Chapter 2
Capacitive Sensing Technology

2.1 Overview

This chapter describes the basic properties of capacitive sensor technologies and their use in various kinds of sensors in industrial applications. Physical properties as well as some limitations of capacitive sensing are described here. The use of capacitive sensors with hazardous fluids, such as gasoline based fuels, and various configurations of capacitive sensors used in the application of fluid level measurement in dynamic environments are described. In brief, this chapter provides information on capacitive sensing technology and its use in dynamic and hostile environments.

2.2 Characteristics of Capacitors

2.2.1 Overview

Capacitors are the basic building blocks of the electronic world. To understand how capacitive sensors operate, it is important to understand the fundamental properties and principles of capacitors. This section provides details on the underlying principles of the capacitor. The physical, geometrical, and the electrical properties of capacitors are discussed in this section.

2.2.2 A Capacitor

A capacitor is a device that consists of two electrodes separated by an insulator [1]. Capacitors are generally composed of two conducting plates separated by a non-

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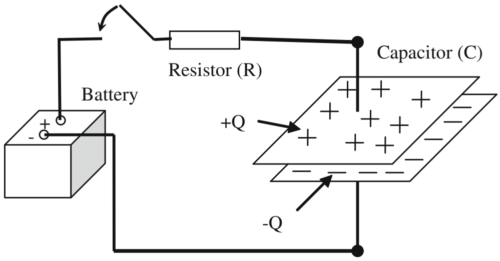


Fig. 2.1 Capacitor used in a circuit to store electrical charge

conducting substance called dielectric (ε_r) [1, 2]. The dielectric may be air, mica, ceramic, fuel, or other suitable insulating material [2]. The electrical energy or charge is stored on these plates. Figure 2.1 illustrates a basic circuit configuration that charges the capacitor as soon as the switch is closed.

Once a voltage is applied across the two terminals of the capacitor, the conducting plates will start to store electrical energy until the potential difference across the capacitor matches with the source voltage. The electrical charge remains on the plates after disconnecting the voltage source unless another component consumes this charge or the capacitor loses its charge because of leakage, since no dielectric is a perfect insulator. Capacitors with little leakage can hold their charge for a considerable period of time [2]. The plate connected with the positive terminal stores positive charge (or +Q) on its surface and the plate connected to the negative terminal stores negative charge (or −Q).

The time required to fully charge a capacitor is determined by *Time Constant* (τ). The value of the time constant describes the time it takes to charge a capacitor to 63% of its total capacity [1]. The time constant (τ) is measured in seconds and can be defined as in Eq. 2.1, where, R is the resistor connected inline with the capacitor having C capacitance.

$$\tau = RC \tag{2.1}$$

2.2.3 Capacitance

Capacitance is the electrical property of capacitors. It is the measure of the amount of charge that a capacitor can hold at a given voltage [2]. Capacitance is measured in Farad (F) and it can be defined in the unit *coulomb per volt* as:

$$C = \frac{Q}{V} \tag{2.2}$$

where,

C is the capacitance in farad (F),
Q is the magnitude of charge stored on each plate (coulomb),
V is the voltage applied to the plates (volts).

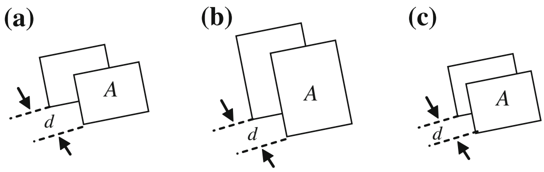


Fig. 2.2 Factors influencing capacitance value. **a** Normal. **b** Increased surface area, increased capacitance. **c** Decreased gap distance, increased capacitance

A capacitor with the capacitance of one farad can store one coulomb of charge when the voltage across its terminals is 1 V [2]. Typical capacitance values range from about 1 pF (10^{-12} F) to about 1,000 μF (10^{-3} F) [3]. An electric field will exist between the two plates of a capacitor if the voltage is applied to one of the plates [1]. The resulting electric field is due to the difference between the electric charges stored on the surfaces of each plate. The capacitance describes the effects on the electric field due to the space between the two plates.

The capacitance depends on the geometry of the conductors and not on an external source of charge or potential difference [2, 4]. The space between the two plates of the capacitor is covered with dielectric material. In general, the capacitance value is determined by the dielectric material, distance between the plates, and the area of each plate (illustrated in Fig. 2.2). The capacitance of a capacitor can be expressed in terms of its geometry and dielectric constant as [5]:

$$C = \varepsilon_r \frac{\varepsilon_0 A}{d} \tag{2.3}$$

where,

C is the capacitance in farads (F),

ε_r is the relative static permittivity (dielectric constant) of the material between the plates,

ε_0 is the permittivity of free space, which is equal to $8.854 \times 10^{-12}\,\mathrm{F/m}$,

A is the area of each plate, in square meters and

d is the separation distance (in meters) of the two plates.

The capacitance phenomenon is related to the electric field between the two plates of the capacitor [6]. The electric field strength between the two plates decreases as the distance between the two conducting plates increases [1]. Lower field strength or greater separation distance will lower the capacitance value. The conducting plates with larger surface area are able to store more electrical charge; therefore, a larger capacitance value is obtained with greater surface area.

