

Level Measurement

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Level is defined as the filling height of a liquid or bulk material, for example, in a tank or reservoir. Generally, the position of the surface is measured relative to a reference plane, usually the tank bottom. If the product's surface is not flat (e.g., with foam, waves, turbulences, or with coarse-grained bulk material) level usually is defined as the average height of a bounded area.

Various classic and modern methods exist to measure product level in process and storage tanks in the chemical, petrochemical, pharmaceutical, water, and food industries, in mobile tanks on vehicles and ships, but also in natural reservoirs like seas, dams, lakes, and oceans. Typical tank heights are approximately between 0.5 m and 40 m.

Two different tasks can be distinguished: (1) continuous level measurements (level indication, LI), and (2) level switches (LS) (e.g., to detect an alarm limit to prevent overfilling). [Figure 11.1](#) shows the principal operational modes of level measurement. Every continuous system can also be used as a programmable switch. Many level devices are mounted on top of the tank and measure primarily the distance d between their mounting position and the product's surface. The level L is then calculated, defining the tank height h as constant, as shown in [Figure 11.1](#) and expressed as:

$$L = h - d \tag{11.1}$$

The following examples describe primarily the measurement of liquids, but most of the methods can also be applied to solids (bulk material). The emphasis of this chapter will be general information about the measurement principles. The focus of the descriptions is on the methods most commonly practiced; other principles are mentioned less comprehensively. Readers interested in more detailed discussions may refer to [1–5].

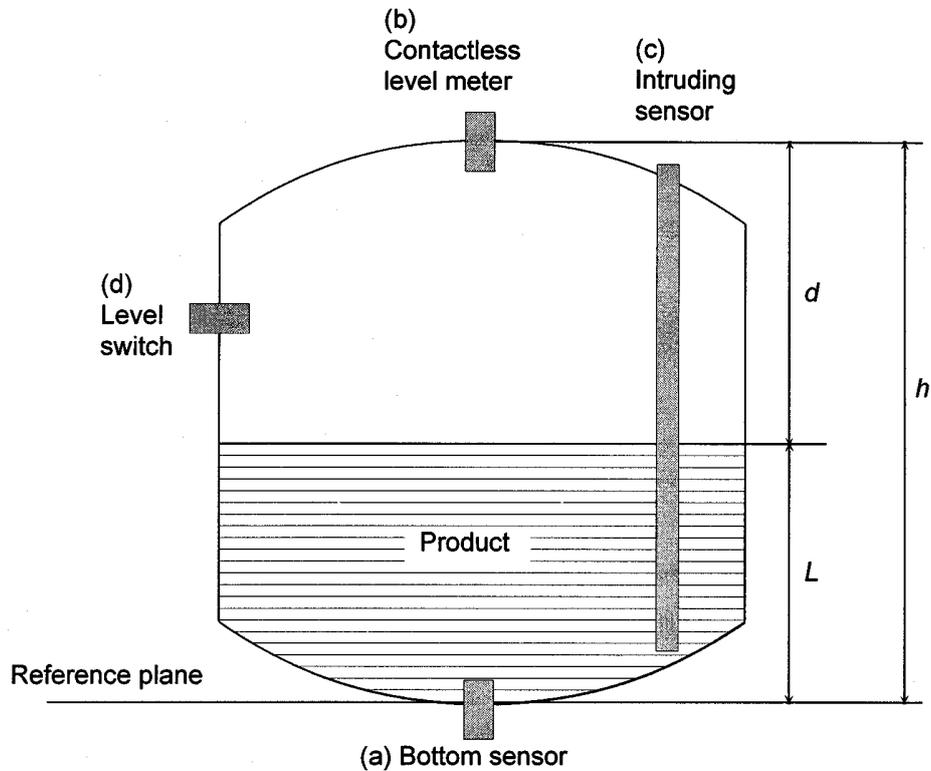


FIGURE 11.1 Representation of a tank with a liquid or solid material (hatched area), the product to be measured. The level sensor can be mounted (a) contacting product at the bottom, (b) as a contactless instrument on top, (c) as an intrusive sensor, or (d) at the sides as a level switch.

11.1 Measurements Using the Effects of Density

All methods described in this chapter have in common that the product in the tank has an effect due to its density ρ , (1) producing buoyancy to a solid submerged into the liquid, or (2) executing a force due to its weight.

Displacer

Displacers measure the buoyancy of a solid body that is partially submerged in the liquid. The change in weight is measured. Figure 11.2 illustrates the parameters used for these calculations. The cross section A of the body is assumed to be constant over its length b . The weight of force F_G due to gravity g and mass m is:

$$F_G = g m = g A b \rho_D \quad (11.2)$$

The buoyant force F_B accounts for the partial length L_d that is submerged with the remainder of the body in the atmosphere:

