Position, Displacement, and Level

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• The measurement of position and displacement of physical objects is essential for many applications: process feedback control, performance evaluation, transportation traffic control, robotics, and security systems—just to name the few.

• By *position*, we mean the determination of the object’s coordinates (linear or angular) with respect to a selected reference.

• *Displacement* means moving from one position to another for a specific distance or angle. In other words, a displacement is measured when an object is referenced to its own prior position rather than to another reference.
• A critical distance is measured by *proximity sensors*. In effect, a proximity sensor is a threshold version of a position detector.

• A position sensor is often a linear device whose output signal represents a distance to the object from a certain reference point.

• A proximity sensor, however, is a somewhat simpler device which generates the output signal when a certain distance to the object becomes essential for an indication.
• A displacement sensor often is part of a more complex sensor where the detection of movement is one of several steps in a signal conversion.

• An example is a pressure sensor where pressure is translated into a displacement of a diaphragm, and the diaphragm displacement is subsequently converted into an electrical signal representing pressure.
When designing or selecting position and displacement detectors, the following questions should be answered:

1. How large is the displacement and of what type (linear, circular)?
2. What resolution and accuracy are required?
3. What is the measured object made of (metal, plastic, fluid, ferromagnetic, etc.)?
4. How much space is available for mounting the detector?
5. How much play is there in the moving assembly and what is the required detection range?
6. What are the environmental conditions (humidity, temperature, sources of interference, vibration, corrosive materials, etc.)?
7. How much power is available for the sensor?
8. How much mechanical wear can be expected over the lifetime of the machine?
9. What is the production quantity of the sensing assembly (limited number, medium volume, mass production)?
10. What is the target cost of the detecting assembly?
Terminology

• **Output (or Output Range)**

  Output describes the type and range of the sensor’s output which will be used to determine the measured dimension. Typical outputs are: 0–10 VDC, ±10 VDC, 4–20 mA, and 0–20 mA. The output indicates the total change of the output as the target moves through the total range. (Proximity switch sensors only have on/off switched outputs).
• **Range (or Measurement Range)**

• *Range* is simply the operating range of the sensor. Sometimes the sensor’s range is plainly stated as a range such as 2 mm–3 mm. This indicates that the sensor can measure the position of the target when its distance from the face of the probe is between 2 mm and 3 mm.

![Diagram of sensors and target](image)

*Figure 8.5.1: How the “Output” and “Range” of a sensor relate to target position.*
• **Offset or Standoff**

  *Offset or Standoff* indicates where the active range is located relative to the probe’s face. The range example above of 2 mm–3 mm may be listed as having a range of 1mm and an offset of 2 mm. This is typical for sensors with a single polarity output such as 0–10 VDC.

  *Some manufacturers may take a bipolar approach and define this same sensor as having a 2.5 mm standoff with a ±0.5 mm range. This is commonly used for sensors that have a bipolar output such as ±10 VDC.*
Figure 8.5.2: Some ranges are defined with an "offset" value.

Figure 8.5.3: Some ranges are defined with a "standoff" value.
• **Sensitivity**

• **Sensitivity** indicates how much the driver output changes as a result of a change in the gap between the target and the probe. If the sensitivity were 0.1 mm/1 V then for every 0.1 mm of change in the gap, the output voltage will change 1 V. When the output voltage is plotted against the gap size, the slope of the line is the sensitivity.
• **Linearity**

  This specification applies only to linear output type sensors, although it may be given occasionally for analog output sensors. This is a measure of how *straight the line is* when the target position is plotted against the driver’s output. It describes how far the actual output varies from a perfect straight line drawn through the points, typically using a least squares fit calculation. It is usually given as a percent of full scale.

  Linearity is important for precise measurements throughout the active range of the sensor. Linearity is only a measure of the straightness of the sensor’s output. It is a major contributor to the accuracy of the sensor but it is not equivalent to accuracy. A sensor may be very linear, but be very inaccurate due to gross sensitivity errors, but a nonlinear sensor’s accuracy will always be limited by the nonlinearity.
• **Bandwidth (Frequency Response)**

• When measuring a vibrating target the output is frequency dependent. As the frequency of the vibration increases, at some frequency the output begins to decrease due to frequency limitations within the driver electronics. Bandwidth usually specifies the frequency at which the output falls to –3 dB—approximately 70 percent; for example, 1 mm of vibration at the bandwidth frequency would appear as 0.7 mm at the output.
• **Resolution**

  *Resolution* is defined as the smallest reliable measurement that a system can make. The resolution of a measurement system must be smaller than the smallest measurement the sensor will be required to make.