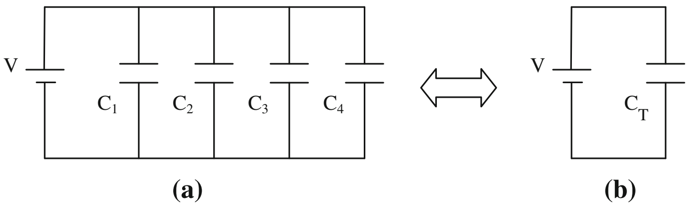


Fig. 2.3 Net capacitance of capacitors connected in parallel

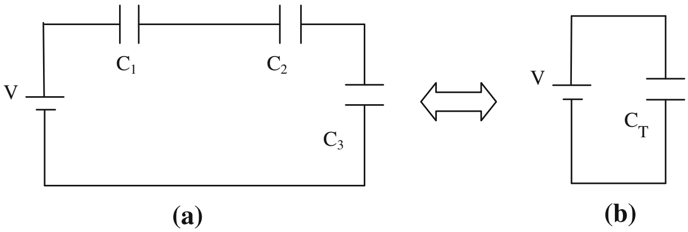


Fig. 2.4 Net capacitance of capacitors connected in series

2.2.4 Capacitance in Parallel and Series Circuits

The net capacitance of two or more capacitors, connected next to each other, depends on their connection configurations [3]. If two capacitors are connected in parallel, they both will have the same voltage across them; therefore, their net capacitance will be the sum of the two capacitances. The net capacitance of a parallel combination of capacitors is given as [4]:

$$C_{\mathrm{T}} = \frac{Q_1}{V} + \frac{Q_2}{V} + \cdots + \frac{Q_n}{V}, \text{ or} \tag{2.4}$$

$$C_{\mathrm{T}} = C_1 + C_2 + \cdots + C_n \tag{2.5}$$

where, C_{T} is the total capacitance of the capacitors connected in parallel.

Figure 2.3 shows the circuit configuration of multiple capacitors having capacitances (C_1, C_2,…, C_4). Both circuits (a) and (b) have the equivalent capacitance C_{T}, which is the sum of all capacitances. However, if two or more capacitors are connected in series, the voltage across the two terminals may be different for each capacitor; although the electric charge will be the same on all of them [4]. The equivalent capacitance of capacitors connected in series can be stated as (Fig. 2.4):

$$\frac{1}{C_{\mathrm{T}}} = \frac{V_1}{Q} + \frac{V_2}{Q} + \cdots + \frac{V_n}{Q}, \text{ or} \tag{2.6}$$

$$\frac{1}{C_{\mathrm{T}}} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots + \frac{1}{C_n} \tag{2.7}$$

Table 2.1 Commonly used dielectric materials and their values [4, 6]

Material	Dielectric constant	Material	Dielectric constant
Accetone	19.5	Mica	5.7–6.7
Air	1.0	Paper	1.6–2.6
Alcohol	25.8	Petroleum	2.0–2.2
Ammonia	15–25.0	Polystyene	3.0
Carbon dioxide	1.0	Powdered milk	3.5–4.0
Chlorine liquid	2.0	Salt	6.1
Ethanol	24.0	Sugar	3.3
Gasoline	2.2	Transformer oil	2.2
Glycerin	47.0	Turpentine oil	2.2
Hard paper	4.5	Water	80.0

2.2.5 Dielectric Constant

The gap between the two surfaces of a capacitor is filled with a non-conducting material such as rubber, glass or, wood that separates the two electrodes of the capacitor [4]. This material has a certain dielectric constant. The *dielectric constant* is the measure of a material's influence on the electric field. The net capacitance will increase or decrease depending on the type of dielectric material. Permittivity relates to a material's ability to transmit an electric field. In the capacitors, an increased permittivity allows the same charge to be stored with a smaller electric field, leading to an increased capacitance.

According to Eq. 2.3, the capacitance is proportional to the amount of dielectric constant. As the dielectric constant between the capacitive plates of a capacitor rises, the capacitance will also increase accordingly. The capacitance can be stated in terms of the dielectric constant, as [4]:

$$C = \varepsilon_r \cdot C_0 \tag{2.8}$$

where, C is the capacitance in Farads, ε_r is the dielectric constant and C_0 is the capacitance in the absence of dielectric constant.

Different materials have different magnitudes of dielectric constant. For example, air has a nominal dielectric constant equal to 1.0, and some common oils or fluids such as gasoline have nominal dielectric constant of 2.2. If gasoline is used as dielectric instead of air, the capacitance value using the gasoline as dielectric will increase by a factor of 2.2. This factor is called *Relative dielectric constant* or *Relative electric permittivity* [2]. Some commonly used dielectric materials and their corresponding dielectric values are listed in Table 2.1.

2.2.6 Dielectric Strength

The electrical insulating properties of any material are dependent on dielectric strength [7]. The dielectric strength of an insulating material describes the

Table 2.2 Approximate dielectric strengths of various materials [4]

Material	Dielectric strength (10^6 V/m)	Material	Dielectric strength (10^6 V/m)
Air (dry)	3	Polystyrene	24
Bakelite	24	Polyvinyl chloride	40
Fused quartz	8	Porcelain	12
Mylar	7	Pyrex glass	14
Neoprene rubber	12	Silicone oil	15
Nylon	14	Strontium titanate	8
Paper	16	Teflon	60
Paraffin-impregnated paper	11		

maximum electric field of that material. If the magnitude of the electric field across the dielectric material exceeds the value of the dielectric strength, the insulating properties of the dielectric material will breakdown and the dielectric material will begin to conduct [1]. The breakdown voltage or rated voltage of a capacitor represents the largest voltage that can be applied to the capacitor without exceeding the dielectric strength of the dielectric material [1]. The applied voltage across a capacitor must be less than its rated voltage. The operating voltage across a capacitor can be increased depending on the insulating material or the dielectric constant. Teflon and Polyvinyl chloride have greater dielectric strength. The dielectric constant can be increased by adding high dielectric constant filler material [8]. Table 2.2 lists the dielectric strength values for different types of materials at room temperature.

Factors such as thickness of the specimen, operating temperature, frequency, and humidity can affect the strength of the dielectric materials.

2.3 Capacitive Sensor Applications

2.3.1 Overview

A capacitive sensor converts a change in position, or properties of the dielectric material into an electrical signal [9]. According to the Eq. 2.3 in Sect. 2.2.3, capacitive sensors are realized by varying any of the three parameters of a capacitor: *distance* (d), *area of capacitive plates* (A), and *dielectric constant* (ε_r); therefore:

$$C = f(d, A, \varepsilon_r) \tag{2.9}$$

A wide variety of different kinds of sensors have been developed that are primarily based on the capacitive principle described in Eq. 2.3. These sensors' functionalities range from humidity sensing, through level sensing, to

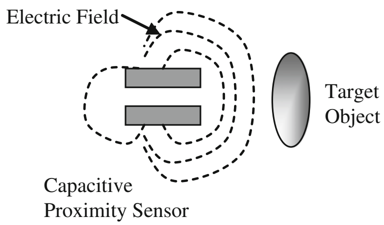


Fig. 2.5 Capacitance based proximity sensor

displacement sensing [10]. A number of different kinds of capacitance based sensors used in a variety of industrial and automotive applications are discussed in this section.