$$F_B = g A L_d \rho_L + g A (b - L_d) \rho_A \quad (11.3)$$

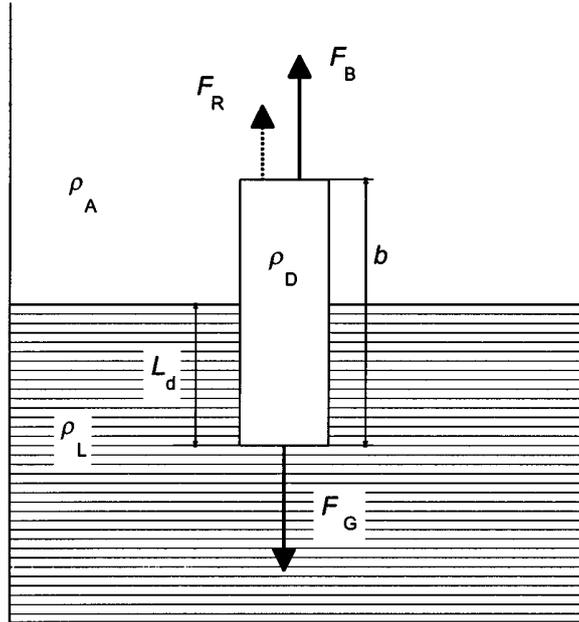


FIGURE 11.2 Quantities of a solid body immersed into a liquid. The forces F can be calculated from Equations 2, 3, and 4. ρ = density; b = length of the body; L_d = dipped length.

Combining Equations 11.2 and 11.3 gives the resulting force to be measured by an appropriate method (see Chapter 23 of this handbook):

$$F_R = F_G - F_B \quad (11.4)$$

The result for level L_d , related to the lower edge of the displacer is:

$$L_d = \frac{b(\rho_D - \rho_A) - \frac{F_R}{gA}}{\rho_L - \rho_A} \quad (11.5)$$

The density of the body should be higher than the density of the liquid; otherwise, the measurement operating range is limited (until the displacer floats on the liquid). In another version, a servo-gage moves the displacer up and down to detect the interface between the atmosphere and a liquid, or between two different liquids, by measuring the change in buoyancy. Figure 11.3 shows a special configuration, in which a small ball with volume V is mounted to a thin wire driven by a stepping motor and put into resonant vibration. The resulting force F can be measured from the resonating frequency f of the wire between points A and B:

$$F = \rho_w A_w 4f^2 l^2 \quad (11.6)$$

where l = length of the wire between the points A and B

ρ_w = density of the wire

A_w = cross-sectional area of the wire

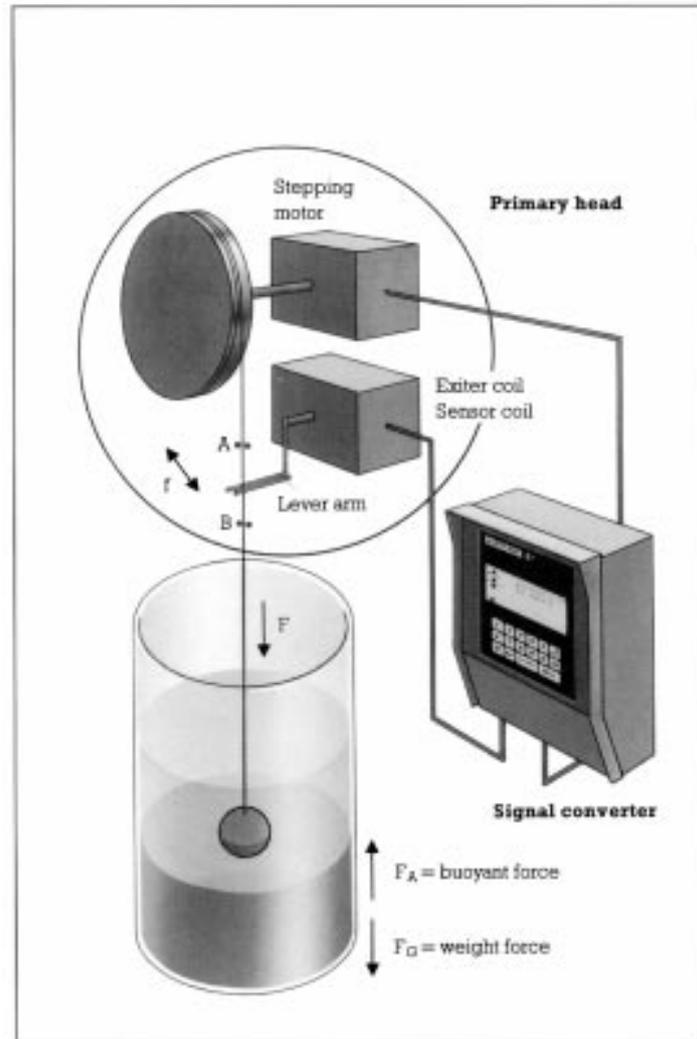


FIGURE 11.3 Level, interface and density sensor using the effects of buoyancy. A stepping motor drives the small ball attached to the thin wire to different heights in the liquid or to the interfaces. The resulting force F as a difference between weight force and buoyant force is measured from the resonant frequency of the wire-ball system. The lever arm excites the wire into oscillation and a sensor coil coupled to the lever arm measures its frequency. The signal converter controls the stepping motor and calculates the measured values [6].