  The primary determining factor of resolution is electrical noise. Electrical noise appears in the output causing small instantaneous errors in the output. Even when the probe/target gap is perfectly constant, the output of the driver has some small but measurable amount of noise that would seem to indicate that the gap is changing. This noise is inherent in electronic components and can be minimized, but not eliminated.

  Resolution is bandwidth dependent. Lower bandwidth means less electrical noise and therefore smaller resolution.
• **Thermal Errors**
  
  • All things electronic have the possibility of changing with temperature. In addition to electronic drift, physical changes in probes due to expansion and contraction can create output change that is related to temperature.
  
  • Many of today’s sensors are well designed to minimize and/or compensate for thermal errors but they are always present to some extent.
  
  • Specifications may include thermal information listed as *temperature coefficient* or *thermal drift*. These specifications normally indicate the amount of change in the output per degree of temperature change.
Limit Switches

Figure 15.1.1: Limit switches on a conveyor.

Figure 15.1.3: Operating characteristics for limit switches with in-line plunger actuators.
Potentiometric Sensors

• A position or displacement transducer may be built with a linear or rotary *potentiometer* or a *pot* for short. The operating principle of this sensor is based *on* wire resistance.

• Because a resistance measurement requires passage of an electric current through the pot wire, the potentiometric transducer is of an active type; that is, it requires an excitation signal, (e.g., dc current).
• The voltage across the wiper of a linear pot is proportional to the displacement $d$:

$$V = E \frac{d}{D},$$

Fig. 7.1. (A) Potentiometer as a position sensor; (B) gravitational fluid level sensor with a float; (C) linear potentiometer. (Courtesy of Piher Group, Tudela, Spain.)
Figure 7.2A shows one problem associated with a wire-wound potentiometer. The wiper may, while moving across the winding, make contact with either one or two wires, thus resulting in uneven voltage steps (Fig. 7.2B) or a variable resolution. Therefore, when the coil potentiometer with $N$ turns is used, only the average resolution $n$ should be considered:

$$\quad n = \frac{100}{N\%}.$$
Fig. 7.2. Uncertainty caused by a wire-wound potentiometer: (A) a wiper may contact one or two wires at a time; (B) uneven voltage steps.
• Although quite useful in some applications, potentiometers have several drawbacks:
  • 1. Noticeable mechanical load (friction)
  • 2. Need for a physical coupling with the object
  • 3. Low speed
  • 4. Friction and excitation voltage cause heating of the potentiometer
  • 5. Low environmental stability
<table>
<thead>
<tr>
<th></th>
<th>Conductive plastic</th>
<th>Wirewound</th>
<th>Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>Infinitesimal</td>
<td>Quantized</td>
<td>Infinitesimal</td>
</tr>
<tr>
<td>Power rating</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Temperature stability</td>
<td>Poor</td>
<td>Excellent</td>
<td>Very good</td>
</tr>
<tr>
<td>Noise</td>
<td>Very low</td>
<td>Low, but degrades with time</td>
<td>Low</td>
</tr>
<tr>
<td>Life</td>
<td>$10^6$–$10^8$ cycles</td>
<td>$10^5$–$10^6$ cycles</td>
<td>$10^6$–$10^7$ cycles</td>
</tr>
</tbody>
</table>
FIGURE 6.6 Mechanisms that extend a precision potentiometer’s capabilities include belts and pulleys (a), rack-and-pinion (b), lead-screws (c), cabled drums (d), cams (e), bevel gears (f), and spur gears (g).
Gravitational Sensors

• The transducer’s main element is a float—a device whose density is lower than that of water. In most tanks, it is directly coupled to a water valve to keep it either open or shut, depending on how much water the tank holds.
• The float is a detector of the position of the water surface. For the measurement purposes, the float can be coupled to a position transducer, such as a potentiometric, magnetic, capacitive, or any other direct sensor (Fig. 7.1B).
• It should be noted that the gravitational sensor is susceptible to various interfering forces, resulting from friction and acceleration.
• Obviously, such a sensor will not work whenever gravity is altered or absent. A space station or a jet is not an appropriate place for such a sensor.
• *Inclination detectors,* which measure the angle from the direction to the Earth’s center of gravity, are employed in road construction, machine tools, inertial navigation systems, and other applications requiring a gravity reference.