2.3.2 Proximity Sensing

A proximity sensor is a transducer that is able to detect the presence of nearby objects without any physical contact. Normally a proximity sensor emits an electromagnetic or electrostatic field, or a beam of electromagnetic radiation (e.g. infrared), and detects any change in the field or return signal. Capacitive type proximity sensors consist of an oscillator whose frequency is determined by an inductance–capacitance (LC) circuit to which a metal plate is connected. When a conducting or partially conducting object comes near the plate, the mutual capacitance changes the oscillator frequency. This change is detected and sent to the controller unit [11]. The object being sensed is often referred to as the proximity sensor's target. Figure 2.5 shows an example of the capacitive proximity sensor. As the distance between the proximity sensor and the target object gets smaller, the electric field distributed around the capacitor experiences a change, which is detected by the controller unit.

The maximum distance that a proximity sensor can detect is defined as 'nominal range'. Some sensors have adjustments of the nominal range or ways to report a graduated detection distance. A proximity sensor adjusted to a very short range is often used as a touch switch. Capacitive proximity detectors have a range twice that of inductive sensors, while they detect not only metal objects but also dielectrics such as paper, glass, wood, and plastics [12]. They can even detect through a wall or cardboard box [12]. Because the human body behaves as an electric conductor at low frequencies, capacitive sensors have been used for human tremor measurement and in intrusion alarms [12]. Capacitive type proximity sensors have a high reliability and long functional life because of the absence of mechanical parts and lack of physical contact between sensor and the sensed object.

An example of a proximity sensor is a limit switch, which is a mechanical push-button switch that is mounted in such a way that it is activated when a mechanical part or lever arm gets to the end of its intended travel [13]. It can be implemented in an automatic garage door opener; where the controller needs to know if the door is all the way open or all the way closed [13]. Other applications of the capacitive proximity sensors are:

- *Spacing*—If a metal object is near a capacitor electrode, the mutual capacitance is a very sensitive measure of spacing [14].
- *Thickness measurement*—Two plates in contact with an insulator will measure the insulator thickness if its dielectric constant is known, or the dielectric constant if the thickness is known [14].
- *Pressure sensing*—A diaphragm with stable deflection properties can measure pressure with a spacing-sensitive detector [14].

2.3.3 Position Sensing

A position sensor is a device that allows position measurement. Position can be either an absolute position or a relative one [15]. Linear as well as angular position can be measured using position sensors. Position sensors are used in many industrial applications such as fluid level measurement, shaft angle measurement, gear position sensing, digital encoders and counters, and touch screen coordinate systems. Traditionally, resistive type potentiometers were used to determine rotary and linear position. However, the limited functional life of these sensors caused by mechanical wear has made resistive sensors less attractive for industrial applications. Capacitive type position sensors are normally non-mechanical devices that determine the position based on the physical parameters of the capacitor. Position measurement using a capacitive position sensor can be performed by varying the three capacitive parameters: Area of the capacitive plate, Dielectric constant, and Distance between the plates. The following applications are some examples of the utilization of capacitive position sensors in:

- *Liquid level sensing*—Capacitive liquid level detectors sense the liquid level in a reservoir by measuring changes in capacitance between conducting plates which are immersed in the liquid, or applied to the outside of a non-conducting tank [14].
- *Shaft angle* or *linear position*—Capacitive sensors can measure angle or position with a multi-plate scheme giving high accuracy and digital output, or with an analogue output with less absolute accuracy but faster response and simpler circuitry.
- *X–Y tablet*—Capacitive graphic input tablets of different sizes can replace the computer mouse as an x–y coordinate input device. Finger-touch-sensitive devices such as iPhone [16], z-axis-sensitive and stylus-activated devices are available.
- *Flow meter*—Many types of flow meters convert flow to pressure or displacement, using an orifice for volume flow or Coriolis Effect force for mass flow. Capacitive sensors can then measure the displacement.

2.3.4 Humidity Sensing

The dielectric constant of air is affected by humidity. As humidity increases the dielectric increases [17]. The permittivities of atmospheric air, of some gases, and of many solid materials are functions of moisture content and temperature [10]. Capacitive humidity devices are based on the changes in the permittivity of the dielectric material between plates of capacitors [10]. Capacitive humidity sensors commonly contain layers of hydrophilic inorganic oxides which act as a dielectric [18]. Absorption of polar water molecules has a strong effect on the dielectric constant of the material [18]. The magnitude of this effect increases with a large inner surface which can accept large amounts of water [18].

The ability of the capacitive humidity sensors to function accurately and reliably extends over a wide range of temperatures and pressures. They also exhibit low hysteresis and high stability with minimal maintenance requirements. These features make capacitive humidity sensors viable for many specific operating conditions and ideally suitable for a system where uncertainty of unaccounted conditions exists during operations. There are many types of capacitive humidity sensors, which are mainly formed with aluminium, tantalum, silicon, and polymer types [10].

2.3.5 Tilt Sensing

In recent years, capacitive-type micro-machined accelerometers are gaining popularity. These accelerometers use the proof mass as one plate of the capacitor and use the other plate as the base. When the sensor is accelerated, the proof mass tends to move; thus, the voltage across the capacitor changes. This change in voltage corresponds to the applied acceleration. Micromachined accelerometers have found their way into automotive airbags, automotive suspension systems, stabilization systems for video equipment, transportation shock recorders, and activity responsive pacemakers [19].

Capacitive silicon accelerometers are available in a wide range of specifications. A typical lightweight sensor will have a frequency range of 0–1,000 Hz, and a dynamic range of acceleration of ± 2 to ± 500 g [19]. Analogue Devices, Inc. [20] has introduced integrated accelerometer circuits with a sensitivity of over 1.5 g [14]. With this sensitivity, the device can be used as a tiltmeter [14].

