Chapter 2
Ultrasonic Sensing Technology

2.1 Overview

This chapter describes the basic properties of ultrasonic technologies and their associated use in various ranges of sensors in industrial applications. Physical properties as well as the limitations of the piezoelectric devices used in ultrasonic sensors are described here. Particularly, the usage of ultrasonic sensors in fluid level measurement systems is discussed. Various configurations of ultrasonic sensors used with hazardous fluids, particularly gasoline-based fuels, in the application of level measurement have also been described in this section. In summary, this chapter provides the detailed background to ultrasonic type sensors and their application in dynamic environments.

2.2 Principles of Ultrasonic Sensing

2.2.1 Overview

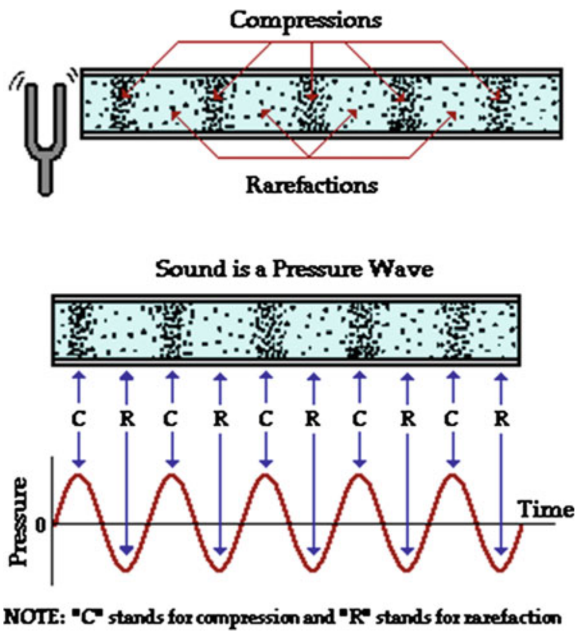
Fundamentals of ultrasonic transducers are discussed in this section. The nature of the ultrasound waves and their associated parameters such as ultrasound velocity and range are described.

2.2.2 Ultrasound Waves

Ultrasound waves are similar to sound waves, where both travel through a medium. Ultrasound waves consist of high-frequency sound waves that are inaudible to human beings. The frequency of the ultrasound waves is normally above 20 kHz. However, some creatures such as bats can hear as well as generate the high-frequency ultrasound waves [1, 2].

J. Terzic et al., *Ultrasonic Fluid Quantity Measurement in Dynamic Vehicular Applications*, DOI: 10.1007/978-3-319-00633-8_2,

Fig. 2.1 Sound waves produced by a fork [3]



As the sound waves travel through the air, they produce vibration in the air particles which changes the density and pressure of the air particles along the direction of motion of the wave. If a sound wave is moving from left to right through air, particles of air will be displaced both rightward and leftward as the energy of the sound wave passes through it. If the source of the sound waves vibrates sinusoidally, the pressure variations are also sinusoidal. Figure 2.1 illustrates the propagation of the sound waves produced by a fork. Patterns of high and low pressure points will be created in the air by the vibration of the fork. These patterns of varying pressure points can be observed using a sound wave detector [3].

Ultrasound can be thought of as analogous to ultraviolet light in that it characterizes that region of acoustical phenomena which is not accessible to human perception [4]. Some creatures such as bats, dolphins, and whales are able to hear and generate ultrasonic waves. Figure 2.2 shows a graph of different hearing ranges in animals and humans.

2.2.3 Sound Velocity

The sound velocity is defined by the rate of change of particle displacement with respect to time. Sound or ultrasound waves can only be propagated in a material medium. Different characteristics of different materials will influence the velocity

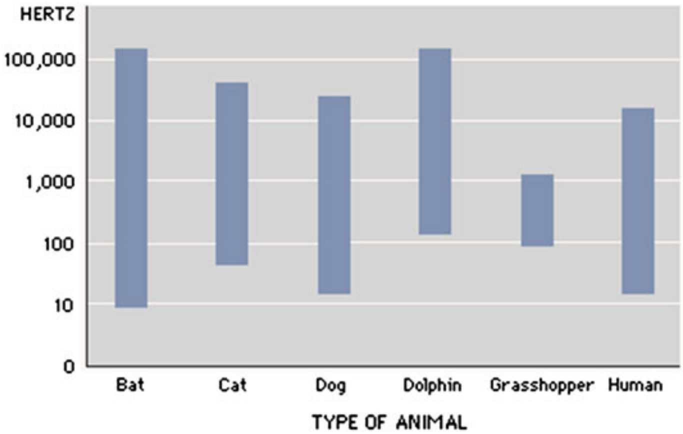


Fig. 2.2 Hearing range threshold in different living beings, *courtesy* Microsoft Encarta 2008

of the sound differently. The characteristics of the material medium have effects on the velocity and the attenuation of ultrasound waves. The speed of sound waves in a medium depends on the compressibility and density of the medium [5]. If the medium is a liquid or a gas and has a bulk modulus K and density ρ, the speed of sound waves in that medium or fluid is given by Cheeke and David [6]:

$$c_{\text{fluid}} = \sqrt{\frac{K}{\rho}} \tag{2.1}$$

The general expression of the speed of all mechanical waves in a given material is expressed as [5]:

$$v = \sqrt{\frac{\text{elastic\_properties}}{\text{inertial\_properties}}} \tag{2.2}$$

The speed of sound changes according to the surrounding temperature. The speed of sound in atmosphere reaches 331.45 m/s at 0 °C. The speed of sound in terms of temperature can be determined with the following equation:

$$c_{\text{air}}(t) = C_0 + kt \tag{2.3}$$

where, c_{air} is the speed (m/s) of the sound in air,

t is the air temperature in degree Celsius, and

k is the rate at which the speed changes with respect to the temperature, which is approximately 0.607 m/s at every change of 1 °C in temperature.

Table 2.1 lists some materials and their characteristics that relate to the speed of ultrasonic waves. The characteristic impedance factor (Ns/m^3) represents the resistance to propagation of ultrasonic sound in a given material.

