

Capacitance Level Measurement

Introduction

This technical bulletin describes the basic concept of capacitance level measurement and the RF (radio frequency) techniques that have been successfully applied to these principles.

Basic Measurement Principle

A capacitor is formed when a level-sensing electrode is installed in a vessel. The metal rod of the electrode acts as one plate of the capacitor and the tank wall (or reference electrode in a non-metallic vessel) acts as the other plate. As the level of the material being measured rises, the air or gas normally surrounding the electrode is displaced by the material's different dielectric constant. The value of the capacitor changes because the dielectric between the two plates has changed. RF capacitance instruments detect this change and convert it into a relay actuation or proportional output signal. The following equation illustrates the capacitance relationship:

$$C = 0.225 K (A \div D)$$

where: C = Capacitance in picoFarads
 K = Dielectric constant of material
 A = Area of plates in square inches
 D = Distance between the plates in inches

The dielectric constant is a numerical value between 1 and 100 that relates to the ability of the dielectric (material measured between the plates) to store an electrostatic charge. The dielectric constant of a material is determined in an actual test cell. Values for many materials are published by the National Bureau of Standards.

In actual practice, capacitance change is produced in different ways depending on the material being measured and the level electrode being used. However, the basic principle always applies. If a higher dielectric material replaces a lower one, the total capacitance output of the system will increase. If the electrode is made larger (effectively increasing the surface area) the capacitance output increases; if the distance between measuring electrode and reference decreases, then the capacitance output increases.

Level measurement can be organized into three basic categories: the measurement of non-conductive materials, conductive materials, and proximity or non-contacting measurement. While the following explanations oversimplify the measurement principle, they provide the basics that must be used to properly specify a capacitance level measurement system.

■ **Non-Conductive Materials** -- As previously stated, capacitance changes as material comes between the plates of the capacitor. For example, suppose the sensor and the metal wall are measuring the increasing level of a non-conductive material such as olive oil. Figure 1 depicts a typical system.

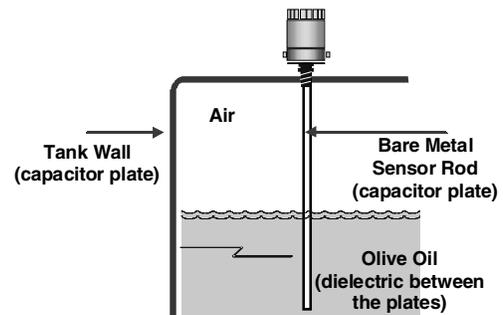


FIGURE 1
 Capacitive Measurement in Non-Conductive Material

While the actual capacitive equation is very complex, it can be approximated for the above example as follows:

$$C = \frac{0.225 (K_{air} \times A_{air})}{D_{air}} + \frac{0.225 (K_{material} \times A_{material})}{D_{material}}$$

Since the electrode and tank wall are fixed in place, the distance between them will not vary. Similarly, the dielectric of air (1) and the measured material, olive oil (3.1), also remain constant. Therefore, the capacitance output of the system example can be reduced to this very basic equation:

$$C = (1 \times A_{air}) + (3.1 \times A_{material})$$

As this equation demonstrates, the more material in the tank, the higher the capacitance output will be. The capacitance is directly proportional to the level of the measured material.

■ **Conductive Materials** -- The same logic for non-conductive materials applies to conductive materials, except that conductive material acts as the ground plate of the capacitor rather than the tank wall. This changes the distance aspect of the equation, whereby the output would be comparatively higher than for a non-conductive material. However, it still remains fixed; therefore, as level rises on the vertically mounted sensor, the output increases proportionately.

A material is considered conductive when it has a conductivity value of greater than 10 microSiemens/cm.

The level-sensing electrode must be insulated. A non-insulated sensor is tip sensitive and acts like a conductive switch.

■ **Proximity (non-contacting) Measurements** -- The level electrode is normally a flat plate mounted parallel to the measured material surface. The material, if conductive, acts as the ground plate of the capacitor. As level rises to the sensor plate, the effective distance between plates is decreased, thus causing an increase in capacitance. When measuring non-conductive materials, the vessel acts as the ground plate and the mass of material between the plates is the variable. With the measurement of non-conductive and conductive materials, the area changes and the distance is fixed. Proximity measurement is exactly the opposite in that the area is fixed, but distance varies. Proximity measurement does not produce a linear output and can only be used when the level varies by several inches.

Some typical level sensor installations for measuring conductive and non-conductive materials and proximity level measurement are shown in Figures 2 and 3.