2.4 Capacitors in Level Sensing

2.4.1 Overview

The general properties of the capacitor described in Sect. 2.2.3 can be used to measure the fluid level in a storage tank. In a basic capacitive level sensing system, capacitive sensors have two conducting terminals that establish a capacitor. If the

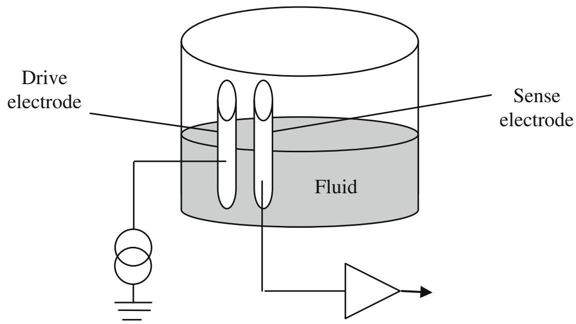


Fig. 2.6 Basic liquid level sensing system

gap between the two rods is fixed, the fluid level can be determined by measuring the capacitance between the conductors immersed in the liquid. Since the capacitance is proportional to the dielectric constant, fluids rising between the two parallel rods will increase the net capacitance of the measuring cell as a function of fluid height. To measure the liquid level, an excitation voltage is applied with a drive electrode and detected with a sense electrode. Figure 2.6 illustrates a basic set-up of a liquid level measurement system.

In this section, various aspects and configurations of capacitive fluid level measurement systems have been described in detail.

2.4.2 Sensing Electrodes

The sensing electrodes of the capacitive sensor could be shaped into various forms and structures. The geometry of the sensing electrodes influences the electric field between them. For example, the capacitance between two parallel rods will be different from that between two parallel plates because of the nature of electric field distribution around an electrically charged object. A few types of sensing electrodes, such as cylindrical rods, rectangular plates, helixical wires, and tubular shaped capacitors are described in this subsection.

2.4.2.1 Cylindrical Rods

Cylindrical rods are made of conductors, where the negative electrode stores the negative charge and the positive electrode stores the positive charge. An electrical field will exist between the two electrodes if a voltage is applied across them.

Figure 2.7 illustrates the two cylindrical rods separated by distance d. The capacitance between the two parallel rods can be determined by the following rule [21]:

$$C = \frac{\pi \varepsilon_0 \varepsilon_r}{\ln \frac{d}{r}} L, \quad \text{If } d \gg r \tag{2.9}$$

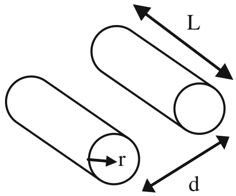


Fig. 2.7 Cylindrical sensing electrodes

$$C = \frac{\pi \varepsilon_0 \varepsilon_r}{\ln\left(\frac{d + \sqrt{d^2 - 4r^2}}{2r}\right)} L, \quad \text{where } d \ll r \tag{2.10}$$

where,

- C is the capacitance in farads (F),
- ε_r is the relative static permittivity (dielectric constant) of the material between the plates,
- ε_0 is the permittivity of free space, which is equal to $8.854 \times 10^{-12}\,\mathrm{F/m}$,
- L is the rod length in meters,
- d is the separation distance (in meters) of the two rods,
- r is the radius of the rod in meters.

2.4.2.2 Cylindrical Tubes

Cylindrical tube based electrodes are commonly used in tubular capacitive sensors. Tubular capacitive sensors have a simple design, which makes them easier to manufacture. Maier [22] has used capacitive sensors that are formed as concentric, elongated cylinders for sensing the fuel level in aircraft fuel tanks. The capacitance of the sensor varies as a function of the fraction of the sensor wetted by the fuel and the un-wetted fraction in the airspace above the fuel/air interface [22].

Figure 2.8 shows an illustration of the cylindrical tube capacitor. A cylindrical capacitor can be thought of as having two cylindrical tubes, inner and outer. The inner cylinder can be connected to the positive terminal, whereas the outer cylinder can be connected to the negative terminal. An electric field will exist if a voltage is applied across the two terminals. If r_a is the radius of the inner cylinder and r_b is the radius of the outer cylinder then the capacitance can be calculated by using:

$$C = \frac{\pi \varepsilon_0 \varepsilon_r}{\ln \frac{r_b}{r_a}} L\,\mathrm{F}. \tag{2.11}$$

Qu et al. [23] used an electrode arrangement having a plurality of electrodes arranged next to each other to measure the liquid level. The device measures the capacitance between a first (lowest) electrode, which is the measurement electrode, and a second electrode as the counter electrode. A controllable switching circuit connects the electrodes to the measurement module. The connection can be switched

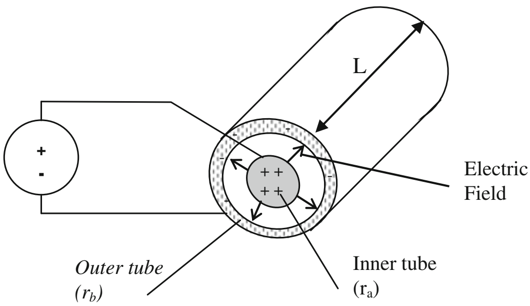


Fig. 2.8 Cylindrical tube capacitor

in a definable manner by the switching module. As the switching module controls the electrodes, each electrode of the electrode arrangement can be switched in alternation as the measurement electrode. At least one of the other electrodes can thereby be switched as the counter electrode to a definable reference potential [23]. The distance between the electrodes is preferred to be the smallest possible. Several electrodes can be implemented in groups to increase the measurement accuracy. By grouping the electrodes, each electrode group can then be alternately switched as a measurement electrode. At least one of the other respective electrode groups will be switched as the counter electrode to the definable reference potential by the switching device [23].