• An old and still quite popular detector of a position is a mercury switch (Figs. 7.3A and 7.3B). The switch is made of a nonconductive (often glass) tube having two electrical contacts and a drop of mercury.

• When the sensor is positioned with respect to the gravity force in such a way that the mercury moves away from the contacts, the switch is open.

• A change in the switch orientation causes the mercury to move to the contacts and touch both of them, thus closing the switch.
Fig. 7.3. Conductive gravitational sensors: (A) mercury switch in the open position; (B) mercury switch in the closed position; (C) electrolytic tilt sensor.
Fig. 7.4. Optoelectronic inclination sensor: (A) design; (B) a shadow at a horizontal position; (C) a shadow at the inclined position.
Capacitive Sensors

Fig. 7.5. Operating principle of a flat plate capacitive sensor A-balanced position; B-disbalanced position
• Now, let us assume that the central plate moves downward by a distance \( x \) (Fig. 7.5B). This results in changes in the respective capacitance values:

\[
C_1 = \frac{\varepsilon A}{x_0 + x} \quad \text{and} \quad C_2 = \frac{\varepsilon A}{x_0 - x},
\]

\[
V_{\text{out}} = V_0 \left( -\frac{x}{x_0 + x} + \frac{\Delta C}{C} \right).
\]
Fig. 7.6. A capacitive probe with a guard ring: (A) cross-sectional view; (B) outside view. (Courtesy of ADE Technologies, Inc., Newton, MA.)
Fig. 7.7. Driven shield around the electrode in a capacitive proximity sensor.
Fig. 7.8. Parallel-plate capacitive bridge sensor: (A) plate arrangement, (B) equivalent circuit diagram.

\[ C_1 = \frac{\varepsilon_0 b}{d} \left( \frac{L}{2} + x \right). \]
Table 15.1.3: Dielectric constants for different targets