Table 2.1 Sound velocity and characteristic impedance of gases and liquids [4]

Material	Temperature (°C)	Density (kg/m^3)	Sound velocity (m/s)	Characteristic impedance (Ns/m^3)
Gases				
Air	0	1.293	331.45	429
Argon	0	1.783	319	569
Helium	0	0.178	965	172
Oxygen	0	1.429	316	452
Nitrogen	0	1.251	334	418
Ammonia	0	0.771	415	320
Liquids				(106 Ns/m^3)
Water	20	998	1483	1.48
Diesel oil	20	800	1250	1.0
Mercury	20	13500	1451	19.6
Methyl alcohol	20	720	1120	0.89
Ethyl alcohol	20	790	1159	0.92
Ethyl ether	20	714	1006	0.72
Glycerine	20	1228	1895	2.33
Acetone	20	794	1189	0.94
Transformer oil	20	890	1425	1.27

2.2.4 Ultrasonic Wave Generation

The generation of ultrasonic waves is similar to the generation of an audible sound wave using a speaker. The diaphragm of the speaker is electronically driven to move back and forth, which produces low pressure and high pressure points in the air. For ultrasonic wave generation, the diaphragm needs to move back and forth at a much greater rate than for an audible sound wave.

The frequency and amplitude of sound waves can be measured by measuring the fluctuations and the pressure difference in air particles propagating sound waves through air. The diaphragm of the microphone, shown in Fig. 2.3, produces electrical signals which are a replica of the sound pressure experienced by the diaphragm. The vibration of the diaphragm and the pressure on it reflects the frequency and amplitude of the sound waves.

2.2.5 Piezoelectric Effect

Since ultrasonic waves are high-frequency waves, sensitivity of a device to detect high-frequency waves plays an important role in ultrasonic wave detection. The piezoelectric effect can be used to detect as well as generate ultrasonic waves.

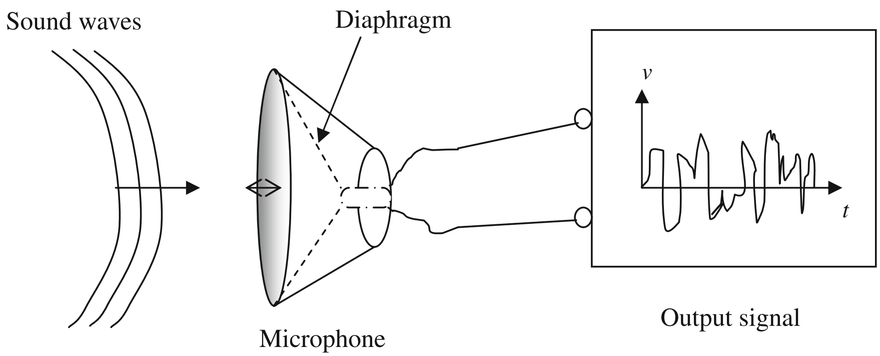


Fig. 2.3 Sound detection using microphone

These days, most practical ultrasound sources are based on the piezoelectric principle of transconduction [4]. Piezoelectric sources have the advantage of simple construction and operation, which makes them suitable for a variety of applications.

A piezoelectric ultrasound generator consists of a layer of piezoelectric material with thin metal electrodes on both its sides. If an alternating electrical voltage is applied to these electrodes, the thickness of the layer will vary according to the variations of the electrical field [4], thus fluctuations in the air or a medium will be produced. Alternatively, the piezoelectric effect can be reversed to detect ultrasonic waves and to transform waves into an electrical signal. Figure 2.4 illustrates the piezoelectric effect, where the induced voltage is increased as the applied pressure increases.

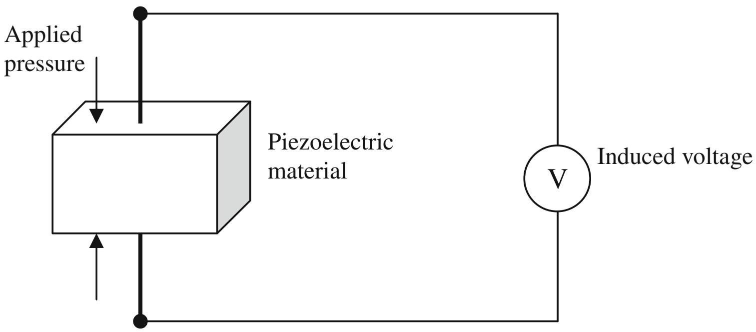


Fig. 2.4 Piezoelectric effects

2.2.6 Characteristics of Ultrasonic Waves

2.2.6.1 Overview

This section discusses some characteristics and physical factors that influence the propagation of ultrasonic waves. Phenomena such Reflection, Refraction, Diffraction, and Absorption of the ultrasonic wave during its propagation are described in the following subsections.

2.2.6.2 Reflection

When a wave is traveling through one material and impinges on a boundary between it and a second medium, part of the energy travels forward as one wave through the second medium while a part is reflected back into the first medium, usually with a phase change [7]. Specific acoustic impedance is the characteristic that determines the amount of reflection and it is the product of the density and velocity. The amplitude of the reflected wave is given as:

$$A_r = \frac{R_1 - R_2}{R_1 + R_2} \tag{2.4}$$

where, $R_1 = \rho_1 c_1$,
$R_2 = \rho_2 c_2$,
ρ is the density of each material,
c is the speed of the source, and
A_r is the ratio between reflected and incident amplitudes.

2.2.6.3 Refraction

A wave traveling from one material into another material can experience a change in its course. A wave at θ_1 in medium A can end up traveling at θ_2, as illustrated below (Fig. 2.5).

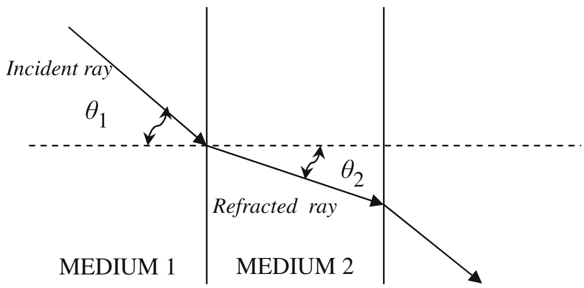


Fig. 2.5 Refraction of mechanical waves in different media

The ratio of the two angles is proportional to the ratio of the speed in both media, and it is given by:

$$\frac{\sin(\theta_1)}{\sin(\theta_2)} = \frac{c_1}{c_2} \tag{2.5}$$

The principles of refraction can cause a ray traveling at a critical angle to disappear as total refraction. The critical angle θ_c can be determined by the following equation. For liquids and solids, θ_c is about 15° [7].

$$\theta_c = \theta_1 = \sin^{-1}\frac{c_1}{c_2} \tag{2.6}$$

2.2.6.4 Diffraction

Ultrasonic waves do not always propagate in a rectilinear manner. For example, a wave passing near the edge of an object has a tendency to become bent toward and around it. This bending of the wave, as shown in Fig. 2.6, is called diffraction.

Ultrasonic signals that would normally be received at a certain point may be diverted by diffraction and received at some other position [7]. If the object is small compared to the wavelength there will be no noticeable shadow behind it at all since the sound is strongly deflected by the object [4].