The signals induced on the cable or wire connecting a probe could disturb the analogue measurement signal. The signal disturbances can be caused by an external electromagnetic field, such as generated by a vehicle radio set. To reduce these disturbances, the use of coaxial cables is often preferred [24]. Pardi et al. [24] described a capacitive level sensing probe of a coaxial cylindrical type having a constant diameter. The probe comprises a pair of spaced coaxial electrodes constituting a cylindrical plate capacitor between the plates of which the fuel enters to vary the probe capacitance as a function of fuel level [24]. Yamamoto et al. [25] described a capacitive sensor, where the detecting element comprises: a film portion made of a flexible insulating material extending in a longitudinal direction; and a pair of detecting electrodes juxtaposed to each other on a layer of the film portion and extending in the longitudinal direction. The detecting electrodes are immersed at least partially in the liquid to be measured. The state of the measured liquid is detected on the basis of an electrostatic capacity between a pair of detecting electrodes. The liquid state detecting element further comprises reinforcing portions made of a conductive material and disposed on the layer of film portion on an outer side of the detecting electrodes. The reinforcing portions include: a grounding terminal for being connected with a ground line; and a pair of parallel reinforcing portions extending in the longitudinal direction along side edges of the film portion so as to sandwich the pair of detecting electrodes [25].

2.4.2.3 Multi-Plate Capacitors

Capacitive type fluid level measurement systems can be constructed to have multiple capacitors. There are various advantages of having multiple capacitors

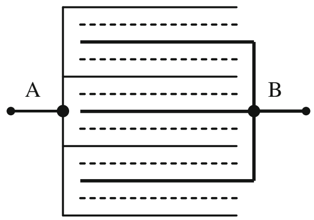


Fig. 2.9 Multiplate capacitor [5]

such as increased capacitance value. Multicapacitor systems share the common dielectric constant, which is essentially the fluid itself in capacitive type fluid level measurement systems.

If a capacitor is constructed with n number of parallel plates, the capacitance will be increased by a factor of ($n-1$). For example, the capacitor illustrated in Fig. 2.9 has seven plates, four being connected to A and three to B. Therefore, there are six layers of dielectric overlapped by the three plates, thus the total resultant area of each set is ($n-1$)A, or [5]:

$$C = \frac{\varepsilon_r \varepsilon_0 (n-1)\mathrm{A}}{d}. \tag{2.12}$$

Tward [26, 27] described a multicapacitor sensor that is tubular in shape. The designs are in association with a simple alternating current bridge circuit, including detector and direct readout circuitry, which is insensitive to changes in the environmental characteristics of such fluid, to the fluid motion and disorientation of the container, or to stray capacitance in the sensor bridge system. Figure 2.10 shows an illustration of this multicapacitor system.

Wood [28] described a capacitive type liquid level sensor, where the sensor housing is described as being cylindrical and includes multiple capacitors being configured as “Y,” triangular, and circular. Its configuration extends from the top of a liquid storage tank in a direction generally normal to the horizontal plane level that the liquid seeks. The sensor capacitor plates monitor liquid levels at the separate locations and associated circuitry interrogates these sensor capacitors to derive output pulse characteristics of their respective capacitance values (liquid level). As a result of interrogation, pulses having corresponding pulse widths are produced, and are compared to derive the largest difference between them. The largest difference is then compared with a predetermined maximum difference value. If the maximum difference value is greater, the capacitance values of the sensor capacitors are considered to be close enough for the system to read any one of them, and determine the quantity of liquid remaining in the tank. Hence, an enabling signal is generated and one of the pulses from a sensor capacitor is read to determine the liquid level [28].

2.4.2.4 Helixical Capacitors

Peter [29] described a capacitive probe that is comprised of two rigid wires formed in a bifilar helix. The use of a bifilar helix structure enables small changes in fluid

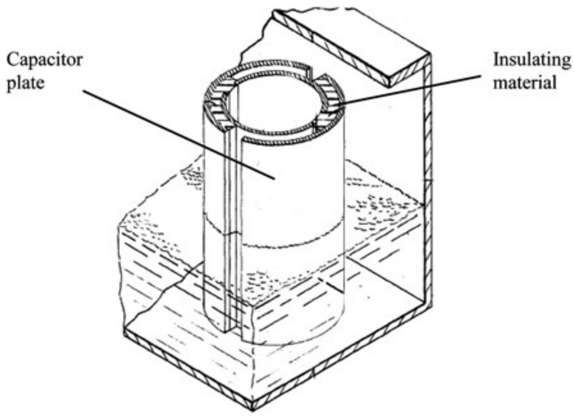


Fig. 2.10 Tubular shaped multicapacitor level sensor [27]

level to produce relatively large changes in probe capacitance [29]. Another advantage of the helixical geometry is that the sensing probe is compact, stable, rugged, and low in cost. Since the helix can be fabricated from any conductive material, the probe may be adapted to virtually any operating environment. The helix may also be entirely self-supporting or may be formed around a tubular support structure [29].

2.4.3 Conducting and Non-Conducting Liquids

A dielectric material that can conduct electric current will decrease the performance of the capacitor. The dielectric material should ideally be an insulator. But, the water content and other components mixed with the fluid can increase the conductivity of electrons in the fluid material. Several methods have been proposed for using a capacitive sensor to measure the fluid level in conducting and non-conducting liquids. A common method used places an insulating layer onto the conducting rods. The insulating layer will prevent the flow of electrons; hence a stable electric field could be produced.

Lee et al. [30] described a capacitive liquid level sensor that consists of a low-cost planar electrode structure, a capacitance-controlled oscillator, and a micro-controller. The sensor described is able to measure absolute levels of conducting and non-conducting liquids with high accuracy [30]. Qu et al. [23] described a level sensor, where the electrodes are insulated with low dielectric constant material. Lenormand et al. [31] described a capacitive probe for measuring the level in conducting and non-conducting fluids. The probe comprises a tubular insulating layer made of a dielectric heat resisting material baked at a high temperature.

Tward [27] described a fluid level sensor for mounting in a fluid storage vessel for sensing the level of the fluid within the vessel which is comprised of four similar electrically conductive capacitor elements each formed to present two electrically connected capacitive plates disposed at angles to each other. A material of known constant dielectric value fills two of the dielectric spaces thereby forming with their respective space defining capacitive plates two capacitors of known fixed and substantially similar capacitive value. The remaining two dielectric spaces are open to receive varying levels of fluid thereby forming with their respective capacitive plates, and the fluid within the spaces, two capacitors of variable capacitive value [27].