<table>
<thead>
<tr>
<th>Material</th>
<th>Dielectric Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetone</td>
<td>19.5</td>
</tr>
<tr>
<td>Acrylic Resin</td>
<td>2.7–4.5</td>
</tr>
<tr>
<td>Air</td>
<td>1.000264</td>
</tr>
<tr>
<td>Ammonia</td>
<td>15–25</td>
</tr>
<tr>
<td>Aniline</td>
<td>6.9</td>
</tr>
<tr>
<td>Aqueous Solutions</td>
<td>50–80</td>
</tr>
<tr>
<td>Benzene</td>
<td>2.3</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>1.000–0.85</td>
</tr>
<tr>
<td>Carbon Tetrachloride</td>
<td>2.2</td>
</tr>
<tr>
<td>Cement Powder</td>
<td>4</td>
</tr>
<tr>
<td>Cereal</td>
<td>3–5</td>
</tr>
<tr>
<td>Chlorine Liquid</td>
<td>2.0</td>
</tr>
<tr>
<td>Ebonite</td>
<td>2.7–2.9</td>
</tr>
<tr>
<td>Epoxy Resin</td>
<td>2.5–6</td>
</tr>
<tr>
<td>Ethanol</td>
<td>24</td>
</tr>
<tr>
<td>Ethylene Glycol</td>
<td>38.7</td>
</tr>
<tr>
<td>Fired Ash</td>
<td>1.5–1.7</td>
</tr>
<tr>
<td>Flour</td>
<td>2.5–3.0</td>
</tr>
<tr>
<td>Freon R22 &amp; 502 (liquid)</td>
<td>6.11</td>
</tr>
<tr>
<td>Gasoline</td>
<td>2.2</td>
</tr>
<tr>
<td>Glass</td>
<td>3.7–10</td>
</tr>
<tr>
<td>Glycerin</td>
<td>47</td>
</tr>
<tr>
<td>Marble</td>
<td>8.5</td>
</tr>
<tr>
<td>Melamine Resin</td>
<td>4.7–10.2</td>
</tr>
<tr>
<td>Mica</td>
<td>5.7–6.7</td>
</tr>
<tr>
<td>Nitrobenzene</td>
<td>96</td>
</tr>
<tr>
<td>Nylon</td>
<td>4.5</td>
</tr>
<tr>
<td>Paper</td>
<td>1.6–2.6</td>
</tr>
<tr>
<td>Paraffin</td>
<td>1.9–2.5</td>
</tr>
<tr>
<td>Perspex</td>
<td>3.5</td>
</tr>
<tr>
<td>Petroleum</td>
<td>2.0–2.2</td>
</tr>
<tr>
<td>Phenol Resin</td>
<td>4–12</td>
</tr>
<tr>
<td>Polyacetal</td>
<td>3.6–3.7</td>
</tr>
<tr>
<td>Polyester Resin</td>
<td>2.8–8.1</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>2.0–2.2</td>
</tr>
<tr>
<td>Polyvinyl Chloride Resin</td>
<td>2.8–3.1</td>
</tr>
<tr>
<td>Porcelain</td>
<td>5.7</td>
</tr>
<tr>
<td>Powdered Milk</td>
<td>3.5–4</td>
</tr>
<tr>
<td>Press board</td>
<td>2.5</td>
</tr>
<tr>
<td>Rubber</td>
<td>2.5–35</td>
</tr>
<tr>
<td>Salt</td>
<td>6</td>
</tr>
<tr>
<td>Sand</td>
<td>3.5</td>
</tr>
<tr>
<td>Shellac</td>
<td>2.5–4.7</td>
</tr>
<tr>
<td>Shell Lime</td>
<td>1.2</td>
</tr>
<tr>
<td>Silicon Varnish</td>
<td>2.8–3.3</td>
</tr>
<tr>
<td>Soybean Oil</td>
<td>2.9–3.5</td>
</tr>
<tr>
<td>Styrene Resin</td>
<td>2.3–3.4</td>
</tr>
<tr>
<td>Sugar</td>
<td>3.0</td>
</tr>
<tr>
<td>Sulphur</td>
<td>3.4</td>
</tr>
<tr>
<td>Tetraflouroethylene Resin</td>
<td>2.0</td>
</tr>
<tr>
<td>Toluene</td>
<td>2.3</td>
</tr>
<tr>
<td>Turpentine</td>
<td>2.2</td>
</tr>
<tr>
<td>Urea Resin</td>
<td>5.8</td>
</tr>
<tr>
<td>Vaseline</td>
<td>2.2–2.9</td>
</tr>
<tr>
<td>Water</td>
<td>80</td>
</tr>
<tr>
<td>Wood Dry</td>
<td>2–6</td>
</tr>
<tr>
<td>Wood Wet</td>
<td>10–30</td>
</tr>
</tbody>
</table>
Inductive and Magnetic Sensors

- One of many advantages of using magnetic field for sensing position and distance is that any nonmagnetic material can be penetrated by the field with no loss of position accuracy. Stainless steel, aluminum, brass, copper, plastics, masonry, and woods can be penetrated, meaning that the accurate position with respect to the probe at the opposite side of a wall can be determined almost instantly.

- Another advantage is the magnetic sensors can work in severe environments and corrosive situations because the probes and targets can be coated with inert materials that will not adversely affect the magnetic fields.
Fig. 7.9. Circuit diagram of the LVDT sensor.
Fig. 7.10. A simplified circuit diagram of an interface for an LVDT sensor.
Advantages of the LVDT and RVDT are the following:

1. The sensor is a noncontact device with no or very little friction resistance with small resistive forces;
2. Hystereses (magnetic and mechanical) are negligible;
3. Output impedance is very low;
4. There is low susceptibility to noise and interferences;
5. Its construction is solid and robust,
6. Infinitesimal resolution is possible.
Eddy (circular) currents produce a magnetic field which opposes that of the sensing coil, thus resulting in a disbalance with respect to the reference coil. The closer the object to the coil, the larger the change in the magnetic impedance. The depth of the object where eddy currents are produced is defined by

\[ \delta = \frac{1}{\sqrt{\pi f \mu \sigma}}, \]

where \( f \) is the frequency and \( \sigma \) is the target conductivity.
• One important advantage of the eddy current sensors is that they do not need magnetic material for the operation, thus they can be quite effective at high temperatures (well exceeding the Curie temperature of a magnetic material) and for measuring the distance to or level of conductive liquids, including molten metals.