And the surrounding density ρ_L can be calculated:

$$F = gV(\rho_D - \rho_L) \Leftrightarrow \rho_L = \rho_D - \frac{F}{gV} \quad (11.7)$$

Float

Floats are similar to displacers, but are swimming on the liquid's surface due to the buoyancy. Hence, the density of the float must be lower than the density of the liquid. [Figure 11.4\(a\)](#) shows the principle

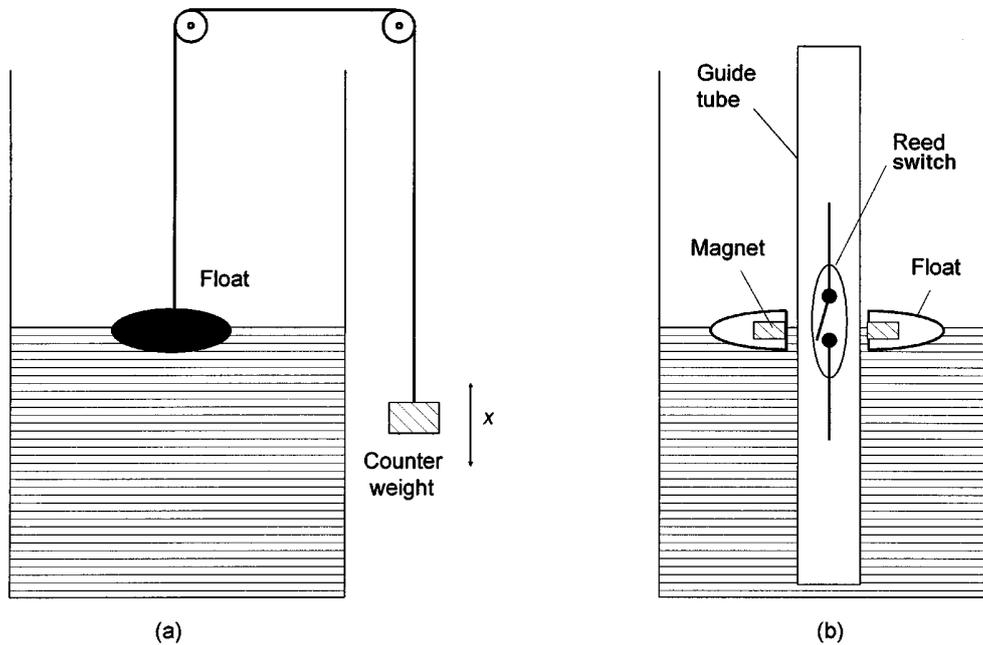


FIGURE 11.4 Principle of operation for float level meters. (a) A counter weight balances the float that swims on the liquid's surface. Its position represents the level. (b) The float contains a magnet that contacts a reed switch inside a guide tube. Using a bistable relay, this system is used as a level switch. One can also insert multiple relays into the tube to achieve different switching points for quasicontinuous operation.

of operation. The position of the float is (1) observed visually, or (2) transferred to an external display or to an angle transmitter. In general, the float is coupled to the transmitter magnetically. Figure 11.4(b) shows a level switch, using a reed relay magnetically coupled with the float. Also, a magnetostrictive linear sensor may determine the position of the float. For more information about this, refer to Chapter 6, Section 9 of this handbook.

If the float is very flat, it is called a "sensing plate". This plate is mechanically guided, e.g., by a servo control, on the surface until uplift is detected. For solids, specially shaped perpendicular floats are helpful.

Pressure Gages

A hydrostatic pressure p , caused by the weight of the product, is present at the bottom of a tank, in addition to the atmospheric pressure p_0 :

$$p = p_0 + g \rho_L L \Leftrightarrow L = \frac{p - p_0}{g \rho_L} \quad (11.8)$$

Pressure gages at the bottom of the tank measure this pressure. In process tanks with varying atmospheric pressure, a differential pressure measurement is achieved by measuring the difference between the pressure at the bottom and that at the top of the tank, above the liquid. Figure 11.5(a) shows such a configuration with a differential pressure sensor. For techniques of pressure measurement, refer to Chapter 26, Section 1 of this handbook. Because measurement by hydrostatic pressure is proportional to the density, level errors result if density changes; see Equation 11.8. Primary pressure gaging is a mass measurement. Figure 11.5(b) shows a vertical arrangement with three sensors; the measurements of p_1 and p_2 are used to compensate for the influence of density ρ_L , and to calculate the level:

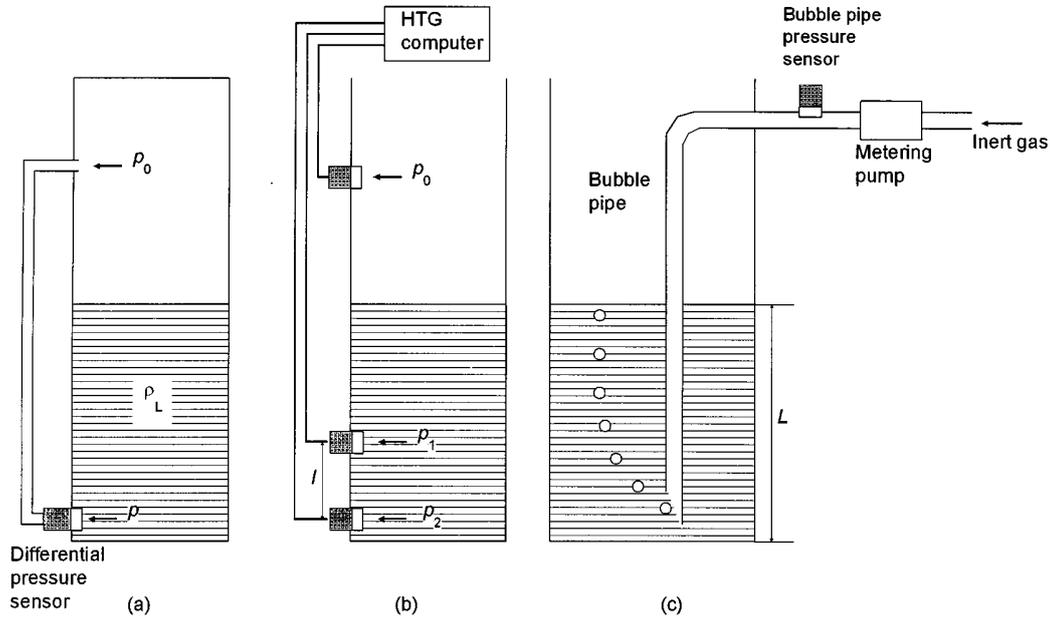


FIGURE 11.5 Level gaging by hydrostatic pressure measurement. The bottom pressure p is proportional to level. (a) The atmospheric pressure p_0 can be taken into consideration by a differential measurement. The low side of the differential pressure sensor is connected via a thin pipe to the top of the tank. (b) A differential measurement within the liquid is called “hydrostatic tank gaging, HTG” and can be used to compensate errors due to density variations of the liquid. The signals from all three sensors are evaluated by a computer. (c) With a so-called “bubble tube,” the sensor can be mounted on the top of the tank: an inert gas is injected into the tube such that bubbles of gas escape from the end of the tube. The flow rate of the gas is constant so the head pressure in the system can be measured at the inlet of the pipe.

$$\rho_L = \frac{p_2 - p_1}{gl} \Rightarrow L = \frac{p_2 - p_0}{p_2 - p_1} l \quad (11.9)$$

A system of this configuration is often called “hydrostatic tank gaging” (HTG). Figure 11.5(c) shows a further arrangement, called “bubble tube,” in which the bottom pressure is transmitted to the top of the tank. This is often used for level gaging if the sensor cannot be mounted at the bottom of the tank. It requires a tank with pressure equalization due to the steady insertion of inert gas.

Balance Method

Here simply the weight F of the complete tank is measured, dependent on the level L :

$$F = F_0 + gAL\rho_L \quad (11.10)$$

where F_0 is the weight of the empty tank and A the cross-sectional area, which is assumed to be constant throughout the tank height. In order to measure the weight force correctly, it is necessary to isolate the complete tank mechanically. For precise measurements, the buoyancy in air must be taken into consideration:

$$F = F_0 + gAL(\rho_L - \rho_A) \Leftrightarrow L = \frac{F - F_0}{gA(\rho_L - \rho_A)} \quad (11.11)$$

For techniques of weight measurement, refer to Chapter 20 of this handbook.

This method has severe disadvantages when the tank is not inside a building. Outside, wind forces and the weight of snow and rain can cause errors.

11.2 Time-of-Flight Measurements

An indirect measurement of level is evaluating the time-of-flight of a wave propagating through the atmosphere above the liquid or solid. This is primarily a distance measurement; the level can then be calculated accordingly. The increasing demand of industry for nonintrusive continuous level gaging systems has been instrumental in accelerating the development of technologies using time-of-flight measurements [7].

Basic Principle

Although different types of physical waves (acoustic or electromagnetic) are applied, the principle of all these methods is the same: a modulated signal is emitted as a wave toward the product, reflected at its surface and received by a sensor, which in many cases is the same, (e.g., the ultrasonic piezoelectric transducer or the radar antenna). Figure 11.6 demonstrates the principle of operation. The measuring system evaluates the time-of-flight t of the signal:

$$t = \frac{2d}{v} \quad (11.12)$$

where v is the propagation velocity of the waves.

One can generate an unmodulated pulse, a modulated burst as in Figure 11.6(b), or special forms. Table 11.1 lists the main properties of the three preferred types of waves, used for time-of-flight level gaging.

The very short time spans of only a few nanoseconds for radar and laser measurement techniques require the use of time expansion by sampling (see Chapter 85 of this handbook) or special evaluation methods (see below).

Ultrasonic

Ultrasonic waves are longitudinal acoustic waves with frequencies above 20 kHz. Ultrasonic waves need a propagation medium, which for level measurements is the atmosphere above the product being measured. Sound propagates with a velocity of about 340 m s^{-1} in air; but this value is highly dependent on temperature and composition of the gas, and also on its pressure (see Chapter 6, Section 7 of this handbook). In vacuum, ultrasonic waves cannot propagate. In practice, the reflection ratio is nearly 100% at the product's surface (e.g., at transitions gas/liquid or gas/solid). Piezoelectric transducers (see Chapter 26, Section 3 of this handbook) are utilized as emitter and detector for ultrasonic waves, a membrane coupling it to the atmosphere. The sensor is installed as in Figure 11.1(b), the signal form is as in Figure 11.6(b). Level gaging is, in principle, also possible with audible sound 16 Hz to 20 kHz or infrasonic waves less than 16 Hz.