2.5 Effects of Dynamic Environment

2.5.1 Overview

Environmental factors such as temperature, pressure, and humidity affect the dielectric constant of a capacitor and therefore these effects severely deteriorate the precision of level measurement [17]. Changes in temperature can alter the distance and area of the conducting plates of a capacitor. The dielectric constant is subject to atmospheric changes such as temperature, humidity, pressure, and composition [17]. These factors influence the resulting capacitance value. Several methods have been employed to compensate for these factors. A reference probe can be used to recalibrate the dielectric constant, which can compensate for the changes in dielectric constant.

2.5.2 Effects of Temperature Variations

Changes in the temperature of the liquid or gas can result in significant shifts in the dielectric constant of the liquid or gas, which introduces inaccuracies in the sensor readings. This section describes some methods and techniques that have been used in the past to overcome the effects of temperature changes on sensing devices.

Variations in temperature values can alter the geometry and size of the capacitive sensor. Any change in the electrode gap will alter the value of the capacitance and therefore an inaccurate or even invalid level measurement will be obtained. The electronic components can also behave differently at different temperatures. The sensing electronics used to determine fluid level can therefore produce inaccurate level readings at different temperatures. Peter [29] described a method that can be used to monitor the level of a fluid in elevated temperature environments. The design consists of a high-performance thermal insulator for thermally insulating the system's electronic circuitry from the sensor probe. Atherton et al. [32] described a sensor based on the design described by Peter [29] for sensing the level of oil or transmission fluid under both normal and extreme temperature conditions. The active components of the sensor have input and leakage currents substantially lower than those of diodes and current sources under high temperature conditions.

Lawson [33] described a method for collecting liquid temperature data from a fuel tank by using a thermal sensitive resistive element that produces a value proportional to the liquid's temperature, a capacitor for storing a charge representative of this value, and a resistor through which the capacitor is discharged. Circuitry and software are provided that compares the voltage across the resistor to a reference as the capacitor discharges. This determines the number of clock counts for which a predetermined relationship exists between the voltage across the resistor and the reference and then consults a table to determine an absolute temperature based on this clock count [33].

Other methods that use a reference capacitor such as described by McCulloch et al. [34], can eliminate the effects of a changing dielectric constant at different temperatures. The recalibration method calculates the dielectric constant at any temperature to avoid the effects of temperature changes that can shift the values of the dielectric constant.

2.5.3 Effects of Contamination

It was described in Sect. 2.2.3 that the capacitance is dependant on the dielectric constant. Any change in the dielectric material will influence the capacitance value. To avoid the effects of the dielectric material on the capacitance value, several methods have been described that either eliminate the effects of the dielectric material, or recalibrate the dielectric parameter.

Hochstein [35] described a capacitive level gauge which determines the level of substance in the container. The gauge includes a measurement capacitor for measuring the level. Unlike conventional capacitance level gauges which may not detect changes in dielectric constant, this gauge includes a reference capacitor for determining the dielectric constant of the substance. A controller is responsive to the capacitors for producing a level signal which simultaneously indicates the level and dielectric constant of the material. The level signal incorporates a frequency which is representative of the dielectric constant and a pulse width representative of the level. The gauge supports a first pair of parallel conductive members to establish the measurement capacitor and a second pair of parallel conductive members spaced along the gauge and below the measurement capacitor to establish the reference capacitor. An advantage of this device is that its use does not require a predetermined shaped container. Additionally, the level signal simultaneously indicates the level capacitance and reference capacitance for accurate indication of the level.

Fozmula [36] described a capacitive liquid level sensor that can be calibrated using a push button. The sensor works with various fluid types such as oil, diesel, water, and water-based solutions. The calibration option allows the sensor to determine the dielectric constant of the fluid and adjust the output accordingly.

The consequences of neglecting the safety of brake fluid can lead to some serious problems, i.e., water content leads to corrosion in the brake system components. The on-line monitoring of oil quality and level eliminates the inconvenience to check brake fluid manually. It makes the vehicles safer and avoids additional waste by providing a more scientific maintenance interval. Shida et al. [37] described a method for on-line monitoring of the liquid level and water content of brake fluid using an enclosed reference probe as the capacitive sensing component. The probe has an enclosed cavity at the end which is designed to hold fresh brake fluid as an on-line reference. Three capacitances formed by four electrodes are used for the liquid level, water content and reference measurement and form the mutual calibrating output functions of the sensing probe. The liquid level measurement is calibrated to the permittivity changes by the capacitance for water content measurement. Simultaneously, the water content measurement is calibrated to temperature changes and variety of fluids by the capacitance of the reference measurement. Therefore, once the permittivity characteristics of brake fluids are experimentally modeled, the proposed method has a self-calibration ability to accommodate influencing factors including temperature, water content, and variety of brake fluids without an additional sensor supported by a database as in conventional intelligent sensor systems.

McCulloch et al. [34] described a way to overcome the level reading errors caused by variations in the dielectric constant of the fluid. The system is designed to measure liquid level with a high degree of accuracy regardless of dielectric changes which may occur in the liquid or gas due to temperature changes, pressure changes, and other changes affecting the dielectric constant. The primary sensor is an elongated capacitive probe positioned vertically within the container so that the lower portion of the probe is in liquid and the upper portion of the probe extends above the surface of the liquid. A capacitive liquid reference sensor is near the lower end of the probe, and a capacitive gas reference sensor is at the upper end of the probe. A controller is provided for driving each of the sensors with an electrical signal and reading a resultant value corresponding to the capacitance of each of the sensors. The controller is configured to enable the system to be calibrated prior to installation by placing each of the sensors in a calibration or identical medium, reading sensor values corresponding to capacitances for each of the sensors, and calculating and storing calibration values based on the sensor values [34].

