SENSORS AND SIGNAL CONDITIONING

MODULE 4- DIGITAL AND INTELLIGENT SENSORS-

POSITION ENCODERS, RESONANT SENSORS, SENSORS BASED ON QUARTZ RESONATORS, SAW SENSORS, VIBRATING WIRE STRAIN GAGES, VIBRATING CYLINDER SENSORS, DIGITAL FLOW METER.

INTRODUCTION: -

We distinguish here three classes of digital sensors. The first yields a digital version of the measurand. This group includes position encoders.

The second group relies on some physical oscillatory phenomenon that is later sensed by a conventional modulating or generating sensor. Sensors in this group are sometimes designated as self-resonant, variable-frequency, or quasi-digital sensors, and they require an electronic circuit (a digital counter) in order to yield the desired digital output signal.

The third group of digital sensors use modulating sensors included in variable electronic oscillators. Because we can digitally measure the oscillation frequency, these sensors do not need any ADC either.

Silicon technology has achieved circuit densities that permit the fabrication of sensors that integrate computation and communication capabilities, termed intelligent or smart sensors.

4.1 POSITION ENCODERS

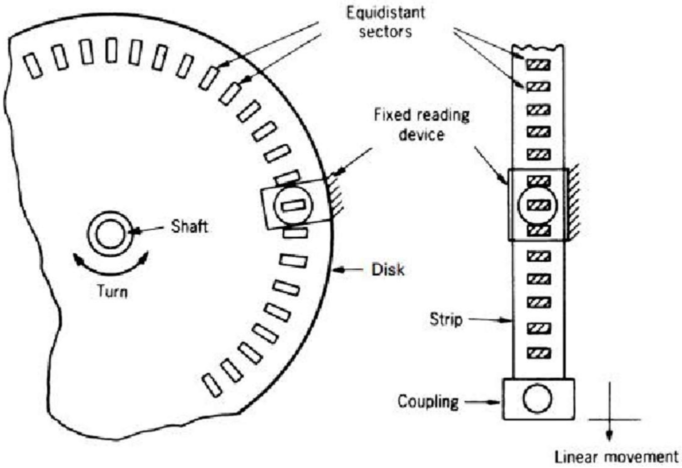


Figure 8.1 Principle of linear and rotary incremental position encoders. (From N. Norton, *Sensor and Analyzer Handbook*, copyright 1982, p. 105. Reprinted by permission of Prentice-Hall, Englewood Cliffs, NJ.)

Linear and angular position sensors are the only type of digital output sensors that are available in several different commercial models.

4.1.1 <u>INCREMENTAL POSITION ENCODERS</u>

An incremental position encoder consists of a linear rule or a low-inertia disk driven by the part whose position is to be determined. That element includes two types of regions or sectors having a property that differentiates them, and these regions are arranged in a repetitive pattern (Figure 8.1).

Or

Incremental rotary encoder uses discs which contains transparent section that are equally spaced. A light-emitting diode serves a sender and it's light is detected by a photo detector. Therefore, the encoder can generate a sequence of pulses. The output is measured in pulses per revolution which can be used to determine either the position or the rotational speed.

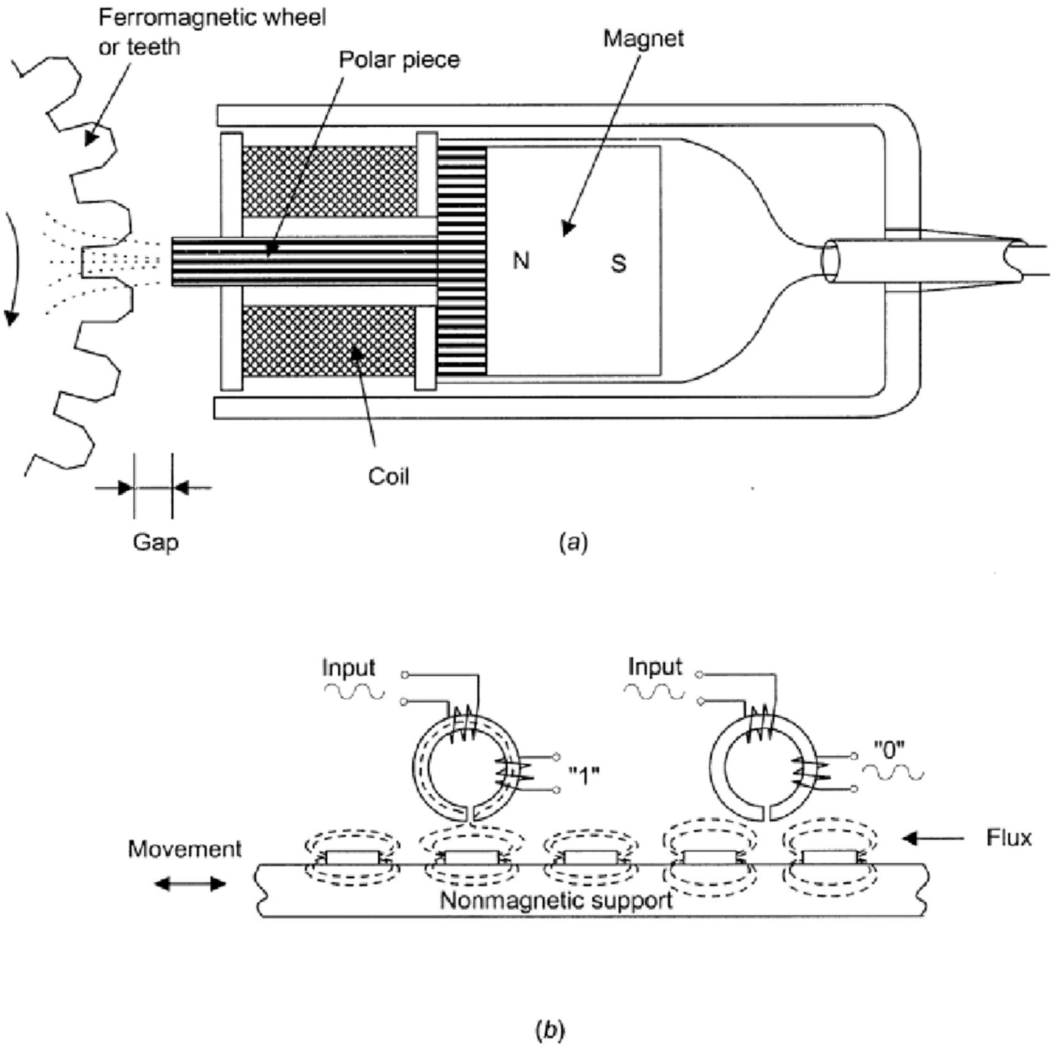


Figure 8.2 Different sensors for magnetic incremental position encoders. (*a*) Coil and magnet (courtesy of Orbit Controls). (*b*) Toroidal core.