2.2.6.5 Absorption

The existence of sound waves is always restricted to a material medium, the nature and the structure of which determines the particular parameters of their propagation. Ultrasonic waves may lose energy and get absorbed depending on the type of material and distance it traveled. The loss of sound energy is caused by the fact that any kind of matter consists of small but finite components such as atoms,

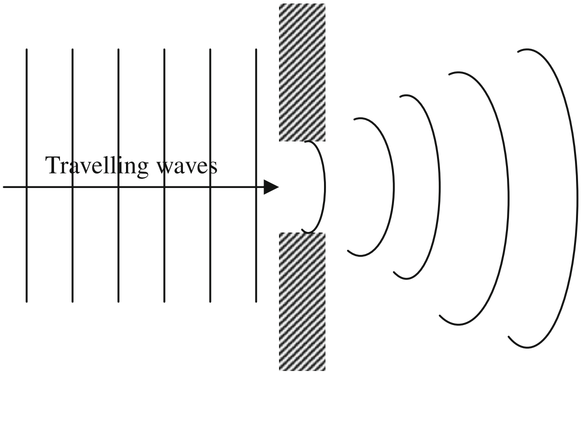


Fig. 2.6 Diffraction phenomenon in mechanical waves

molecules, and ions, which interact with each other [4]. Sound absorption in a plane harmonic sound wave is characterized by an exponential decrease of amplitude with traveling distance as [4]:

$$\hat{p}(x) = \hat{p}_0 e^{-\alpha x} \tag{2.7}$$

where $\hat{p}$ is the amplitude of the fluctuating sound pressure at distance x, $\hat{p}_0$ is the initial pressure, and the quantity α is the absorption constant. Its magnitude depends on the kind of wave medium and on the sound frequency and is the reciprocal of the distance along which the amplitude falls by $\frac{1}{e}$ of its initial value [4]. The attenuation constant D may be derived from the absorption constant α.

$$D = 20\alpha \cdot \log_{10} e \approx 8.69\alpha \ \mathrm{dB/m} \tag{2.8}$$

2.2.7 Ultrasonic Measurement Principles

The ultrasonic wave detection and measurement principle is primarily the reverse operation of ultrasonic wave generation. During ultrasonic wave generation, the transducer element (i.e., piezoelectric) is excited by applying an electrical signal across it. But during ultrasonic wave detection, an electrical voltage signal across the piezoelectric element is monitored. As soon as an ultrasonic wave strikes the transducer, the piezoelectric element vibrates accordingly; thus it generates a voltage signal across its terminals.

Figure 2.7 shows a simple configuration of an ultrasonic sensor in a level sensing application. An ultrasonic wave reflector (obstacle) floats on the liquid surface. A transducer is mounted at the bottom of the tank and transmits a signal. It determines the fluid level by detecting and measuring the time-of-flight of the reflected ultrasonic wave.

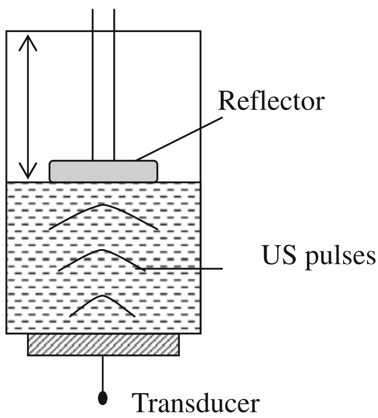
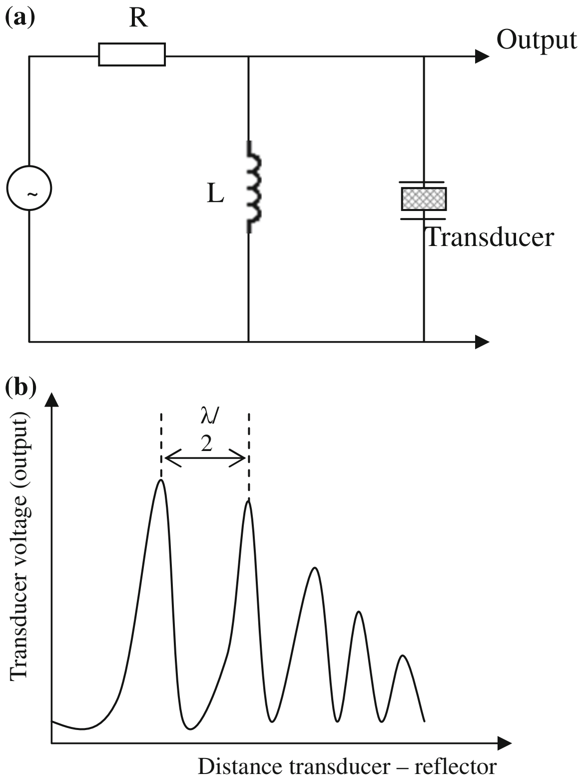


Fig. 2.7 A simple configuration of an ultrasonic level sensor system

A technique known as *Interferometry* can be used with an ultrasonic sensor to determine fluid level. Interferometry consists of diagnosing the properties of two or more waves by studying the pattern of interference created by their superposition. In interferometry, a wave of some specific shape is transmitted and then incoming waves that have the same pattern (i.e., frequencies) are detected. The difference between the two waves (transmitted wave and received wave) is identified. In ultrasonic level sensing systems, the same principle of interferometry can be applied. Figure 2.8a shows a simple circuit that can be used to generate a pulse of an ultrasonic wave signal (shown in Fig. 2.8b). After transmitting a pulse signal, the circuit listens for any incoming reflected echo pulse that has similar features (i.e., frequency) as the transmitted echo. The time difference or time-of-flight is calculated based on the times of transmission and reception of the pulse wave.

Paulsen [8] has used the same method for detecting fluid levels as described above, in which an ultrasonic transducer driver generates a voltage proportional to the resonant frequency of the ultrasonic transducer. A reference voltage is then generated and the reference voltage and the first voltage are monitored and compared, and a surface detect signal is generated when the first voltage drops below the reference voltage [8].

Fig. 2.8 Example of an ultrasound interferometer



Wang [9] also developed a system based on the principle described above. But instead of a simple pulse, a switch-mode ultrasonic Radio Frequency (RF) burst emission circuit was used, which is based on the optimum transient response formed between a series resonance network of a piezoelectric crystal oscillator of an ultrasonic transducer and an active switch device (transistor). Wang [9] has claimed that the circuit produces a highly efficient emission of an ultrasonic RF burst. Figure 2.9 illustrates a basic setup of the ultrasonic RF burst emission generator designed by Wang [9]. The circuit consists of a transistor T, two diodes D1, D2, and a load network of piezoelectric oscillator TD. The function of diodes D1 and D2 is to form an isolating stage between the switch transistor and receiver amplifier.