Another procedure is to propagate the waves within the liquid by a sensor mounted at the bottom of the tank. The velocity of sound in the liquid must be known, considering the dependence on temperature and type of liquid. This method is similar to an echo sounder on ships for measuring the water depth. For more information about time-of-flight ultrasound evaluation techniques, refer to Chapter 6, Section 7 of this handbook.

Microwaves

Microwaves are generally understood to be electromagnetic waves with frequencies above 2 GHz and wavelengths of less than 15 cm. For technical purposes, microwave frequencies are used up to max. 120 GHz; in practice, the range around 10 GHz (X-band) is preferred.

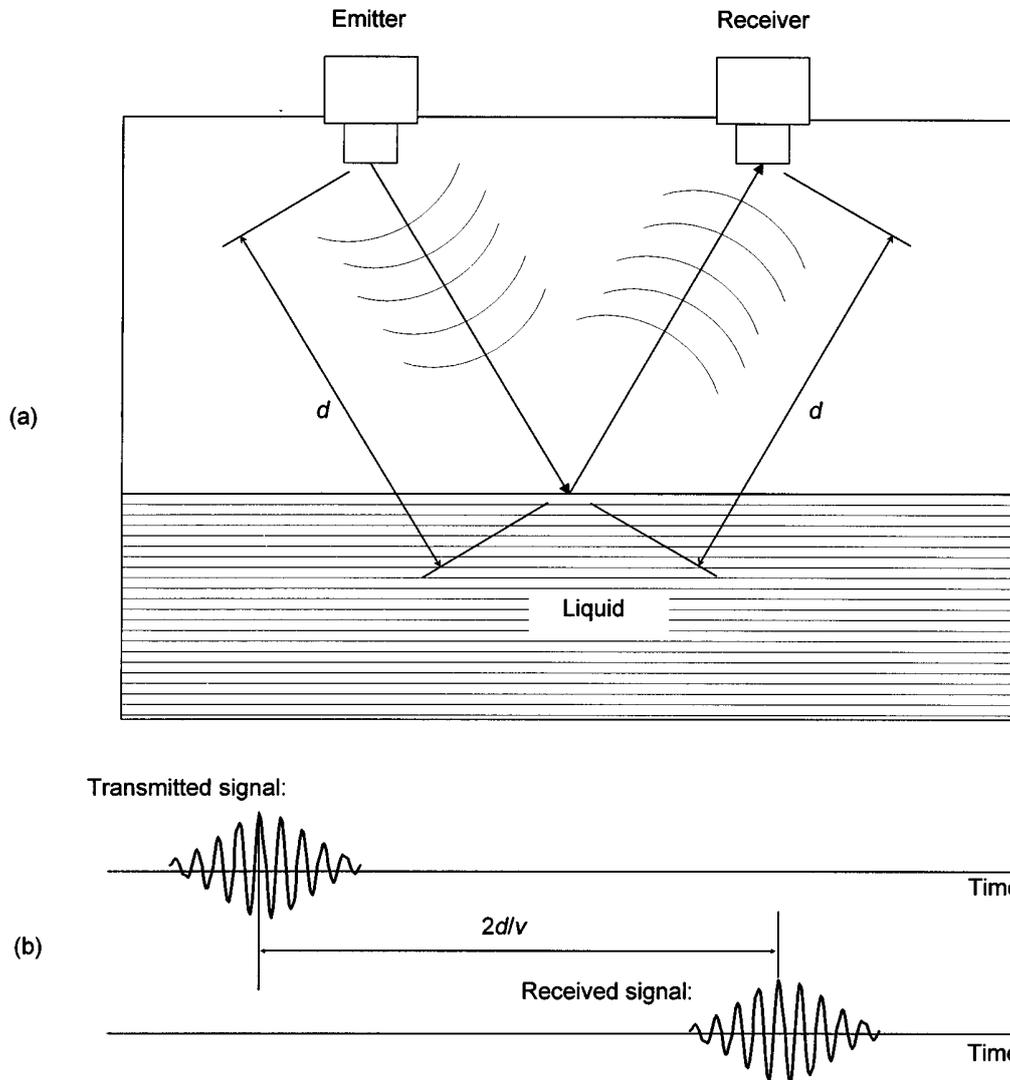


FIGURE 11.6 (a) Representation of time-of-flight measurements. The emitter couples a wave (ultrasonic or electromagnetic) into the atmosphere that propagates the wave toward the liquid. Its surface reflects the wave and a sensor receives it. (b) Due to the propagation velocity v , a time delay is measured between emission and receipt of the signal. This example is characterized by a modulated burst. The time scale is arbitrary.

TABLE 11.1 Properties of the wave types for time-of-flight measuring.