Figure 8.2b shows another inductive system but this time based on a toroid with two windings. One winding is used for exciting, using currents between 20 kHz and 200 kHz, and the other is used for detection.

Silver-in-glass technology offers low cost, ruggedness, high-resistance to corrosion, and life expectancy of up to fifteen million cycles, far above the 100,000 cycles of former PCB designs.

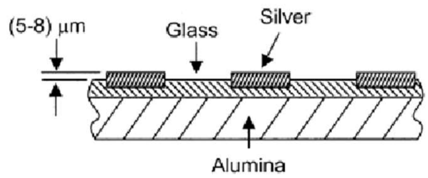


Figure 8.3 Silver-in-glass technology for contacting incremental position encoder (courtesy of Spectrol).

Optical encoders can be based on opaque and transparent regions, on reflective and non-reflective regions, and also on interference fringes. Whatever the case, the fixed reading head includes a light source (infrared LED), and a photodetector (phototransistor or photodiode).

Main problems (Disadvantages) result from dust-particle buildup, time and temperature drifts for electronic components, and vibration effects on focusing elements. High-performance sensors have either a lens or an aperture to provide collimated light output and minimal spurious reflections.

OPAQUE AND TRANSPARENT REGIONS

When opaque and transparent regions, chromium on glass, slotted metal, and so forth (Figure 8.4a) are used, the emitter and the receiver must be placed on each side of the moving element.

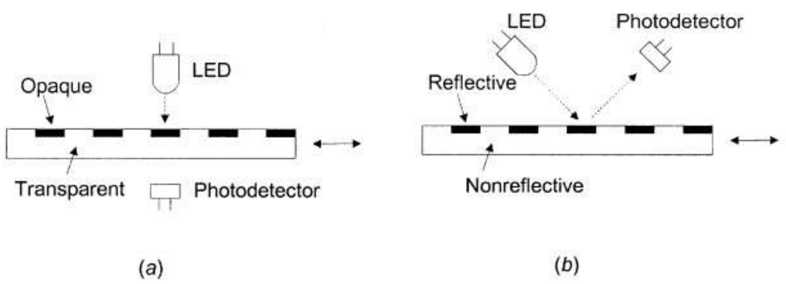


Figure 8.4 Incremental optical encoder. (*a*) With opaque and transparent sectors. (*b*) With reflective and nonreflective sectors.

REFLECTIVE AND NON-REFLECTIVE REGIONS

In contrast, when relying on reflective and nonreflective zones, for example, polished steel with an engraved surface (Figure 8.4b) the emitter and the detector must be on the same side of the coding element. Glass disks are more stable, rigid, hard, and flat than metal disks, but are less resistant to vibration and shock.

INTERFERENCE FRINGES

Interference fringe encoders are based on moire patterns. To create them from a linear movement, we can use a fixed and a movable rule having lines inclined with respect to each other (Figure 8.5).

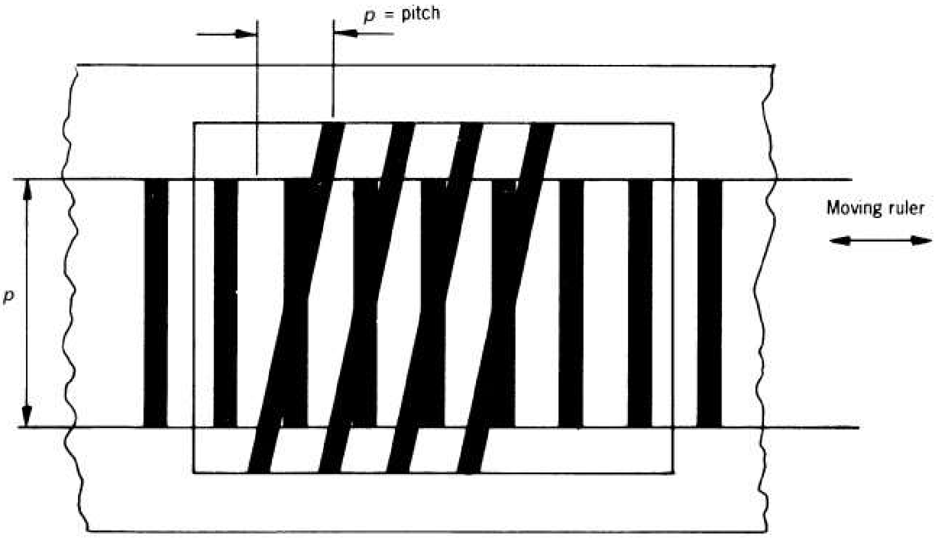


Figure 8.5 Optical incremental encoder based on interference fringes (moiré patterns). The horizontal dark fringe moves in the vertical direction when the sliding rule moves horizontally.