Suzuki [10] described a method of generating and receiving ultrasonic waves using a single ultrasonic transducer. Suzuki [10] has used a negative immittance converter in the circuitry in order to cancel components which impede the damping characteristics of the ultrasonic transducer. This provides the benefits of receiving an ultrasonic wave having good receiving response and sensitivity without using any mechanical damping method [10].

2.3 Level Measurement Using Ultrasonic Sensors

Ultrasonic transducers transmit ultrasonic waves and then receive those ultrasonic waves reflected from an object. The time delay between transmission and reception of the ultrasonic waves is used to detect the position of the object. This technique can be used to determine the height or vertical distance of an object from the ultrasonic sensor. Thus ultrasonic transducers can be used to determine the height or level of fluid in a container (Fig. 2.10).

Durkee [11] described an aircraft fuel gauging and battle damage detection system that comprises an ultrasonic transducer incorporable in the fuel tank of the aircraft. An electrical circuit excites the ultrasonic transducer to transmit an acoustic pulse toward the surface of fuel in the tank. Then the ultrasonic transducer receives the ultrasonic echo pulses reflected from the fuel surface, which is then

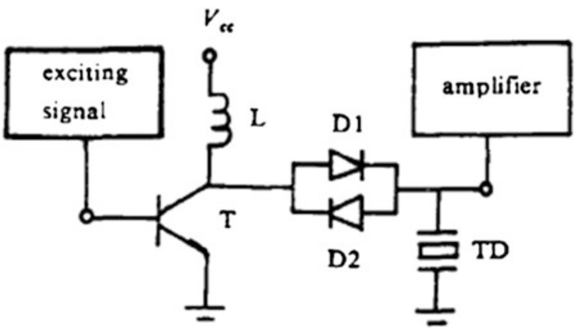


Fig. 2.9 A typical switch-mode ultrasonic RF burst emission circuit [9]

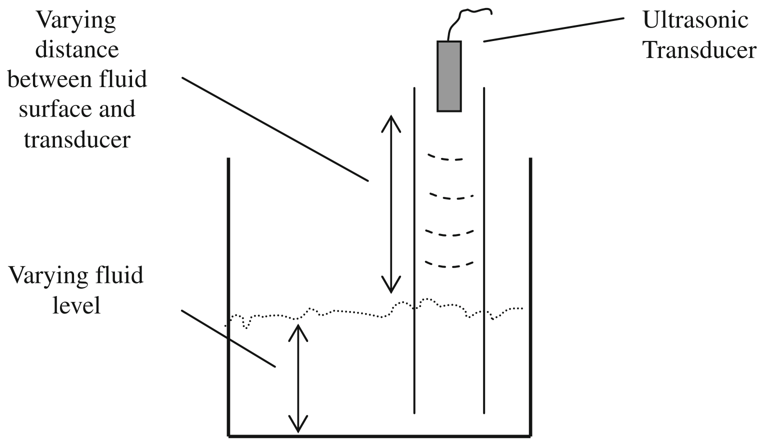


Fig. 2.10 Fluid level measurement using ultrasonic transducer

converted from ultrasonic echo pulses to electrical echo pulses. The system uses another electrical circuit to receive and process the electrical echo pulses from the ultrasonic transducer. The second circuit performs fuel quantity measurements using the electrical echo pulses and also performs battle damage detection using the electrical compression wavefront pulses.

Koblasz et al. [12] described an ultrasound liquid level detection system for automatically controlling the dispensing of a post-mix beverage. The design uses microprocessor-controlled circuitry for monitoring and implementing the automatic dispensing process. The microprocessor is interfaced with an ultrasonic transducer that transmits ultrasonic waves toward the target container that needs to be filled. It receives the reflected ultrasonic wave and then analyzes the characteristics of the received wave. Then, when required, it uses the microprocessor to implement control functions of the automatic dispensing process. The system also has additional safeguards programmed into the microprocessor to preclude operator errors such as triggering of the dispenser system by devices other than the container to be filled [12].

Ellinger et al. [13] described a method that determines the quantity and density of fuels stored in aircraft fuel containers using an ultrasonic transducer. Multiple ultrasonic sensors were used for the application. The ultrasonic sensors, including an altitude sensor, were controlled by a computer. Each ultrasonic transducer was supported within the stillwell by the container. Sensors in the fuel tanks were multiplexed by two redundant synchronized processors; so that failure of a sensor interface of one processor will not affect input to the other processor. An ultrasonic signal was transmitted and received from the transducer within the stillwell. The round-trip time period from sending to receiving the signal is measured. The quantity of fuel in the container is determined from the round-trip time period and data stored on the container volume in the central processing unit. The electrical wiring and sensor are mounted outside of the tank, which not only makes it intrinsically safe but also avoids the possibility of performance degradation due to the contamination in the liquid [13].

Palmer et al. [14] described an ultrasonic sensor based liquid level sensor system that comprises a tubular probe having a peripheral wall and suspended in a liquid container. An ultrasonic signal is transmitted around the wall from a transmitting transducer that is embedded in a block, which is bonded to the inner surface of the wall, to a receiving transducer that is also embedded in the same block. A detector circuit discriminates between the signal levels when the ultrasonic probe is immersed outside of liquid and when the probe is immersed in liquid, hence it provides a corresponding switched output [14].

Getman et al. [15] described a liquid level sensing system that uses the pulse transit time technique to sense the level of liquid in a vessel. An ultrasonic transducer is mounted above the highest permissible level in the vessel, where it emits ultrasonic transmission pulses to the surface of the liquid and receives the ultrasonic echo pulses reflected from the liquid surface. The level in the vessel is established from the transit time of the ultrasonic pulses. To detect an overfill when the ultrasonic transducer is immersed in the liquid, the decaying output signal of the ultrasonic transducer generated by the ringing of the ultrasonic transducer following the end of the each ultrasonic transmission pulse is analyzed. With this arrangement, Getman et al. [15] claim that due to the better coupling of the ultrasonic transducer to the liquid than to air, the ringing duration is shorter when the ultrasonic transducer is covered by the liquid.

Lichte [16] described a fluid volume measurement system, where an ultrasonic sensor is mounted at the bottom of the tank. Echo pulses are transmitted from the sensor and travel through the fluid and reflect back, as shown in Fig. 2.11.