Principle	Wave Velocity	Avg. Carrier Frequency	Wavelength	Avg. Burst Time
Ultrasonic	340 m s^{-1}	50 kHz	7 mm	1 ms
Radar	$300,000 \text{ km s}^{-1}$	10 GHz	3 cm	1 ns
Laser	$300,000 \text{ km s}^{-1}$	300 THz	$1 \mu\text{m}$	1 ns

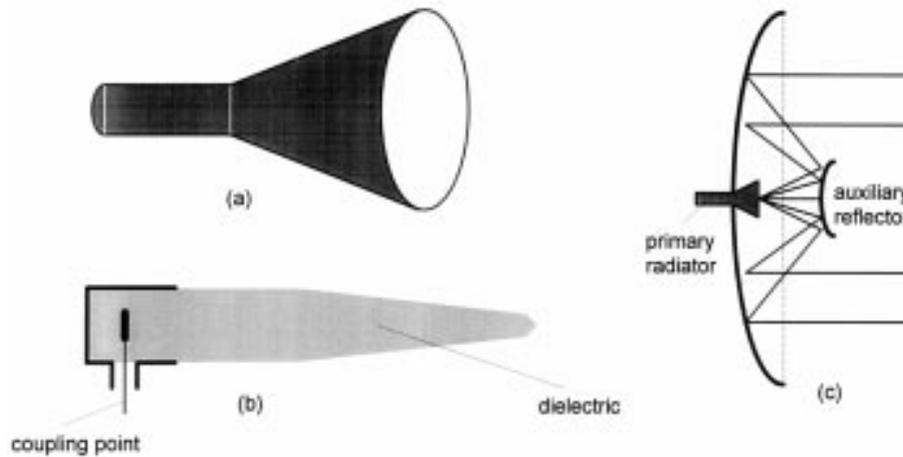


FIGURE 11.7 Practical antenna forms used for radar level instruments: (a) conical horn antenna, (b) dielectric rod antenna, and (c) parabolic mirror with a small antenna as primary radiator and an auxiliary reflector giving a very small beam angle (so-called Cassegrain model).

The usually applied time-of-flight measurements with microwaves are RADAR-based [8, 9]. The term “RADAR” is generally understood to mean a method by means of which short electromagnetic waves are used to detect distant objects and determine their location and movement. It is an acronym from Radio Detection And Ranging. Figure 11.7 shows preferred antenna forms. They are usually combined with a compact sensor, as in Figure 11.8. For level measuring systems, a small radiation angle is desirable in order to avoid interfering reflections from the tank wall or tank internals as much as possible. The larger the aperture area, the smaller the radiation angle and the higher the antenna gain. The power balance is given by the general radar equation:

$$P_R = \frac{P_T G_T R G_R}{D^2} \quad (11.13)$$

where P_R = received power
 P_T = transmitted power
 G_T = transmitting antenna gain
 R = reflection factor of target
 G_R = receiving antenna gain
 D^2 = propagation loss to and from the surface, due to power density decrease and atmospheric influences

The reflection factor R of the product’s surface is dependent on the dielectric permittivity ϵ_r of the liquid or bulk material:

$$R = \frac{\left(\sqrt{\epsilon_r} - 1\right)^2}{\left(\sqrt{\epsilon_r} + 1\right)^2} \quad (11.14)$$



FIGURE 11.8 Design of a compact industrial level radar system. The converter above the flange includes the complete microwave circuitry, signal processing stages, microprocessor control, display, power supply, and output signal [6].

In level measurement situations, the reflecting area is so large that it intersects the beam cross section completely; therefore, D^2 is approximately proportional with distance d^2 . Thus also, the received power decreases proportionately with d^2 , as derived in [8]:

$$P_R \propto \frac{1}{d^2} \quad (11.15)$$

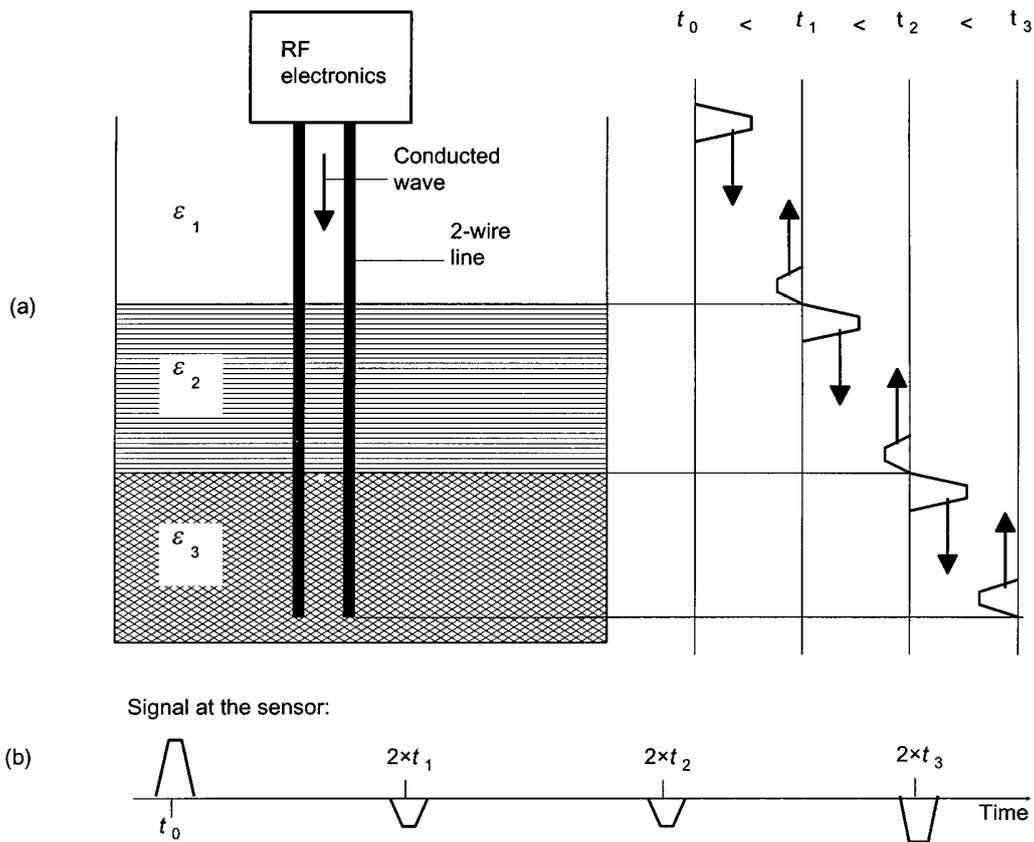


FIGURE 11.9 Principle of operation of a wire-conducting high-frequency level measurement system. (a) An electrical pulse is generated (time t_0) and a two-wire line guides the electromagnetic wave. At every position where the surrounding permittivity ϵ changes, a part of the wave is sharply reflected (time t_1) back to the position where the wave propagates along the entire line and is reflected a second time (t_2) at the interface between the two liquids, and a third time at the end of the line. (b) The signal delay times ($2t_1$, $2t_2$, and $2t_3$) represent the positions of the interfaces with respect to the end of the line, which can be used as a reference. The signal polarity is inverted due to the reflection from lower to higher permittivity. The time scale is arbitrary.

This is not the case if the waves propagate within an electromagnetic waveguide, like a vertical tube dipping into the liquid, called a stilling well. Here, the propagation is nearly without losses.

An alternative method using electromagnetic waves is to propagate them in a cable. Figure 11.9(a) illustrates the operation with a cable dipped into the liquid or bulk material. Where the dielectric permittivity of the surrounding medium changes, part of the wave is reflected. This method can be applied to interface measurements too. Figure 11.9 shows the signals in an application with a two-phase product. This method is called “time domain reflectometry” (TDR).

Laser/Light

Lasers and light-emitting diodes produce electromagnetic waves of very short wavelength (less than $2 \mu\text{m}$), which can also be used for time-of-flight measurements, similar to the described microwave methods. Preferred laser signals are (1) short pulses of less than 1 ns duration, or (2) lasers with amplitude-modulated intensity with frequencies of some megahertz. For more details about laser operation and interferometry methods, refer to Chapter 6, Section 5 of this handbook.

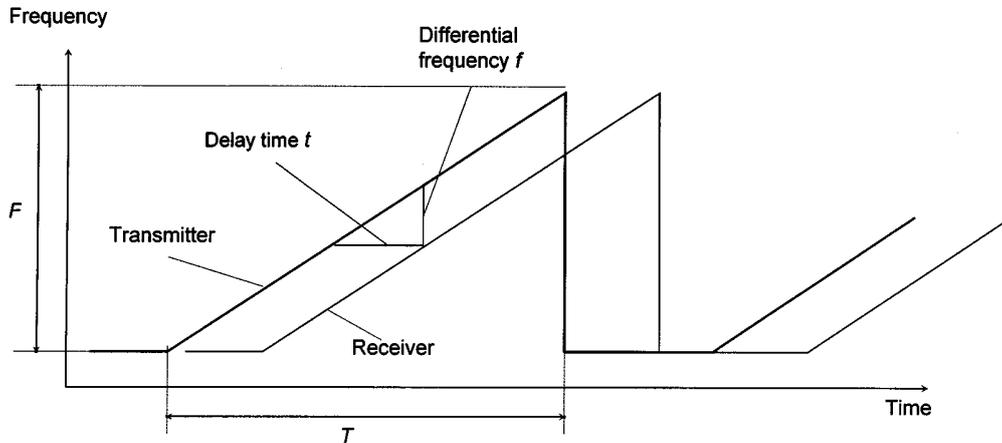


FIGURE 11.10 Operation characteristics of FMCW radar. The frequency of the transmitter changes linearly by time in an interval (sweep). The received signal has the same form, but is time-delayed. At every point of the sweep, the differential frequency is constant and proportional to the time delay. Time and frequency scales are arbitrary.

Laser systems are very precise and can achieve accuracies better than 1 mm. Because the laser beam is very narrow, such level measurement systems can be installed without influence of tank internals. Some practical disadvantages of laser level measurement are: (1) it functions as does your eye to see the product's surface and therefore fails if dust, smoke, etc. are present; (2) it is sensitive to dirt on the optical sensors; and (3) the equipment is expensive.