• Another advantage of the detectors is that they are not mechanically coupled to the object and, thus, the loading effect is very low.
Another position-sensing device is called a \textit{transverse inductive proximity sensor}. It is useful for sensing relatively small displacements of ferromagnetic materials. As the name implies, the sensor measures the distance to an object which alters the magnetic field in the coil.
The advantage of the sensor is that it is a noncontact device whose interaction with the object is only through the magnetic field.

An obvious limitation is that it is useful only for the ferromagnetic objects at relatively short distances.
Fig. 7.13. Transverse sensor with an auxiliary ferromagnetic disk (A) and the output signal as function of distance (B).
Fig. 7.14. Circuit diagrams of a linear (A) and a threshold (B) Hall effect sensor.
During recent years, Hall effect sensors became increasingly popular. There are two types of Hall sensors: linear and threshold (Fig. 7.14).

![Graphs showing the transfer functions of a linear and a threshold Hall effect sensor.](image)

**Fig. 7.15.** Transfer functions of a linear (A) and a threshold (B) Hall effect sensor.
Fig. 7.16. The Hall effect sensor in the interrupter switching mode: (A) the magnetic flux turns the sensor on; (B) the magnetic flux is shunted by a vane. (After Ref. [6].)
• **Magnetoresistive Sensors**

• These sensors are similar in application to the Hall effect sensors.

• For functioning, they require an external magnetic field. Hence, whenever the magnetoresistive sensor is used as a proximity, position, or rotation detector, it must be combined with a source of a magnetic field.

• Usually, the field is originated in a permanent magnet which is attached to the sensor. Figure 7.19 shows a simple arrangement for using a sensor–permanent-magnet combination to measure linear displacement.
Fig. 7.19. Magnetoresistive sensor output in the field of a permanent magnet as a function of its displacement \( x \) parallel to the magnetic axis (A–C). The magnet provides both the axillary and transverse fields. Reversal of the sensor relative to the magnet will reverse the characteristic. (D and E) Sensor output with a too strong magnetic field.
Fig. 7.21. Angular measurement with the KMZ10 sensor.
• **Magnetostrictive Detector**

• A transducer which can measure displacement with high resolution across long distances can be built by using magnetostrictive and ultrasonic technologies.

• The transducer is comprised of two major parts: a long waveguide (up to 7 m long) and a permanent ring magnet (Fig. 7.24).

• The magnet can move freely along the waveguide without touching it. A position of that magnet is the stimulus which is converted by the sensor into an electrical output signal. A waveguide contains a conductor which, upon applying an electrical pulse, sets up a magnetic field over its entire length.

• Another magnetic field produced by the permanent magnet exists only in its vicinity.
Fig. 7.24. A magnetostrictive detector uses ultrasonic waves to detect position of a permanent magnet.
Applications of this sensor include hydraulic cylinders, injection-molding machines (to measure linear displacement for mold clamp position, injection of molding material, and ejection of the molded part), mining (for detection of rocks movements as small as 25 μm), rolling mills, presses, forges, elevators, and other devices where fine resolution along large dimensions is a requirement.
Table 8.6.1: Comparing capacitive and inductive sensors.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Capacitive</th>
<th>Inductive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Range</td>
<td>.01 mm–10 mm</td>
<td>0.1 mm–15 mm</td>
</tr>
<tr>
<td>Resolution</td>
<td>2 nm</td>
<td>2 nm</td>
</tr>
<tr>
<td>Required Sensing Area</td>
<td>130% of probe diameter</td>
<td>300% probe diameter</td>
</tr>
<tr>
<td>Typical Probe Size</td>
<td>800% of Range</td>
<td>300% of range</td>
</tr>
<tr>
<td>Rotating Targets</td>
<td>Unaffected</td>
<td>Small errors on ferrous targets</td>
</tr>
<tr>
<td>Target Material</td>
<td>Conductive targets</td>
<td>Conductive targets only</td>
</tr>
<tr>
<td></td>
<td>Not affected by material differences</td>
<td>Affected by conductive material differences</td>
</tr>
<tr>
<td></td>
<td>Also measures nonconductors (i.e., plastics)</td>
<td>Does not measure nonconductors</td>
</tr>
<tr>
<td>Gap Material</td>
<td>Senses changes in nonconductive gap material</td>
<td>Ignores nonconductive gap materials</td>
</tr>
<tr>
<td>Cost</td>
<td>$$</td>
<td>$</td>
</tr>
</tbody>
</table>
Optical Sensors