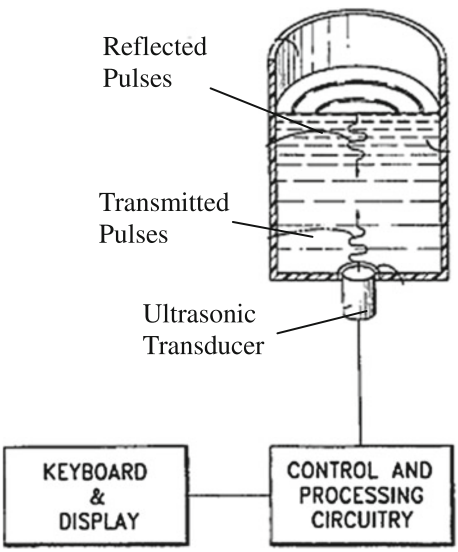


Fig. 2.11 An ultrasonic sensor based volume sensing system [16]

Marini et al. [17] described a method that determines the ratio of the volume of the gas present in an enclosure containing a diphase liquid–gas mixture to the total volume of the enclosure. The undissolved gas in the liquid is assumed to be in the form of a layer surmounting the liquid. This method requires an extremely rapid determination of the void coefficient. The time delay between the first frequency and the second frequency is used to determine the form of gas in the enclosure. Thereafter, the void coefficient is determined from the propagation velocities of the ultrasound in the gas and the liquid and from the measured propagation time of the ultrasonic waves. Ultrasonic waves at different frequencies are propagated through the fluid filling the enclosure. The propagation times of the waves are measured and the difference between these propagation times is calculated. If the propagation times are identical, it is deduced that all the gas is in the form of a layer surmounting the liquid. The void coefficient is determined from the propagation velocities of the ultrasound in the gas and the liquid and from the measured propagation time. If the propagation times are different, a part of the gas is in the form of bubbles in the liquid, the void coefficient due to the gas surmounting the liquid and the void coefficient due to the gas bubbles in the liquid are determined separately. The total void coefficient is determined by adding the two values obtained. The void coefficient due to the gas surmounting the liquid may be determined by virtue of the waves reflected by the gas–liquid interface. The void coefficient due to the gas bubbles is determined by virtue of the relationships existing between the velocity of the ultrasound and the frequency of the waves, according to the pressure and the void coefficient. This invention was used in the measurement of the void coefficient in a pressurized water nuclear reactor after an accident [17].

2.4 Ultrasonic Sensor Based Level Measurement in Dynamic Environments

2.4.1 Overview

Any kind of sound—in contrast to electromagnetic waves—can only be propagated in a material medium, and is strongly influenced by that medium, the velocity of sound, as well as its attenuation, depend in a characteristic way on the nature of the medium [4]. As described in Sect. 2.2.3, any change in temperature will alter the velocity of the ultrasonic wave. Since the velocity of sound varies with temperature, if the measurement system assumes the sound velocity to be constant, such a system will produce unreliable results and measurement accuracy will deteriorate. Apart from the temperature factor affecting fluid level measurement systems, contamination could be another factor that acts as a barrier, by reflecting the echo pulse back sooner than it should normally do, thus deceiving the system and creating errors. This section discusses the issues of ultrasonic level sensing in dynamic environments.

2.4.2 Effects of Temperature Variations

As discussed earlier, the variation in the ambient temperature influences the speed of sound. Since the variation in ambient temperature is continuous, the speed of the ultrasonic wave should not be considered constant. In vehicular fuel tanks, the temperature can vary from −40 to 110 °C. To improve the reliability of ultrasonic sensing systems, generally a temperature sensor is included in the system design to adjust the speed of ultrasonic waves used in the level calculation by using Eq. (1.1), which describes the relationship between the speed of the ultrasonic wave and temperature.

Crayton et al. [18] described a way to determine the fuel level in a storage tank using an ultrasonic sensor by controlling a Motorola's 68HC05 type microcontroller. This system is designed to perform calculations and produce fuel level output signals. The microprocessor is programmed to consider the effects of temperature variations on the speed of sound. For this, a temperature sensor is implanted in the tank that feeds temperature values into the microprocessor, which then compensates for the effects of temperature and reduces the output error. Crayton et al. [18] have claimed that the performance of the level sensing system is not degraded by the effects of temperature and rugged terrain that may cause the storage tank to tilt up to 45° in any direction [18].

Forgue [19] described a fluid level sensor that is able determine the ultrasonic velocity for the purpose of calibration of the fluid level measurement that is compensated for temperature, fluid composition, and other velocity affecting factors. It generally consists of a single ultrasonic transceiver and a housing component. The ultrasonic transceiver has a measurement section and a reference section that are separated by an insulating section, while the housing component has a reference element and an aperture that are located at the axial end. The measurement section transmits ultrasonic measurement signals that pass through the aperture and reflect off a fluid surface. The ultrasonic transceiver includes a disk-shaped measurement section and a ring-shaped reference section. An impedance layer is located adjacent to the ultrasonic transceiver such that ultrasonic signals pass through the impedance layer. The sensors signals are fed into an electronic controller to determine a signal velocity calibrated measurement of the fluid level that is compensated for temperature, fluid composition, and other velocity affecting factors [19].

Combs et al. [20] described an ultrasonic liquid level measurement device used to measure the depth of a flowing liquid in a channel using an ultrasonic transducer. An ultrasonic burst is directed toward the channel and the reflected echo from the surface of the liquid is returned and sensed by the transducer. The transit time of ultrasonic transmission and echo return is indicative of the liquid level. An adjustable discriminator is provided to specify a maximum liquid level in the channel and a minimum liquid level, which, typically is the floor of the channel. The maximum and minimum levels are adjustable to accommodate variable channel configurations and transducer mounting arrangements. Automatic adjustment is provided to compensate for different cable lengths which may be used to connect the ultrasonic transducer to the transducer driver and receiving section. Temperature compensation is provided to accommodate changes in ultrasonic transmission propagation through ambient air with temperature, and time variable gain amplification is provided to compensate for geometric spreading of reflected ultrasonic energy echo pulses and for air path absorption [20].

Durkee [21] described an ultrasonic based fluid quantity measurement system that takes the effects of liquid temperature into consideration. The method does this by measuring the temperature of the liquid at at least two different heights. The method then determines the velocity of sound in the liquid at at least two different predetermined heights. It then establishes an approximation of a velocity of sound versus temperature profile for the liquid and determining an approximation of a velocity of sound versus height profile for each of at least two height regions based on the temperature measurements [21].