Wallrafen [38] described a sensor for measuring the filling level of a fluid in a vessel. The sensor has an electrode group which extends vertically over the fillable vessel height, and dips into the fluid, and forms electrical capacitors whose capacitances change in a measurable fashion when there are changes in the filling level. The capacitances are determined by a connected evaluation circuit and are represented as a signal which describes the filling level. There is at least one measuring electrode which extends over the entire fillable vessel height. A plurality of reference elements are arranged at different reference heights within the fillable vessel height. Optionally, a plurality of measuring electrodes are arranged in such a way that each measuring electrode has a significant change in width at a reference height assigned to it, and wherein the entire fillable vessel height is passed over by the measuring electrodes. The measuring electrode, the opposing electrode, and five reference electrodes are printed on to a carrier which is bent in a U-shape. The electrodes are connected to an electronic circuit on the carrier by means of lines which are also printed on.

Takita [39] described a capacitive sensor that provides a high level of precision by taking the effects of environmental changes into consideration and compensating for any and all changes to the plate area and to the value of the dielectric constant before determining an accurate measurement. Such compensation can be achieved through use of a plurality of environmental sensors to mathematically calculate the change according to the variant conditions surrounding the capacitive sensor. However, the compensation would be made through the use of a reference capacitor with a fixed gap between the plates that is otherwise identical in both form and reaction to environmental changes as the capacitive sensor that it monitors to compensate for all environmental parameters other than the parameter of interest [39].

Other methods described by Wells [40], Tward [27], Stern [41], Gimson [42], and Park et al. [43] all use a reference capacitor to compensate for the effects of contamination in the fluid.

2.5.4 Influence of Other Factors

2.5.4.1 Sensitivity to Noise

Sensor plates may have signal capacitances in the fractional picofarad (pF) range, and connecting to these plates with a 60 pF per meter coaxial cable could totally obscure the signal. However, with correct shielding of the coaxial cable as well as any other stray capacitance one can almost completely eliminate the effects of noise [44].

2.5.4.2 Sensitivity to Stray Capacitance

One hazard of the oscillator circuits is that the frequency is changed if the capacitor picks up capacitively coupled crosstalk from nearby circuits. The sensitivity of an *RC* oscillator to a coupled narrow noise spike is low at the beginning of a timing cycle but high at the end of the cycle. This time variation of sensitivity leads to beats and aliasing where noise at frequencies which are integral multiples of the oscillator frequency is aliased down to a low frequency. This problem can usually be handled with shields and careful power supply decoupling [45].

2.5.4.3 Distance Between the Electrodes

The capacitance is dependent on the gap or distance between the conducting electrodes. This distance can, however, increase or decrease, depending on the environmental conditions, and the material, which could incorporate inaccuracies in the level readings. In some cases, movement of the fluid container can skew or bend the sensor, which will alter the distance between the electrodes, thereby errors will be produced in the capacitance value, and hence the fluid level.

2.6 Effects of Liquid Sloshing

2.6.1 Overview

In mobile fluid tanks, such as automotive fuel tanks, acceleration will induce slosh 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, for example, automotive fuel tanks, can be usually described by considering only 2-dimensional fluid flow, if the width of the tank is much less than its breadth [46]. 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 [47, 48]. A detailed analysis of liquid sloshing using the numerical approach for various tank configurations has been provided in the literature [47–55].

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.

2.6.2 Slosh Compensation by Dampening Methods

Fluid sloshing can be physically and electrically dampened to suppress the sloshing effects. Electrical damping methods include the use of low-pass filters and numerical averaging on digital sensor readings. Physical or mechanical damping of slosh includes the use of baffles and geometrical methods. Figure 2.11 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.

Wood [28] described a capacitive type liquid level sensor that is useful for both stationary and mobile storage tanks. The sensor is sensitive when the fuel is disoriented with respect to a reference level. Its configuration extends from the top

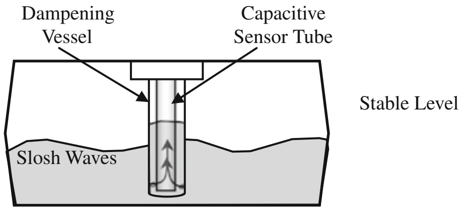


Fig. 2.11 Geometrically dampening the slosh waves

of a liquid storage tank in a direction generally normal to the horizontal plane level that the liquid seeks. The sensor capacitor plates monitor liquid levels at the separate locations and associated circuitry interrogates these sensor capacitors to derive output pulses characteristic of their respective capacitance values. As a result of interrogation, pulses having corresponding pulse widths are produced and are compared to derive the largest difference between them. The largest difference is then compared with a predetermined maximum difference value. If the maximum difference value is greater, the capacitance values of the sensor capacitors are considered to be close enough for the system to read any one of them and determine the quantity of liquid remaining in the tank. Hence, an enabling signal is generated and one of the pulses from a sensor capacitor is read to determine the liquid level [28].

Tward et al. [27] described methods to solve the problem of liquid sloshing and liquid level shift. They also address the effects on liquid level and volume measurement of changes in the physical and chemical characteristics of the liquid being measured and of the multiple characteristics of the environment of the liquid and its container. Multiple capacitors can provide improved liquid level measurement in both stationary and dynamic conditions for liquid storage containers and tanks [27].

2.6.3 Tilt Sensor

Another method used to compensate for the dynamic effects determines the tilt angle, usually by incorporating an inclinometer. Nawrocki [56] described a method that incorporates an inclinometer in the fuel gauging apparatus. A signal from a fuel quantity sensor can be transmitted to a fuel gauge or display 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 memory can be applied to the signal received from the fuel sensor to calculate a corrected signal indicative of the amount of fuel