Optical encoders yield the highest resolution. The limiting factor is the photodetector size. Resolution increases by using one or several fixed grids or masks with opaque and transparent regions, placed between the movable elements and the detector, and having the same pitch as the

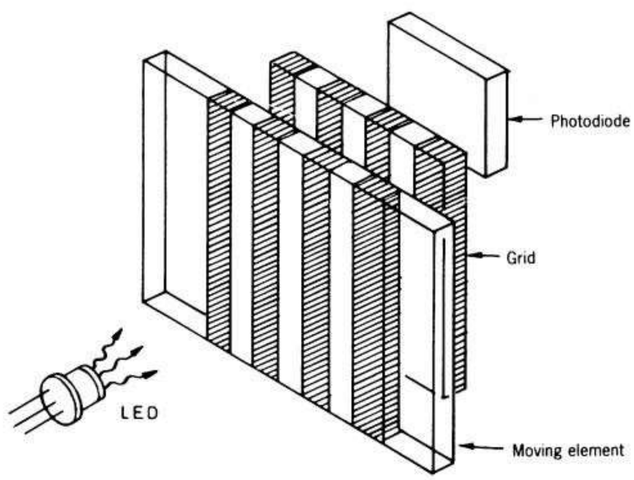


Figure 8.6 Use of a fixed grid to limit the field for a photodetector, thus increasing its resolution (courtesy of TRW Electronics Components Group).

encoded element (Figure 8.6).

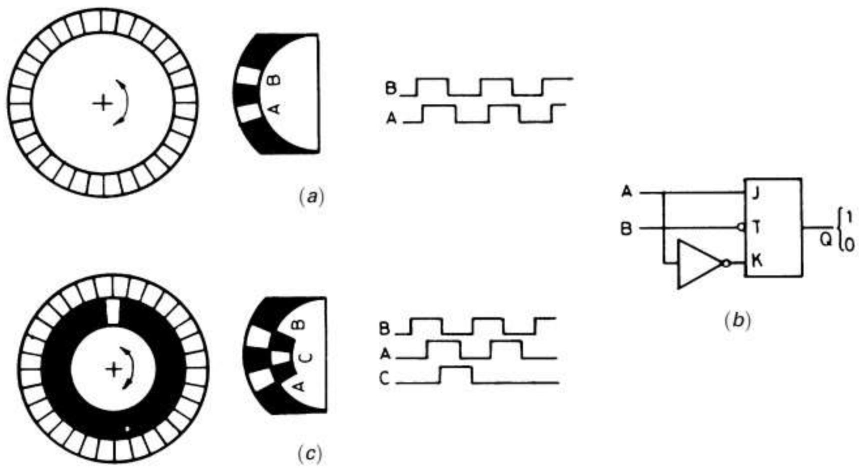


Figure 8.7 Detection of movement direction in incremental encoders. (*a*) By means of two outputs with 90° phase shift. (*b*) Output electronic circuit. (*c*) Additional marker for absolute positioning.

4.1.2 ABSOLUTE POSITION ENCODERS

Absolute position encoders yield a unique digital output corresponding to each resolvable position of a movable element, rule, or disk, with respect to an internal reference. The movable element is formed by regions having a distinguishing property, and designated with the binary values 0 or 1. But unlike incremental encoders, their tracks are so arranged that the reading system directly yields the coded number corresponding to each position (Figure 8.11). Each track corresponds to an output bit, with the innermost track yielding the most significant bit. The most common sensors for these encoders are optical sensors.

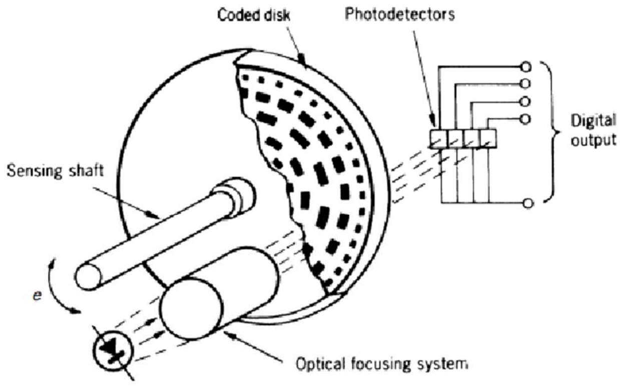


Figure 8.11 Principle of absolute position encoders for linear and rotary movements.

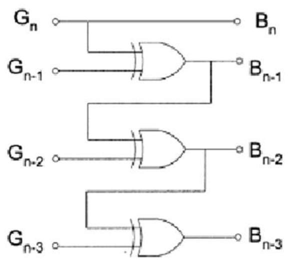


Figure 8.12 Gray-to-binary code converter.

Figure 8.12 shows the corresponding circuit. The Gray code does not permit error correction for example, when transmitting signals in a noisy environment.

Common applications for absolute position encoders are high-resolution measurement and control of linear and angular positions.

They suit applications involving slow movements or where the movable element remains inactive for long time periods, such as parabolic antennas.

They are used, for example, in robotics, plotters, machine tools, read head positioning in magnetic storage disks, radiation source positioning in radiotherapy, radar, telescope orientation, overhead cranes, and valve control.

They can also sense any quantity that we convert to a displacement by means of an appropriate primary sensor for example, in liquid level measurements using a float.

4.2 RESONANT SENSORS

Sensors based on a resonant physical phenomenon yield an output frequency that depends on a measurand (measured quantity) affecting the oscillation frequency. They require a frequency-counter in order to measure either the frequency or the oscillation period based on an accurate and stable clock. Resonant structures of single-crystal silicon are particularly suited to IC integration.

Sensors use either harmonic oscillators or relaxation oscillators.

Harmonic oscillators store energy that changes from one form of storage to another, for example from kinetic energy in a moving mass to potential energy in a stressed spring.

In relaxation oscillators there is a single energy storage form, and the stored energy is periodically dissipated through some reset mechanism.

Quartz clocks are accurate enough to derive a time base for most sensor applications, but they drift with time and temperature.

Time drifts arise from structural changes due to defects in crystal lattices, mechanical stress from supporting elements (that decrease as time passes and change after thermal cycling), and mass changes because of absorption and desorption of contaminant gases inside the crystal package.