Crayton et al. [18] described a measuring system that determines the height of liquid contained in a storage tank. A tube is placed inside the tank which contains a float that is buoyed on the surface of the liquid. An ultrasonic transducer is placed inside the tube. The ultrasonic transducer emits ultrasonic pulses directed at the float, receives the reflected ultrasonic pulses, and responsively produces an echo signal. The float has a top portion and a bottom portion separated by a cylindrical portion. The bottom portion including a spherical surface which receives the ultrasonic pulses. The spherical surface has a predetermined radius which is a function of the inside diameter of the tube, the height of the cylindrical portion of the float, and the outside diameter of the cylindrical portion of the float. A temperature sensor monitors the temperature of the liquid and produces a thermometric signal in response to the liquid temperature. A microprocessor receives the echo and thermometric signals, determines the speed of the ultrasonic pulse traveling in the liquid, and responsively determines the liquid height [18].

2.4.3 Electromagnetic Interference

Birkett [22] has described a method of fluid level measurement that reduces the effects of electromagnetic interference (EMI) that can adversely affect the measurements obtained by the device. For providing better shielding from EMI, the piezoelectric crystal and other electrical components are enclosed in a tube. The piezoelectric device is positioned at the end of the tube so as to direct the ultrasonic pulse along the axis of the stillwell. The interior walls of the enclosure are provided with a metallic layer to block electromagnetic interference from the interior space [22].

2.4.4 Effects of Contaminants and Obstacles

Puttmer et al. [23] introduced a low noise ultrasonic density sensor configuration with high accuracy, long-term stability, and robustness by taking into account significant effects such as: drift of the piezoceramic transducer and electronic system; chemical, geometric, and acoustic properties of the reference material; reduction of signal amplitude or signal-to-noise-ratio (SNR) by the acoustic reference path; and the acoustic field. The sensor consists of a transducer with a piezoceramic disk mounted between two reference rods of quartz glass. Additionally, a second transducer is used as an ultrasound receiver. The density is obtained from the reflection coefficient of ultrasound at the interface between the quartz glass rod and the liquid and the transit time of sound between this interface and the second transducer. The reference signal is generated using the sound radiated from the rear side of the piezoceramic disk [23].

Borenstein et al. [24] categorized different types of noise and discussed methods for eliminating effects of each type of noise. Borenstein et al. [24] introduced a method called error eliminating rapid ultrasonic firing (EERUF), which combines different noise rejection techniques and optimizes them for rapid firing. EERUF almost completely eliminates crosstalk. Its unique noise rejection capability allows multiple mobile robots to collaborate in the same environment, even if their ultrasonic sensors operate at the same frequencies. For each noise category, methods are described to identify and reject the resulting errors. These individual rejection measures were combined into one error rejection method which was then combined with a fast firing algorithm. The resulting combination was EERUF. The EERUF method was implemented on a mobile robot; as a result, a mobile robot was able to traverse an obstacle course of densely spaced, pencil-thin poles at speeds of up to 1 m/s.

Soltz [25] described an ultrasonic liquid level measurement gauge that can determine true ultrasonic echo pulses from false parasitic pulses originating from reflecting wall surfaces and other obstacles in the vicinity of the tank. The parasitic pulses may be confused with the main echo pulses and can result in an erroneous reading [25].

Durkee [26] described an ultrasonic liquid gauging systems that is generally related to improving the detection of valid echoes under low liquid level and echo drop out conditions to improve the accuracy of the measured liquid quantity. A particular problem that can arise at low liquid levels is the detection of secondary and tertiary echoes from multiple or harmonic reflections at the liquid surface of the transmitted ultrasonic energy. The effects can cause echoes to be lost or missed, including echoes from the surface as well as from the target.

Kumar [27] has described an ultrasonic liquid level gauging system that can discriminate true echoes from false echoes. The device uses echo energy as a factor to distinguish a true echo from a false echo [27].

2.5 Effects of Liquid Sloshing

2.5.1 Overview

In mobile fluid tanks such as automotive fuel tanks, acceleration will induce waves in the storage tank. This phenomenon of fluid fluctuation is called *sloshing*. The magnitude of sloshing is dependent on the value of the acceleration or deceleration that may be caused by braking, speeding, and irregular terrain. A level measurement device observing the fluid level under sloshing conditions will produce erroneous level readings.

The sloshing phenomenon in moving rectangular tanks (e.g., automotive fuel tanks) can be usually described by considering only two-dimensional fluid flow, if the width of the tank is much less than its breadth [28]. The main factors contributing to the sloshing phenomenon are the acceleration exerted on the tank, amount of existing fluid, internal baffles, and the geometry of the tank [29, 31]. A detailed analysis of liquid sloshing using the numerical approach for various tank configurations has been provided in the literature [29–39].

Different designs of fluid level measurement systems have used different techniques to compensate for the erroneous reading of liquid level due to the effects of sloshing. This section of the literature review focuses on some level sensing devices that attempt to operate effectively in both static and dynamic environments.

2.5.2 Slosh Compensation by Dampening Methods

Fluid sloshing can be physically and electrically dampened to compensate for the sloshing effects. The following diagram shows a basic geometrical dampening method. The sensor is placed inside a vessel, where fluid can enter from the bottom of the vessel. The fluid stored in the vessel will experience less slosh than the fluid outside the vessel. Therefore, the fluid inside the vessel will be stable relative to the outside level. Various methods have been investigated that generally follow a similar principle (Fig. 2.12).

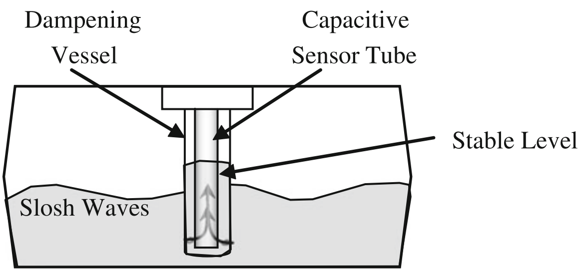


Fig. 2.12 Geometrically dampening the slosh waves

Kikuta et al. [40] described an ultrasonic level gauge that measures the level of a test surface inside a tank. It can measure the level of a test surface even when the distance between the test surface and the ultrasonic transceiver is very small. The level gauge includes a guiding pipe that guides the ultrasonic wave transmitted by an ultrasonic transceiver to the test surface, and guides the ultrasonic wave reflected by the test surface back to the ultrasonic transceiver. The gauge is capable of having an extended portion at the base of the guiding pipe that extends the propagation distance of the ultrasonic wave guided by this guiding pipe. A helical portion or a slanting portion may be provided in the guiding pipe to make the ultrasonic wave transmitted by the ultrasonic transceiver enter the test surface in a slanting direction. Since the ultrasonic wave making a round trip between ultrasonic transceiver and the liquid surface is guided by the guiding pipe, reflection of the ultrasonic wave by any of the inner walls of the tank does not occur. As a result, any measurement error due to the reflection by the inner walls of the tank, other than the liquid surface, can be prevented. It can also minimize the measurement error of the liquid level of the test surface even when the liquid is shaken, as in a fuel tank inside a car, while the car is moving.