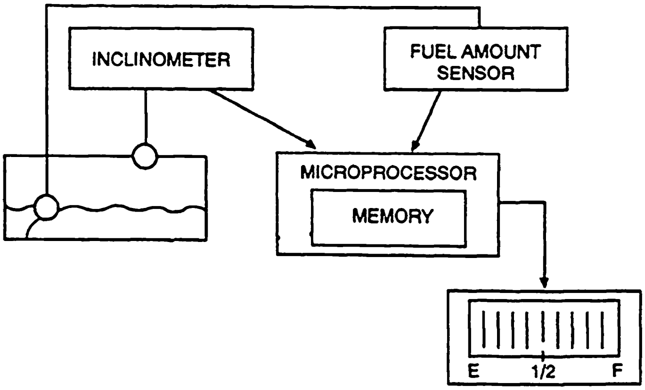
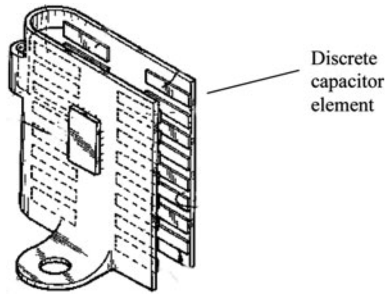


Fig. 2.12 Fuel level measurement system having an inclinometer [56]

Fig. 2.13 Fluid and tilt level sensing probe system [57]



remaining in the fuel tank. Figure 2.12 shows an overview of the method described by Nawrocki [56].

Lee [57] described a digital tilt level sensing probe system comprising a set of multiple capacitor elements in a fluid container arranged along an axis of measurement where each multiple capacitor element represents a discrete level increment in dielectric material fluid to be measured. Individual capacitors in each element are horizontally spaced to reflect a level differential on tilting of the fluid container from its normal attitude. In the case of a probe for sensing tilt angle in a single plane, the device includes integral capacitor elements, mounting pad, connector, custom IC pad, and circuitry moulded into the body [57] (Fig. 2.13).

Shiratsuchi et al. [58] described a capacitive type fuel level sensing system that uses three capacitors to determine the fuel surface plane angle, and a fourth capacitor is used as a reference capacitor to compensate for the variations in the dielectric constant. The high cost associated with having multiple capacitors makes this approach impractical. Furthermore, Shiratsuchi et al. [58] have assumed the fuel surface as always a plane, whereas, even under normal driving conditions, the surface of the fuel actually portrays slosh waves that fluctuate at a varying rate. The method described by Shiratsuchi et al. [58] determines the fluid level when the slope angle of the fluid level is at zero, which relates to the static state condition, and does not accurately determine fluid level under dynamic conditions.

2.6.4 Averaging Methods

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

2.6.4.1 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:

$$\mathrm{mean}(x) = \bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i. \tag{2.13}$$

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:

$$x = [1.21, 1.30, 1.25, 1.27, 1.23, 1.91] \tag{2.14}$$

$$\bar{x} = \frac{1.21 + 1.30 + 1.25 + 1.27 + 1.23 + 1.91}{6} = 1.36 \tag{2.15}$$

$$\bar{x} = \frac{1.21 + 1.30 + 1.25 + 1.27 + 1.23}{5} = 1.25. \tag{2.16}$$

The average value obtained in the presence of an abnormal entry '1.91' in signal x is given in (2.15), which is significantly larger than the average value when obtained without '1.91' element in x (2.16).

An improved version of averaging is described by Tsuchida et al. [59] who presented a method that determines the center value of the past sensor readings. The center value is assumed to be the accurate level reading. This method includes the operations of performing sampling detection of an amount of fuel remaining in the fuel tank of a vehicle, determining a center value for a plurality of remaining fuel quantity values detected by a microcomputer, determining limit values each thereof being apart from the center value by a predetermined amount, using any subsequent detected value exceeding the limit values as a new limit value, computing an average value of a predetermined number of detected sampling values, and indicating it on a display. It also performs the function of discriminating and eliminating any suddenly changed abnormal detected values due to changes in the attitude of the vehicle thereby producing stable measurement readings of the remaining fuel quantity [59].

2.6.4.2 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:

$$W_{\text{mean}}(x) = \bar{x} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}, \quad w_i > 0. \tag{2.17}$$

2.6.4.3 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 time constant or the averaging period is reduced to a small interval to quickly update the sensor readings by assuming that there will be negligible slosh. During dynamic conditions, the averaging period is increased to average the sensor readings over a longer period of time. To determine the running state of the vehicle, normally a speed sensor is used.

Kobayashi et al. [60] described a sensor that uses digital signals as opposed to analogue 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 high response speed when the vehicle is being refueled and additionally, fluctuations in the fuel volume readings 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 [60].

Guertler et al. [61] described a process that determines the quantity of a liquid situated in a largely closed system. The liquid fluctuations in a dynamic or a moving vehicle can produce erroneous results. The process described Guertler et al. [61] determines the running state of the vehicle, the momentary driving condition, and, at least during selected driving conditions in the driving operation. The process continuously senses the filling level, as well as determines the momentary filling quantity via a given dependence of the liquid quantity reading on the driving condition and on the filling level. These fluctuations can be calculated as the result of the predetermined dependence of the liquid level and therefore of the amount of fluid on the driving condition. In addition, the level can be statistically averaged 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. This occurs not only when the vehicle is stopped and the engine is switched-off, but also in the continuous driving operation [61].

Kobayashi et al. [62] utilized the information about the various states of the vehicle, such as ignition ON–OFF, idle state, 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, and the position of the 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 [62].

2.7 Summary

A detailed investigation of the capacitive sensing technology as described in this chapter reveals the fact that capacitive technology is increasingly being used in a broad range of applications due to its non-mechanical characteristic, robustness in harsh environments, its ability to work with a wide range of chemical substances, compact and flexible size, and, longer functional life.

Even though the use of capacitive 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 limitations of capacitive sensing technology in relation to its accuracy in fluid level measurements pertaining to dynamic environments. Level sensing in dynamic environments is characterized by three factors:

- Slosh.
- Temperature variation.
- Contamination.

Solutions provided to address each of these three above mentioned factors have been reviewed in this chapter. In most cases common solutions to overcome these environmental factors require an additional capacitive sensor to be included to serve as a reference capacitor. The purpose of this reference capacitor is to provide additional measurement signal taking into account factors above. This measurement is then used to calculate offset in combination with the main capacitive sensor to improve the accuracy of overall measurement system. However, these solutions entail either higher production cost because of the requirement for an additional sensor, or they provide only marginal improvement in terms of accuracy compared to current systems.

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