4.3 SENSORS BASED ON QUARTZ RESONATORS

Quartz is piezoelectric and therefore an applied voltage stresses the crystal. If the voltage alternates at a proper rate, the crystal begins vibrating and yields a steady signal. C0 is the electrostatic capacitance of the crystal between the electrodes plus the holder and the leads.

$$f_s = \frac{1}{2\pi\sqrt{L_1 C_1}}$$

As the frequency increases, the crystal behaves as a positive reactance in series with a resistance. At the anti-resonant-frequency fa, the crystal's reactance is maximal. The range from fs to fa is referred to as the crystal's bandwidth. The series resonant circuit (Figure 8.17a) operates above fs, where the reactance is slightly inductive. Series capacitance is then added to tune the circuit. Figure 8.17b shows a basic oscillator based on CMOS inverters. Because quartz is inert, using a high-purity single crystal yields a mechanical resonance with large long-term stability.

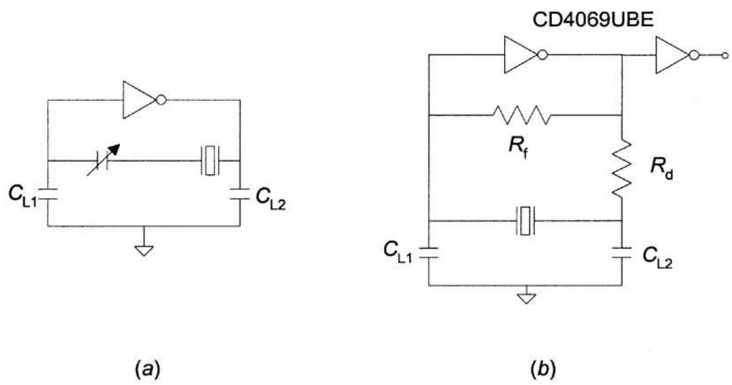


Figure 8.17 (*a*) Series resonator oscillator based on a quartz crystal. (*b*) Crystal (series) oscillator based on CMOS inverters.

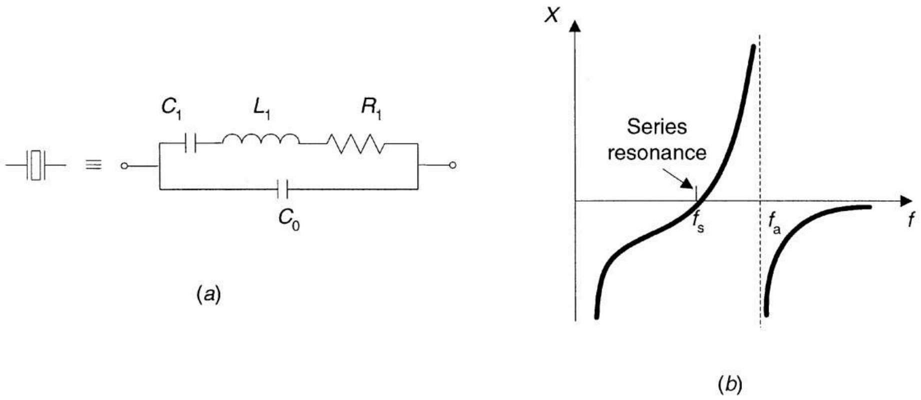


Figure 8.16 (*a*) High-frequency equivalent circuit for a piezoelectric material such as quartz with metal electrodes deposited on two faces. (*b*) The reactance of a quartz crystal varies with the operating frequency near resonance.

DIGITAL QUARTZ THERMOMETER

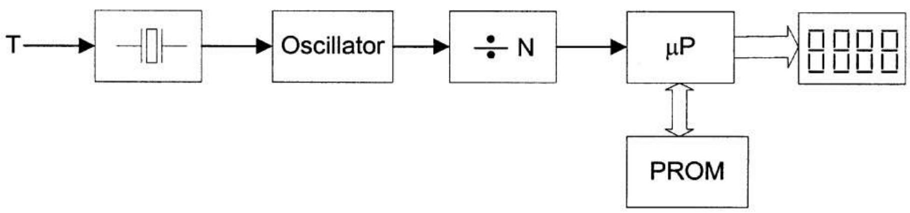


Figure 8.18 Simplified diagram for a quartz digital thermometer.

The values for the elements in the equivalent circuit for a quartz crystal depend on the temperature, and therefore the oscillation frequency displays a thermal drift. If precision-cut quartz crystals are used, the relationship between temperature and frequency is very stable and repeatable.

QUARTZ MICROBALANCE

A quartz microbalance estimates a mass per unit area by measuring the change in resonance frequency. Open quartz microbalance can be used in liquid or air for biological or chemical sensing.

Quartz crystals oscillators are widely used as thin-film thickness monitors to control deposition rates and measurement of coating film thickness in the semiconductor and optical industries. They on a sensor function that considers the influence of the different acoustic impedances of the deposition materials upon the resonant frequency.

QUARTZ RESONATORS FOR FORCE AND PRESSURE SENSING

Quartz crystals, the same as other single-crystal materials, have highly stable elastic properties with very low creep and hysteresis. Hence, they suit mechanical resonators whose resonance frequency depends on the applied stress.

Quartz has the added advantage of being piezoelectric, so that the vibration can be excited by a driving alternating voltage.

Figure 8.19b shows a sensor for tensile and compressive force based on a single quartz beam.

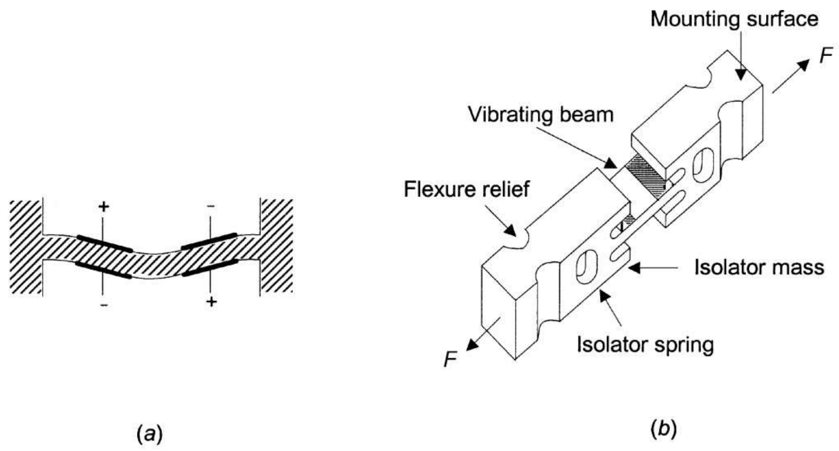


Figure 8.19 (*a*) Voltage applied to surface electrodes creates an electric field that flexes a quartz beam. (*b*) Force sensor based on a quartz vibrating beam with electrodes on both surfaces.