• After mechanical contact and potentionometric sensors, optical sensors are probably the most popular for measuring position and displacement.

• Their main advantages are simplicity, the absence of the loading effect, and relatively long operating distances. They are insensitive to stray magnetic fields and electrostatic interferences, which makes them quite suitable for many sensitive applications.

• An optical position sensor usually requires at least three essential components: a light source, a photodetector, and light guidance devices, which may include lenses, mirrors, optical fibers, and so forth.
Fig. 7.27. Proximity detector with two polarizing filters positioned at a 90° angle with respect to one another: (A) polarized light returns from the metallic object within the same plane of polarization; (B) nonmetallic object depolarizes light, thus allowing it to pass through the polarizing filter.
Fig. 7.28. Optical liquid-level detector utilizing a change in the refractive index.

Fig. 7.29. U-shaped fiber-optic liquid-level sensor: (A) When the sensor is above the liquid level, the light at the output is strongest; (B) when the sensitive regions touch liquid, the light propagated through the fiber drops.
Figure 15.1.62: A photoelectric sensor uses a small diameter diffuse scan fiber optic cable to detect electronic component lead wires.
Let us assume that the beam incidence strikes the surface at distance $x$ from the A electrode. Then, the corresponding resistance between that electrode and the point of incidence is respectively, $R_x$. The photoelectric current $I_0$ produced by the beam is proportional to its intensity. That current will flow to both outputs (A and B) of the sensors in corresponding proportions to the resistances and, therefore, to the distances between the point of incidence and the electrodes:

$$I_A = I_0 \frac{R_D - R_x}{R_D} \quad \text{and} \quad I_B = I_0 \frac{R_x}{R_D}.$$
If the resistances versus distances are linear, they can be replaced with the respective distances on the surface:

\[ I_A = I_0 \frac{D - x}{D} \quad \text{and} \quad I_B = I_0 \frac{c}{D}. \]

To eliminate the dependence of the photoelectric current (and of the light intensity), we can use a ratiometric technique; that is, we take the ratio of the currents,

\[ P = \frac{I_A}{I_B} = \frac{D}{x} - 1, \]

which we can rewrite for a value of \( x \):

\[ x = \frac{D}{P + 1}. \]

Figure 7.35 shows geometrical relationships between various distances in the measurement system. Solving two triangles for \( L_0 \) yields

\[ L_0 = f \frac{L_B}{x}, \]

where \( f \) is the focal distance of the receiving lens. Substituting Eq. (7.12) we obtain the distance in terms of the current ratio:

\[ L_0 = f \frac{L_B}{D} (P + 1) = k(P + 1), \]

where \( k \) is called the module geometrical constant. Therefore, the distance from the module to the object linearly affects the ratio of the PSD output currents.
Ultrasonic Sensors

• For noncontact distance measurements, an active sensor which transmits some kind of a pilot signal and receives a reflected signal can be designed. The transmitted energy may be in the form of any radiation—for instance, electromagnetic in the optical range (as in a PSD) electromagnetic in the microwave range, acoustic, and so forth.

• Transmission and reception of the ultrasonic energy is a basis for very popular ultrasonic-range meters, and velocity detectors.