Commonly Used Evaluation Methods

Due to the great benefits of contactless time-of-flight measurement, some typical methods have been evaluated for level gaging within the last few years, mainly in radar techniques [8].

Frequency-Modulated Continuous Wave Radar

Because the flight times in typical level applications are very short (a resolution of 1 mm requires a 7 ps time resolution), it is difficult to evaluate information directly in the time domain. By modulation of the microwave signals, the time delay is transformed into the frequency domain, obtaining low-frequency signals. For general information about modulation, see Chapter 81 of this handbook.

Therefore, Frequency Modulated Continuous Wave (FMCW) radar has been established as the dominant technique. FMCW radar utilizes a linearly frequency-modulated microwave signal; the transmission frequency rises linearly in a time interval T . The frequency difference in this interval is called the frequency sweep F .

Figure 11.10 shows the principle of FMCW radar. Due to the time delay during signal propagation, the transmitted frequency changes such that the difference between the momentary transmitted frequency and the received frequency, a low-frequency signal is obtained. The frequency f of that signal (typically up to a few kilohertz) is proportional to the reflector distance d (see Figure 11.6); in this method, therefore, the delay t is transformed into a frequency f :

$$f = \frac{F}{T}t = \frac{F}{T} \frac{2d}{c} \Leftrightarrow d = \frac{f c T}{2 F} \quad (11.16)$$

In Equation 11.16, c is the speed of light and F/T is the sweep velocity; see Figure 11.10.

Figure 11.11 shows a basic circuit block diagram of an FMCW radar system. Because the resultant signal frequencies are low, further signal processing is technically simple and very accurate. Normally,

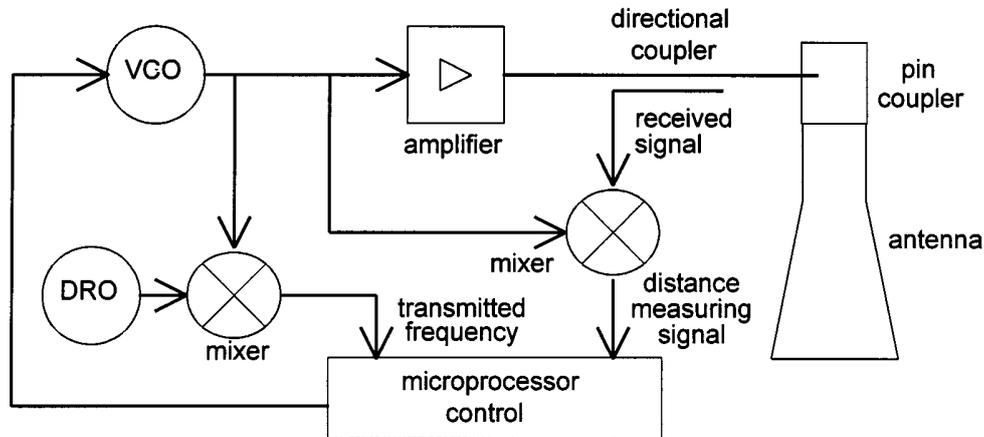


FIGURE 11.11 Basic circuit block diagram of an FMCW radar system: a microprocessor controls a voltage-controlled oscillator (VCO), such that the desired frequency sweep is obtained. This signal is amplified and fed into the transmitting antenna. The instantaneous frequency must be measured in order to ensure good sweep linearity. This is accomplished by counting the frequency after it has been mixed with the known frequency of a dielectric resonance oscillator (DRO). A directional coupler decouples the received signal, which is mixed with the transmission signal and processed by the microprocessor.

evaluation is by means of digital signal processing. For more information about signal processing techniques using spectrum analysis, refer to Chapter 83 of this handbook.

Time-of-Flight Through Product

Alternatively, the propagation time of the waves through a weakly absorbing liquid or bulk material of low permittivity ϵ_r can be measured, as well as the propagation through the air. In cases where the reflection from the interface between air and the upper surface of the product is poor, part of the signal travels through the liquid and is reflected a second time at the tank bottom or at an interface between two liquids (e.g., oil on water).

Figure 11.12 demonstrates this technique. The evaluation is done in the following four steps:

1. Where microwaves in the tank atmosphere of height d are propagated at the speed of light c , microwaves in the medium (relative permittivity = ϵ_r , height L) are propagated at a slower velocity v .
2. Hence, the reflection r_2 from the tank bottom appears to be shifted downward, and the apparent tank height h_v is greater than the true height h .
3. The transit time in the medium is $t_1 = L/v$, where for the same distance in an empty tank would be $t_0 = L/c$. The ratio of apparent “thickness layer” ($h_v - d$) to true filling height ($h - d$) therefore corresponds to the ratio of the wave propagation rates:

$$\frac{h_v - d}{h - d} = \frac{c}{v} = \sqrt{\epsilon_r} \quad (11.17)$$

4. When ϵ_r , h , and h_v are known, distance d and, from that, filling height L can be calculated exactly:

$$L = h - d = \frac{h_v - h}{\sqrt{\epsilon_r} - 1} \quad (11.18)$$

By this method, a direct level measurement — not a distance measurement — is attained. It can even be applied when signal r_1 from the surface of the medium is no longer measurable. The evaluation of