2.5.3 *Use of Tilt Sensors*

Tiltmeters or inclinometers can be used in situations where the fluid tank can experience sloppy surfaces such as rough roads in hilly areas. Nawrocki [41] described a method that incorporates an inclinometer into a fuel gauging device. The level signal from the fuel level sensor can be transmitted to the fuel gauge only when the vehicle is tilted less than a predetermined degree. To accomplish this, a signal from the fuel sensor is passed through to the display by a microprocessor only when the vehicle is substantially level and not accelerating or decelerating. When the level condition is met, the signal indicative of the amount of fuel left in the tank is stored in the microprocessor memory and displayed on the fuel gauge, and is updated again when the vehicle reaches the next level condition. Alternatively, a correction factor matrix stored in the memory can be applied to the signal received from the fuel sensor to calculate a corrected signal indicative of the amount of fuel remaining in the fuel tank. Figure 2.13 shows an overview of the method described by Nawrocki [41].

Breed et al. [42] described a fuel level measurement system that measures the quantity of fuel in a tank using one or more load cells or fuel level measuring devices and other sensors to measure the pitch or roll angle of the vehicle. A processor and algorithm, which may be a look-up table or formulae, are combined to correct for the inaccuracies arising from the pitch and roll angles of the vehicle, other external forces, or from variations in fuel density. This method supports a variety of different fuel measuring transducers which by themselves give an inaccurate measurement of the quantity of fuel in the tank, but when combined with an empirically derived algorithm results in a highly accurate fuel quantity

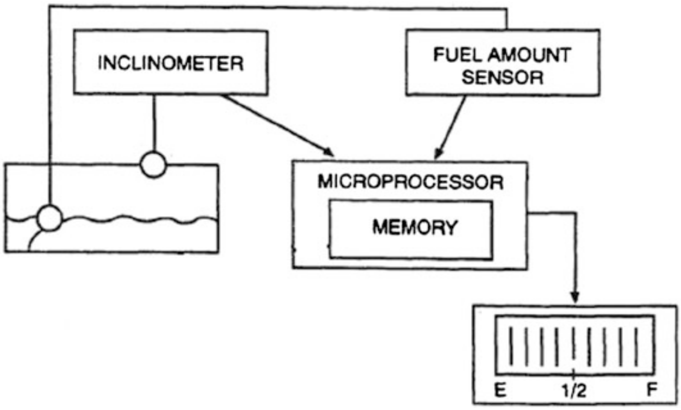


Fig. 2.13 Fuel level measurement system having an inclinometer [41]

measurement system. These transducers can be weight measuring load cells, vehicle angle measuring transducers, or fuel level measuring devices based on either float, ultrasonic, or capacitive measurement devices.

The method described by Breed et al. [42] comprises steps of: generating an algorithm for use on the vehicle by placing a known quantity of fuel into the tank. It then collects reflected wave patterns from ultrasonic transducers arranged on the bottom of the tank at discrete locations. It then compares the wave patterns from the ultrasonic transducers reflected under various conditions from an at rest position to a driving state over a variety of road surfaces. The wave patterns are inputted into a neural network generating program to classify different wave patterns [42].

Figure 2.14 shows an ultrasonic filling level sensor described by Voss [43], which has an elongated measuring chamber that is provided with an opening at each of its two ends. The sensor includes an ultrasonic transceiver, which is associated with one end of the measuring chamber and the emitted sound signals which are reflected at the surface of the liquid and at a calibrating reflector and received by the ultrasonic transceiver, in order to determine the filling level from the relationship between the transit times of the two signals. It is ensured that the cross-section of the measuring chamber and the nature of a wall of the measuring chamber are made to suit the properties of the liquid in such a way that, even in a tilted position of the measuring chamber, the surface of the liquid forms a meniscus which forms a reflection portion directed toward the ultrasonic transceiver. When elongated measuring chambers are used, the sound waves are emitted by a transceiver disposed at the bottom of the measuring chamber. They pass through the elongated measuring chamber substantially without being reflected at the walls of the measuring chamber, to be reflected at the surface of the liquid. Only the portion of the reflected sound signals that is reflected precisely in its direction reaches the transceiver. Such a filling level sensor only functions when the reflection area is directed toward the ultrasonic transceiver, that is to say

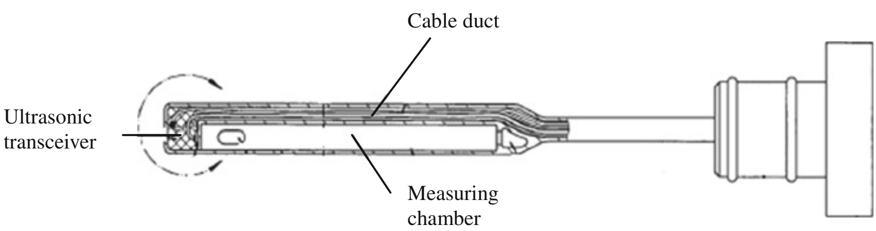


Fig. 2.14 Oil pump dipstick used in motorcycle engines [43]

extends substantially transversely to the longitudinal direction of the measuring chamber. For this reason, the known ultrasonic filling level sensors can only be used in a vertical position. This invention is therefore based on the object of developing an ultrasonic filling level sensor of the generic type which is simpler in terms of production engineering and advantageous in use [43].

2.5.4 Averaging Methods

Averaging method is another method besides the mechanical dampening that can compensate for the sloshing effects and produce better level readings. This statistical method generally collects the past sample values and determines the future level reading by using different calculation techniques. There have been a few different averaging techniques applied in the past that include a simple Arithmetic Mean, Weighted Average, and Variable Averaging Interval.

2.5.4.1 Arithmetic Mean

Arithmetic mean or simply mean is the traditional method of averaging the level sensor readings. The mean value of the sampled signal $x = [x_1, x_2, x_3, \ldots, x_n]$ for n number of samples is calculated using:

$$\mathrm{mean}(x) = \bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{2.9}$$

The downside of averaging is that it produces a significant error for a momentarily large spike or an abnormal data entry in the elements of x. For example, if a sampled signal is given as:

$$x = [1.21, 1.30, 1.25, 1.27, 1.23, 1.91] \tag{2.10}$$

$$\bar{x} = \frac{1.21 + 1.30 + 1.25 + 1.27 + 1.23 + 1.91}{6} = 1.36 \tag{2.11}$$

$$\bar{x} = \frac{1.21 + 1.30 + 1.25 + 1.27 + 1.23}{5} = 1.25 \quad (2.12)$$

The average value obtained in the presence of an abnormal entry '1.91' in signal x is given in (2.11), which is significantly larger than the average value when obtained without '1.91' element in x (2.12).