• Ultrasonic waves are mechanical acoustic waves covering the frequency range well beyond the capabilities of human ears (i.e., over 20 kHz). However, these frequencies may be quite perceptive by smaller animals, like dogs, cats, rodents, and insects. Indeed, the ultrasonic detectors are the biological ranging devices for bats and dolphins.
The distance $L_0$ to the object can be calculated through the speed $v$ of the ultrasonic waves in the media, and the angle, $\Theta$ (Fig. 7.39A):

$$L_0 = \frac{vt \cos \Theta}{2},$$

where $t$ is the time for the ultrasonic waves to travel to the object and back to the receiver.
Fig. 7.41. (A) ultrasonic transducer for air. (B) directional diagram.
Figure 15.1.26: Maximum inclination for smooth, flat targets.
Figure 15.1.30: Sensing range with maximum sensitivity.
Fig. 7.42. Block diagram of micropower radar (A) and the timing diagram (B).
Level Sensing

• **Indirect Level Sensing**

• A commonly used method of indirectly measuring a liquid level is to measure the hydrostatic pressure at the bottom of the container. The level can be extrapolated from the pressure and the specific weight of the liquid. The level of liquid can be measured using displacers, capacitive probes, bubblers, resistive tapes, or by weight measurements.

• *Pressure is* often used as an indirect method of measuring liquid levels. Pressure increases as the depth increases in a fluid. The pressure is given by:

\[ p = \gamma h \]

where *p* is the pressure, *\( \gamma \)* is the specific weight, and *h* is the depth.
Example 8.1
A pressure gauge located at the base of an open tank containing a liquid with a specific weight of 13.6 kN/m³ registers 1.27 MPa. What is the depth of the fluid in the tank?

\[ h = \frac{p}{\gamma} = \frac{127 \text{ MPa}}{13.6 \text{ kN/m}^3} = 93.4 \text{ m} \]
The buoyant force on the cylindrical displacer shown in Figure 8.6 is given by:

\[
Buoyant \text{ Force } (F) = \frac{\gamma \pi d^2 L}{4}
\]

where \( \gamma \) specific weight of the liquid, \( d \) is float diameter, and \( L \) is the length of the displacer submerged in the liquid.

Figure 8.6 Displacer with a force sensor for measuring liquid level.
Example 8.2
A 13-in diameter displacer is used to measure changes in water level. If the water level changes by 1.2m, what is the change in force sensed by the force sensor?

\[
\text{Change in force} = (W - F_1) - (W - F_2) = F_2 - F_1
\]

\[
F_2 - F_1 = \frac{9.8 \text{kN/m}^3 \times \pi (0.13 \text{m})^2 \times 1.2}{4} = 156 \text{N}
\]

Example 8.3
A 7.3-in diameter displacer is used to measure acetone levels. What is the change in force sensed if the liquid level changes by 2.3 ft?

\[
F_2 - F_1 = \frac{49.4 \text{lb/ft}^3 \times \pi \times 7.3^2 \text{m}^2 \times 2.3 \text{ft}}{4 \times 144 \text{in/ft}} = 33 \text{lb}
\]
Capacitive probes can be used in liquids and free-flowing solids for continuous level measurement. Materials placed between the plates of a capacitor increase the capacitance by a factor ($\mu$), known as the dielectric constant of the material. For instance, air has a dielectric constant of 1, and water has a dielectric constant of 80. When two capacitor plates are partially immersed in a nonconductive liquid, the capacitance ($C_d$) is given by:

$$C_d = C_a \mu \frac{d}{r} + C_a$$

Where $C_a$ is the capacitance with no liquid, $\mu$ is the dielectric constant of the liquid between the plates, $r$ is the height of the plates, and $d$ is the depth or level of the liquid between the plates.
Example 8.4
A 1.3m-long capacitive probe has a capacitance of 31 pF in air. When partially immersed in water with a dielectric constant of 80, the capacitance is 0.97 nF. What is the length of the probe immersed in water?

\[ d = \frac{0.97 \times 10^3 \text{ pF} - 31 \text{ pF}}{80 \times 31 \text{ pF}} \times 1.3m = \frac{0.49m}{49cm} \]

Example 8.5
How far below the surface of the water is the end of a bubbler tube, if bubbles start to emerge from the end of the tube when the air pressure in the bubbler is 263 kPa?

\[ h = \frac{p}{\gamma} = \frac{263 \text{ kPa} \times 10^{-4}}{1 \text{ gm/cm}^3} = 26.3 \text{ cm} \]

Figure 8.8  Bubbler device for measuring liquid level.
Reference