QUARTZ ANGULAR RATE SENSORS

A vibrating quartz tuning fork can sense angular velocity because of the Coriolis effect. The sensor typically consists of a double-ended quartz tuning fork micromachined from a single quartz crystal (Figure 8.20) rotating at the angular velocity to measure, Ω. An oscillator at precise amplitude excites the drive tines so that they move toward and away from one another at a high frequency. Because of the Coriolis effect, there is a force acting on each tine,

$$\boldsymbol{F} = 2m\boldsymbol{\Omega} \times \boldsymbol{v}_r$$

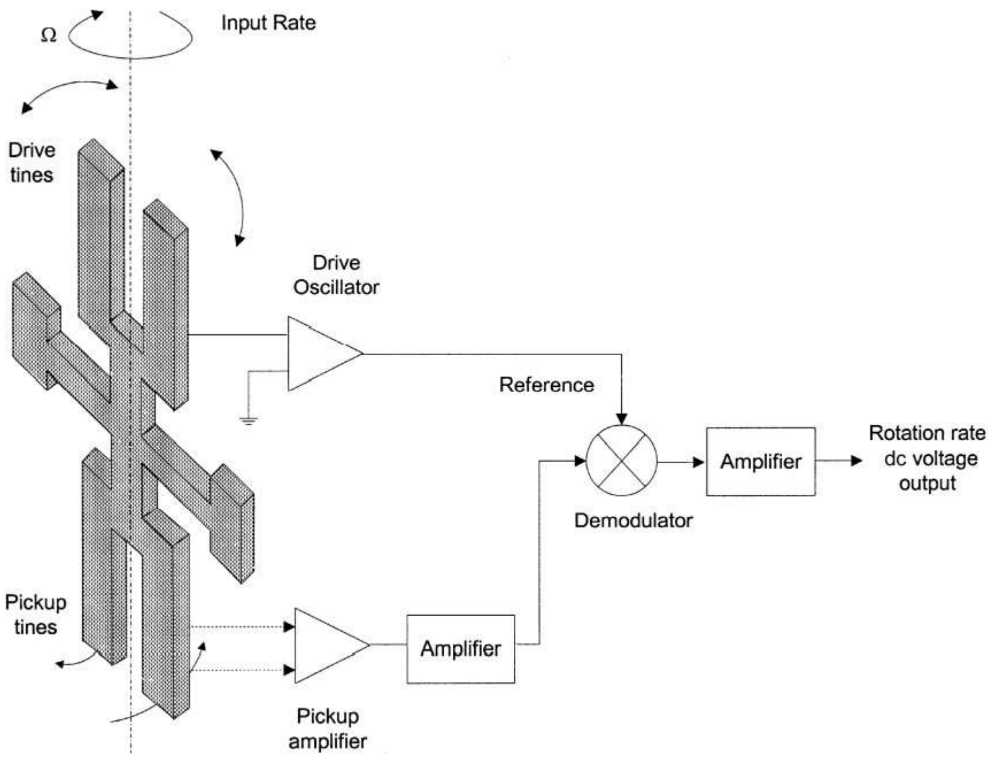


Figure 8.20 Angular rate sensor based on the Coriolis effect on a micromachined quartz tuning fork (courtesy of BEI Sensors and Systems).

where m is the tine mass and v_r is its instantaneous radial velocity.

Quartz angular rate sensors replace spinning-wheel gyroscopes because of their lower cost, increased reliability (there are no moving mechanical parts), and light weight.

It has been used to control angular velocity in aircraft, robots, and hydraulic equipment, to instrument automobile motions during crash tests, to evaluate rider quality in high-speed trains, to navigate autonomous underwater vehicles, to stabilize infrared cameras on helicopters, and in other applications.

4.4 SAW SENSORS

Just like an earthquake, Surface acoustic Wave or SAW is simply a mechanical wave confines to a solid interface. But these waves can exist at much smaller scales and can be used for a wide variety of applications.

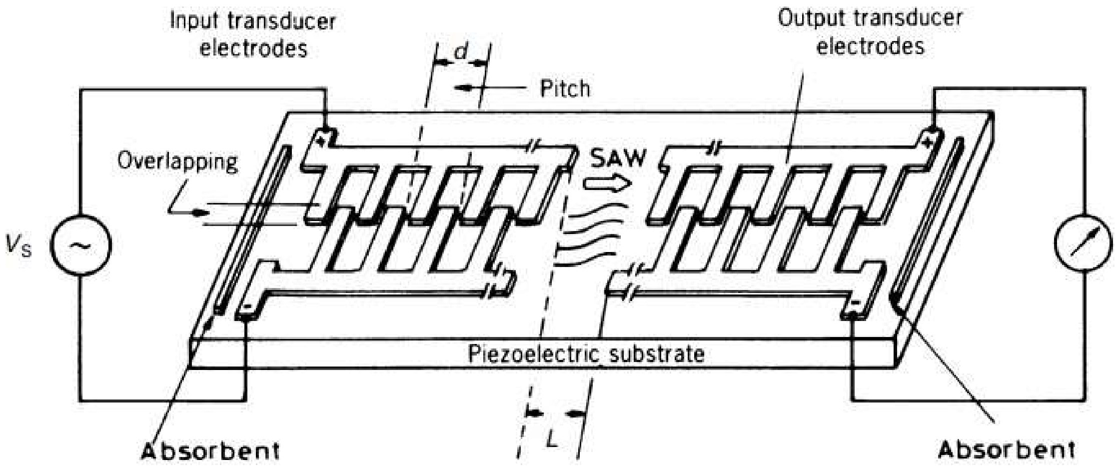


Figure 8.21 Principle of surface acoustic wave (SAW) filters.