Gazis et al. [44] described an ultrasonic liquid level gauge design, in which one or more high-frequency ultrasonic transducers are used to measure the liquid level of tanks containing any type of fluid. The invention relates specifically to tanks that are subject to movement and vibration which generally makes the use of ultrasonic echoes unreliable for obtaining accurate level measurements. A special algorithm is used to obtain the temporal center of the distribution of echo arrival times over a preset time interval. From this temporal center of an echo distribution, the liquid level is readily obtained through the acoustic velocity, time, and distance relationship. An annular piezoelectric plate, independently driven at low ultrasonic frequencies (kHz range), mounted on the tank bottom surrounds the high-frequency ultrasonic transducer. The function of the piezoelectric plate is to send out propagating ultrasonic waves (essentially longitudinal) to maintain the tank area in the immediate region of the high-frequency transducer free from debris and sediment deposits at the bottom of the tank thereby avoiding the uncertainty in the measurement that is introduced by debris on the tank bottom. The device uses a continuous or quasi-continuous signal averaging technique to present a distribution of echo signals as a function of time from which liquid levels can be accurately determined and monitored on a continuous or quasi-continuous basis. Several averaging methods are described from which the temporal center of the distribution can be determined. One or more ultrasonic transducers are firmly mounted on the bottom of a fuel tank to transmit and receive acoustic pulses. The received echo pulses are rectified and filtered before a channel analyzer processes it. Signal processing is used to determine the center of the echo time. This time is then used by a computer to obtain the level of the fluid in the tank [44].

An improved version of averaging is described by Tsuchida et al. [45]. Their method determines the center value of the past sensor readings. The center value is assumed to be the accurate level reading. The method repeatedly reads the amount of fuel remaining in the fuel tank of a vehicle and then it determines a center value from the past fuel quantity readings. A microcontroller is used to determine limit values for the center value by a predetermined margin. A subsequent value that exceeds the limit values is set as a new limit value. The method then determines an average value out of the predetermined number of detected sampling values. The method also performs the function of discriminating and eliminating any sudden changes or abnormal values that may be caused by the sudden changes in the attitude of the vehicle or by the acceleration to provided stable values of the remaining fuel quantity [45].

2.5.4.2 Weighted Average

Weighted average is similar to the simple averaging method, except that there are additional weights (w) assigned to each element in the sample signal $x = [x_1, x_2, x_3,\ldots,x_n]$. In the absence of the weights, all data elements in x contribute equally to the final average value. But, with the usage of the additional weights (w), the final average can be controlled. If all the weights are equal, then the weighted mean is the same as the arithmetic mean. The weighted average of a signal $x = [x_1, x_2, x_3,\ldots,x_n]$ and the weights $w = [w_1,w_2,w_3, \ldots,w_n]$ for n number of sampled points can be calculated using:

$$W_{\text{mean}}(x) = \bar{x} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i},\ w_i > 0 \tag{2.13}$$

2.5.4.3 Variable Averaging Interval

In the variable averaging method, raw sensor readings are averaged at different time intervals depending on the state or motion of the vehicle. During static conditions, when the vehicle is stationary or when the vehicle is operating at a low speed, the averaging time is reduced to a small interval to quickly update the sensor readings by assuming that there will be negligible slosh. During the dynamic conditions, the averaging period is increased for averaging the sensor readings over a longer period of time. Normally, a speed sensor is used to determine the running state of the vehicle.

Kobayashi et al. [46] described a sensor that uses digital signals as opposed to analog signals to determine the fluid volume in a fuel storage tank. The digital fuel volume measuring system can indicate the amount of fuel within a fuel tank precisely in the unit of 1.0 or 0.1 l. The volume detection signals are simply averaged during a relatively short averaging time period at regular measuring cycles when the vehicle is being refueled, and further weight-averaged or moving-averaged at regular measuring cycles when the vehicle is running. Therefore, fuel volume can be indicated quickly at a short response speed when the vehicle is being refueled and additionally fluctuations in the fuel volume reading can be minimized when the vehicle is running. Further, the system discloses the method of detecting the state where the vehicle is being refueled on the basis of the fact that the difference between at least one of the current data signal indicative of fuel volume and at least one of the preceding data signal indicative of fuel volume exceeds a predetermined value [46].

Guertler et al. [47] described a process that determines the quantity of a liquid contained in a largely closed system. The liquid fluctuations in a dynamic or a moving vehicle can produce erroneous results. These fluctuations can be calculated out as the result of the predetermined dependence of the liquid level and therefore of the amount of fluid from the driving condition and, in addition, can be statistically averaged out because of the continuous obtaining of measuring values. This permits the reliable determination of the fluid quantity whose level fluctuates as a function of the driving condition by way of level measurements not only when the vehicle is stopped and the engine is switched-off, but also in the continuous driving operation.

Kobayashi et al. [48] utilize the information about the various different states of the vehicle, such as ignition ON–OFF, idle state, and up and down speeding. The fuel level readings are averaged over time intervals which vary according to whether the liquid level of the fuel in the tank is stable or unstable. A fuel quantity is calculated and displayed according to the averaged value. The stable or unstable condition of the fuel level is discriminated in accordance with vehicle speed, the "on" or "off" position of an ignition switch. Accordingly, when the fuel level is unstable, the signal value is averaged over a time interval which is longer than that used when the fuel level is stable so that the response of display to variation of the fuel level is improved [48].

2.6 Summary

A detailed investigation of ultrasonic sensing technology described in this chapter reveals the fact that ultrasonic technology is increasingly being used in a broad range of applications due to its nonmechanical and contactless nature; robustness in harsh environments; its ability to work with a wide range of chemical substances; compact and flexible size; longer functional life; and lower manufacturing cost.

Even though the uses of ultrasonic sensing technology in fluid level measurement systems has produced satisfactory outcomes in a broad range of applications, the literature review has highlighted some of the weaknesses of ultrasonic sensing technology in relation to its accuracy in level measurement particularly in dynamic environments. Level sensing in dynamic environments is characterized by three factors:

- Slosh
- Temperature variation
- Contamination (obstacles and dust)

Solutions to each of these three above mentioned factors have been reviewed in this chapter. However, all these solutions entail either higher production cost because of the requirement for additional sensors, or they provide only marginal improvement in terms of accuracy compared to current systems [46–48].

To provide a practical and compact solution to the above mentioned problems pertaining to the inaccuracy of ultrasonic level sensing systems in dynamic environments, an intelligent ultrasonic sensor system is to be developed for fluid level sensing with the incorporation of a Support Vector Machine (SMV) based signal characterization and classification methodology.

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