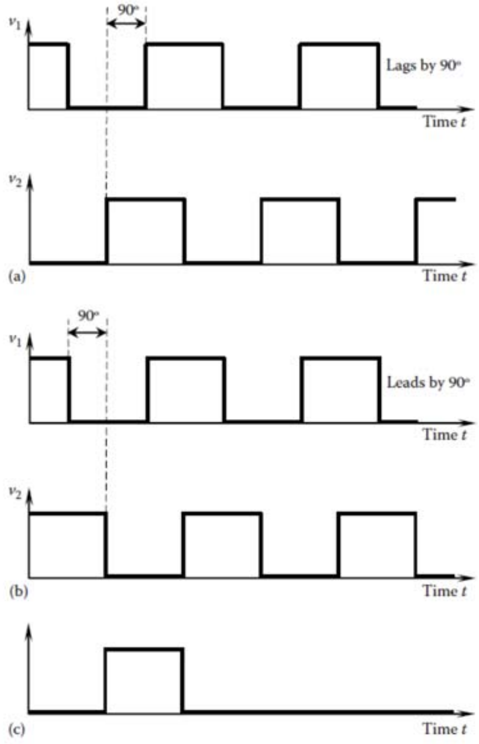


- A proximity *sensor encoder uses a proximity sensor* as the signal pick-off element. for example, a magnetic induction probe or an eddy current probe (recall chapter 5)
- In the *magnetic induction probe*, for example, the disk is made of ferromagnetic material.
- The encoder tracks have raised spots 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:

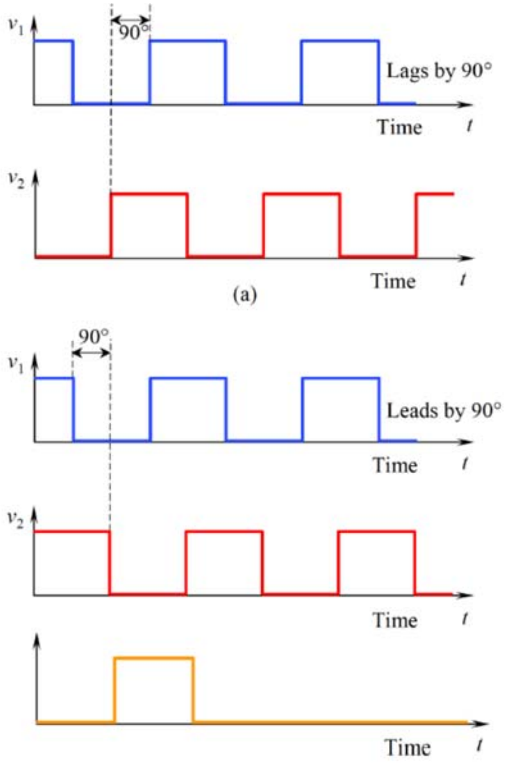
If edge is rising in v_1 when v_2 is at logic high ⇒ cw rotation

If edge is falling in v_1 when v_2 is at logic high ⇒ ccw rotation

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

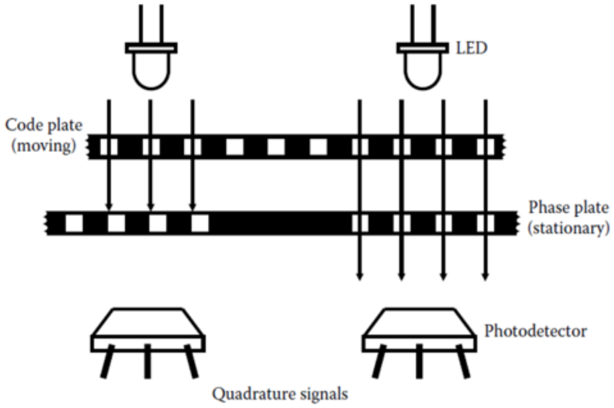
If the next transition in signal v_2 is Low to High → cw rotation

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:

n-pulses

M: Max. Count possible for incremental encoder

Pulse

$$\text{Angular Position} \rightarrow \theta = \frac{n}{M}\,\theta_{max}$$

Range: $\pm\theta_{max}$ —— ①

Digital Resolution:

Encoder Resolution: Smallest realistic measurable change.

$$\text{Displacement Resolution.} \rightarrow \Delta\theta = \frac{\theta_{max}}{M} \qquad \text{——②}$$

(from ①). Suppose encoder Count is stored as digital data of 'r' bits we have $M = 2^{r-1}$; Sub into ② we have digital Resolution

$$③ \text{——} \Delta\theta_d = \frac{\theta_{max}}{2^{r-1}}$$

; Note $\theta_{max} = \pm 180^\circ$ or $\pm 360^\circ$

$$④ \text{——} \therefore \Delta\theta_d = \frac{180}{2^{r-1}} = \frac{360}{2^{r}}$$

Min ⇒ all 0-bits → θ_{min}

Max ⇒ all 1-bits → θ_{max}

$$\therefore \theta_{max} = \theta_{min} + (M-1)\,\Delta\theta \,; \quad \text{Sub } M = 2^{r-1}$$

$$\theta_{max} = \theta_{min} + (2^{r-1}-1)\,\Delta\theta_d$$

$$\text{Digital RES: } \Delta\theta_d = \frac{\theta_{max} - \theta_{min}}{2^{r-1}-1}$$

; Same as ④

$\theta_{max} = 2\pi$, $\theta_{min} = 0$; θ_{min} and θ_{max} → Same position on Code disk

∴ To aVoid this $\theta_{min} = \frac{\theta_{max}}{2^{r-1}}$; we end up as ③.

Physical Resolution:

$$\text{Physical Resolution} \rightarrow \Delta\theta_p = \frac{360}{4N}$$

← No, # of Windows on Code Disk.

Read Examples 6.1, 6-2, 6-3 text

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:

Equation on Last Page $\omega = \frac{2\pi n}{NT}$ | for quadrature signal replace N by 4N

For Unity change in count n

$\Rightarrow$ Speed change $\Delta\omega_c = \frac{2\pi}{NT}$

Time period over which a pulse count is read

# of windows in Code Track

This gives us Velocity Resolution

In pulse-timing Method, Velocity Resolution is

$$\Delta\omega_t = \frac{2\pi f}{Nm} - \frac{2\pi f}{N(m+1)} = \frac{2\pi f}{Nm(m+1)}$$

For Large 'm' (clock cycles), $m+1 \simeq m$

$$\Delta\omega_t = \frac{2\pi f}{Nm^2} = \frac{\omega}{m}$$

$\because$ Last page $\omega = \frac{2\pi f}{mN}$

$$\Delta\omega_t = \frac{\omega^2}{m}\cdot\frac{1}{\omega} = \frac{\omega^2}{\cancel{m}}\cdot\frac{\cancel{m}\cdot N}{2\pi f}$$

$$\boxed{\frac{\Delta\omega_t}{\omega} = \frac{\omega\cdot N}{2\pi f}}$$

| Pulse-timing Method is good for Low Speeds.

Do example 6.4. Text Imp.