To generate SAW, we deposit metal onto a piezoelectric substrate and apply a voltage. This process can be reversed. An incoming wave will be picked up by the metal and create a measurable voltage.

The preferred piezoelectric materials for SAW sensors are quartz and LiNdO3.

Suppose a light bulb is connected to the output transducer. When SAW is picked up by the metal electrodes, it generates a measurable voltage and the bulb lights up. The glowing bulb shows output voltage at the transducer and only lights up when SAW is present.

The energy carried by the wave changes if it encounters a gas in it's path. Different gasses will have different effect it shows in the light bulb. So, it's possible to know which gas has interacted with SAW by looking at the bulb.

SAW is used in smart phones, mobile communications, radio frequency filters and radar because of their simple design.

4.5 VIBRATING WIRE STRAIN GAGES

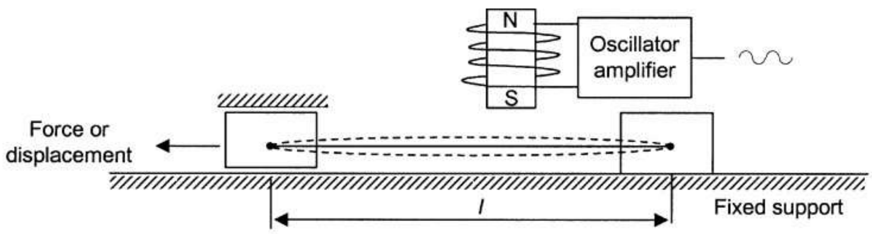


Figure 8.23 Vibrating wire gage. The transverse vibration is excited by a current pulse applied to the coil, which then is used to detect the vibration frequency.

$$f = \frac{1}{2l}\sqrt{\frac{F}{\mu}} \tag{8.12}$$

The lower transverse oscillation frequency for a vibrating taut (stretched, pulled or tight) string or wire of length l is where F is the mechanical force applied to it and μ is the longitudinal mass density (mass/length). If the position of one of the ends changes because it is mounted on a movable support, then the oscillation period is directly proportional to the displacement. If a force is applied, the resulting oscillation frequency is directly proportional. For strain measurement,

$$\varepsilon = \frac{4l^2\mu}{EA} f^2$$

where E is Young's modulus and A is the wire's cross section.

This principle can sense any physical quantity resulting in a change in l, F, or m. A common application is strain or tension measurement [13]. In contrast with resistive strain gages, vibrating-wire strain gages can detect non-plane de-formation. In addition, they are insensitive to resistance changes in connecting wires for example, those due to temperature. Temperature interferes because it affects the sensing wire length l. In order to compensate for temperature, we can measure the change in resistance of the driving coil wire, as in RTDs.

Other reported applications are the measurement of mass, displacement, pressure (using a diaphragm with an attached magnet as primary sensor), force and weight (using a cantilever as primary sensor).

Vibrating strips are used for dust deposition measurement of exhaust gases and also to measure viscosity.

4.6 VIBRATING CYLINDER SENSORS

If instead of a vibrating wire or strip we use a thin (75 mm)-walled cylinder with a closed end, the oscillation frequency depends on the dimensions and

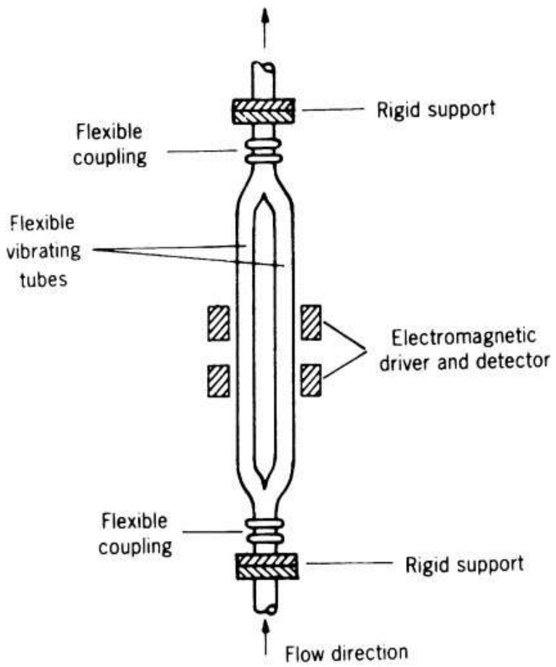


Figure 8.24 Vibrating tube method to measure liquid density.

material for the cylinder and on any mass vibrating together with its walls.

By using an electromagnetic driver as in the previous case in order to keep the system oscillating, it is possible to measure the difference in pressure between both cylinder sides because it results in mechanical stresses in its walls.

We can also apply this system to gas density measurement because the gas near the walls vibrates when the walls do. For corrosive liquids it is better to use a glass or ceramic cylinder and a piezoelectric driver, thus avoiding corrosive-prone elements in electromagnetic drivers.

The most common application for this measurement principle is the measurement of the density of flowing liquids, using an arrangement like that in Figure 8.24. It consists of two parallel conduits through which the liquid flows; the two tubes are clamped at their ends and coupled to the main conduit by a flexible joint. Because the volume is known and the oscillation frequency for both conduits, which behave as a tuning fork.

$$f = \frac{f_0}{\sqrt{1 + \frac{\rho}{\rho_0}}}$$

where f_0 is the conduit oscillation frequency when there is no liquid, and ρ_0 is a constant that depends on system geometry.

4.7 DIGITAL FLOW METER

4.7.1 VORTEX SHEDDING FLOWMETERS

When a fluid stream enters a pipe with a conduit or bluff body, the bluff body separates the obstruction and move around the obstructing body or bluff body in a vortex shedding flowmeter. Flow path is obstructed by bluff body that creates vortex swirls. The bluff body occupies less than 20% of inside diameter of the pipe.

The rate of vortex shedding is detected by an ultrasonic sensor that monitors change in vortex patterns by transmitting pulsating output signal.

This method is fairly accurate (about 0.5 %) and independent of fluid viscosity, density, pressure, and temperature. It is particularly indicated for flow measurements at high temperature and high pressure. Its main shortcomings are that it introduces a large drop in pressure and that it is unsuitable for dirty, abrasive, or corroding fluids.

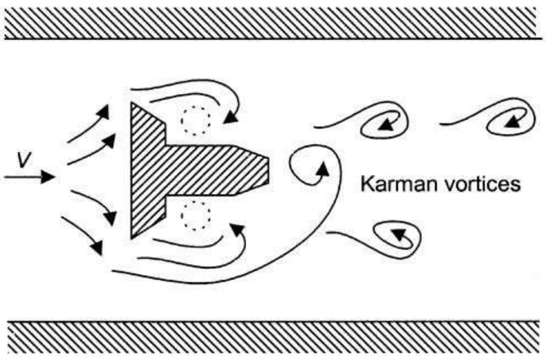
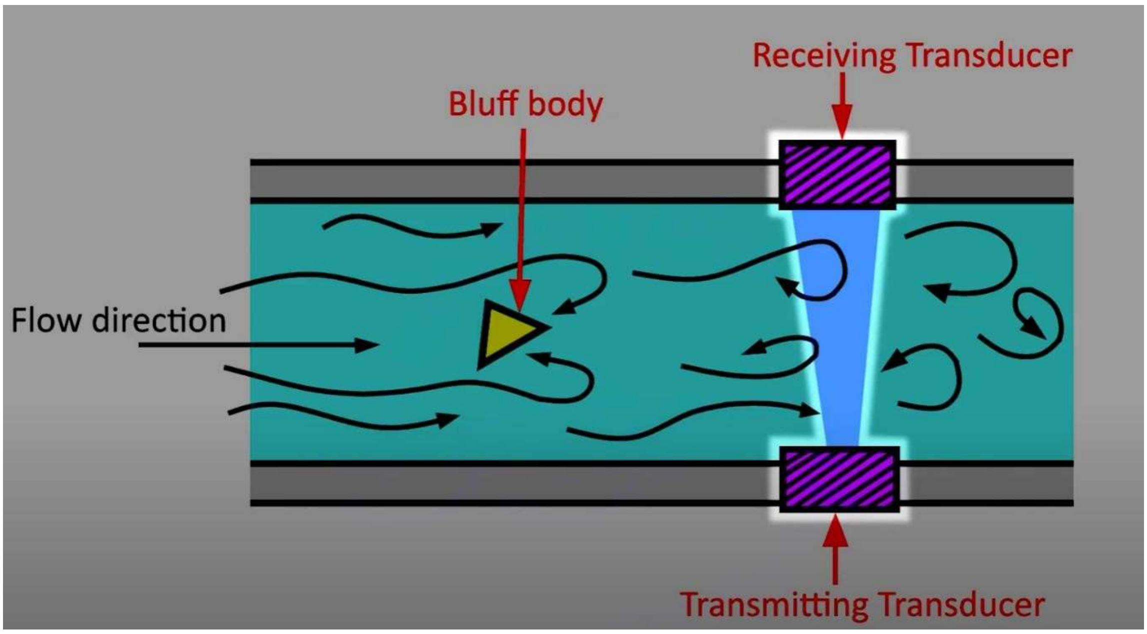


Figure 8.25 A blunt object inside a fluid stream produces downstream vortices whose frequency is proportional to flow velocity.



4.7.2 CORIOLIS EFFECT MASS FLOWMETERS

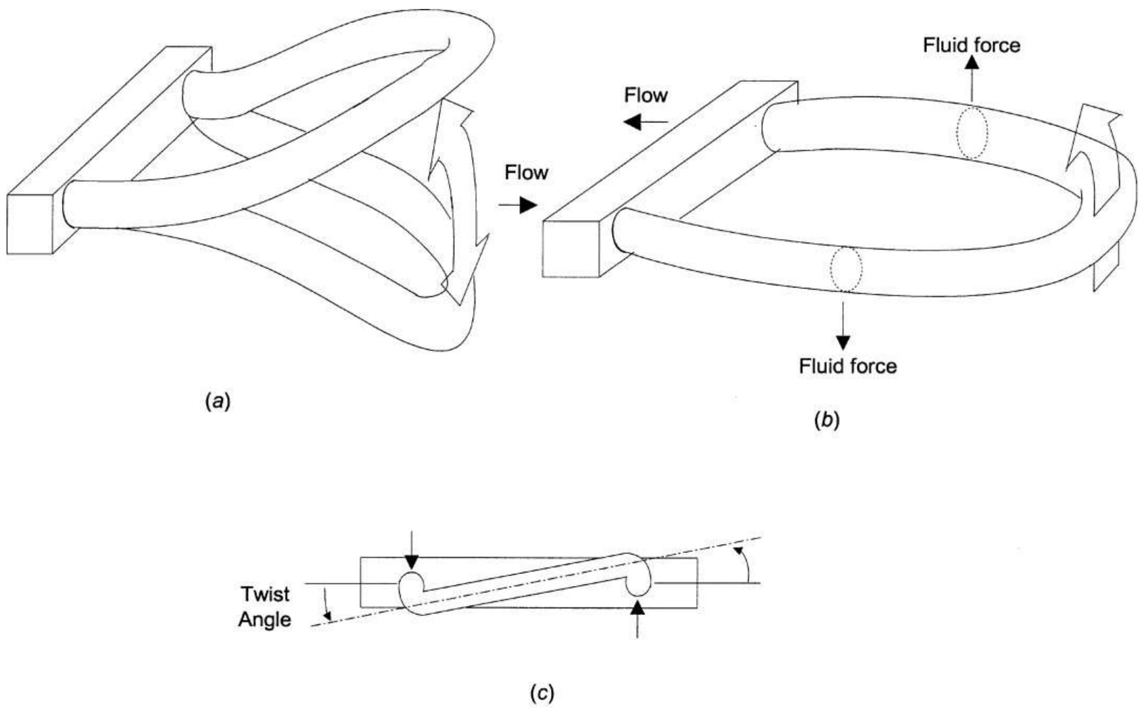


Figure 8.26 (*a*) Coriolis flowmeter based on a vibrating U tube. (*b*) When the tube moves upward, the fluid exerts a downward force at the inlet and an upward force at the outlet that results in (*c*) a tube twist.

A common type of mass flowmeter relies on the Coriolis effect on a U-shaped flow tube (Figure 8.26) vibrated at its natural frequency (about 80 Hz) by an electromagnetic device located at the bend of the tube.

As the liquid flows into the tube, the Coriolis force it experiences because of the vertical movements of the tube has opposite sign to that experienced when it leaves the tube because opposite velocities yield opposite forces. That is, when the liquid enters the tube, it resists being moved upward (or downward) and reacts by pushing down (vise versa); when the fluid leaves the tube after having been forced upward (or downward), it resists having its vertical movement decreased and pushes up (respectively, down). The result is a tube twisting whose amplitude is proportional to the liquid mass flow rate.

Coriolis flowmeters measure mass directly, not through volume or velocity, and can measure corrosive fluids and difficult fluids such as slurries, mud, and mixtures.

They are not affected by changes in fluid pressure, density, temperature, or viscosity and can achieve an uncertainty of about 0.3 %. However, they are not useful for low-pressure gas because of the low forces they develop.

4.7.3 TURBINE FLOWMETERS

A turbine flowmeter consists of two components; mechanical component and an electronic component.

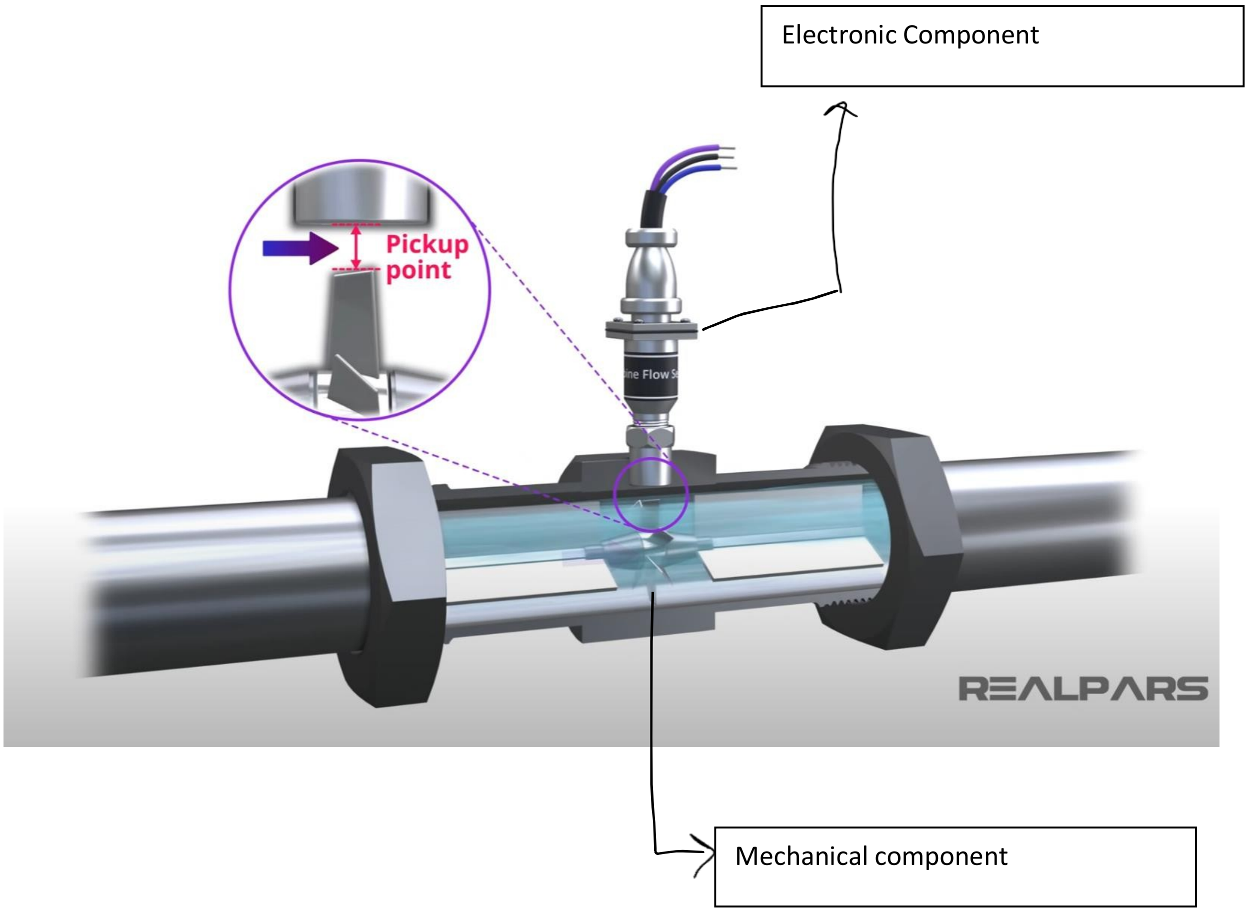
A turbine Flowmeter is inserted in a pipe directly in the flow path. The mechanical part of the Turbine flowmeter has a turbine rotor placed in the path of the flowing stream. The only moving part in the Turbine Flowmeter is the mechanical rotor.

The rotational speed of the rotor depends on the flow velocity. As the rotor spins, the passage of each rotor blade past a pickup point will generate an electrical pulse. The electrical pulses are created in different ways depending upon the rotor blades themselves and the pickup unit characteristics.

In most turbine flowmeters, magnets are fitted to the rotor blades, and a magnetic pickup sensor is used to create the pulses. The higher the rate of flow the faster the rotor turns, and the greater the no. of pulses. The total number of pulses in a given time interval is proportional to the total volume displaced.

The shape and the voltage of the generated pulses depends on the type of pickup unit used.

Turbine flowmeters are used, for example, for fuel flow measurement in aircraft, in water service monitoring, and in monitoring spirometers.


Electronic Component
Pickup
point
REALPARS
Mechanical component