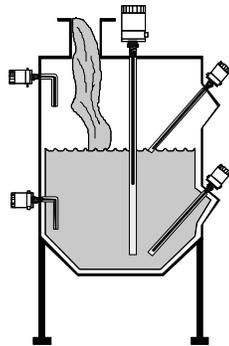


FIGURE 2

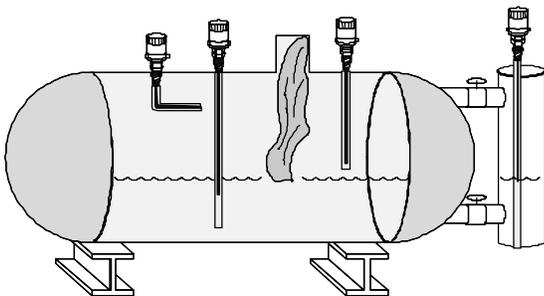


FIGURE 3

Applications

Applications for RF point level controls and analog transmitters/controllers are widespread. Granular applications range from light powders to heavy aggregates. Liquid, slurry, and paste applications are commonplace. Capacitance level can also be used to detect the interface between two immiscible materials.

Selecting the proper level sensing electrode and installing it in the proper location are important factors contributing to the success of any application. A thorough understanding of these factors is required.

- **Electrode Selection** -- The electrode is the primary measuring element and must be capable of producing sufficient capacitance change as it becomes submerged in the measured material. Several electrode types are offered, each having specific design characteristics. Capacitance (per foot of submersion) vs. dielectric constant curves are published for each type of electrode as installed in various size vessels. For non-conductive materials, these curves are non-linear. Figure 4 shows a typical set of curves. As the size of the tank gets smaller, the capacitance per foot of submersion increases. A conductive material essentially transforms the tank into the electrode insulation. In this case, the saturation capacitance is used. Table A on page 4 lists basic capacitance values for different electrodes and tank sizes.

Electrodes selected for point level detection should be capable of producing a minimum capacitance change of 3.0 pF. Continuous level transmitter applications require a minimum span of 10.0 pF and a maximum span of 10,000 pF.

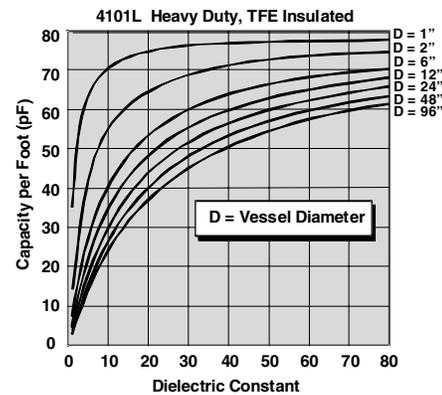


FIGURE 4 -- Capacitance vs. Dielectric Curves Example

- **Electrode Location** -- Mounting positions should be carefully considered. They must be clear of the material inflow as impingement during filling can cause serious fluctuations in the generated capacitance. Side-mounted electrodes for point level control are typically mounted at a downward angle to allow measured material to drain off/fall from the electrode surface. Electrodes mounted in nozzles

should contain a metal “sheath” extending a few inches past the nozzle end. The sheath renders that part of the electrode insensitive to capacitance change, thus ignoring material buildup in the nozzle.

Vertical-mounted electrodes must be clear of agitators and other obstructions and far enough from the vessel wall to prevent “bridging” of material between the electrode and the vessel wall.

In addition to the electrode selection and location factors, there are other considerations which can have a significant impact on the measurement.

Special Considerations

1. *Temperature* -- The dielectric constant of some materials varies with temperature which affects the capacitance measured by the electrode. Generally, materials with a higher dielectric constant are less affected by temperature variation. The temperature effect is usually shown in dielectric constant tables.
2. *Moisture Content* -- The dielectric constant of granular materials changes as moisture content changes. This variation can cause significant measurement errors, so each application must be carefully examined. Accuracy requirements determine the amount of moisture change that is tolerable.
3. *Static Charge* -- Air-conveyed, non-conductive granular materials such as nylon pellets build up a static charge on the electrode that can damage the electronic components in the measuring instruments. Most instruments contain static discharge components to protect the electronic measuring circuits. Consider the magnitude of the charge and the adequacy of the static protection.
4. *Composition* -- The dielectric constant of the measured material must remain constant throughout its volume. Mixing materials with different dielectric constants in varying ratios will change the overall dielectric constant and the resultant capacitance generated. Solutions having a high dielectric constant are less affected due to the saturation capacitance of the electrode system. See the capacitance vs. dielectric constant curve in Figure 4.

Special schemes are available which consist of two electrodes or a segmented electrode. One electrode or segment is constantly submerged and measures the dielectric constant of the material. This measurement is used to correct the measuring span to compensate for the variation.

5. *Conductivity* -- Large variations in the conductivity of the measured material can introduce measurement error. The proper electrode selection can minimize this effect. A thickwall electrode insulation is recommended in this case.

6. *Material Buildup* -- The most devastating effect on the accuracy of RF capacitive measurements is caused by the buildup of conductive material on the electrode surface. Non-conductive buildup is not as serious since it only represents a small part of the total capacitance.

Compensating For Conductive Material Buildup

Point level and RF continuous level systems use different methods to eliminate or compensate for conductive material buildup on the electrode surface.

A. Point Level Detection

A special electrode type is used to ignore the effect of conductive coating on the electrode surface. The electrode has an added second element. This element is electronically maintained at the same voltage and frequency as the measuring section. Since no potential difference can exist across the two sections, no current can flow through the coating to the vessel wall. When the level reaches the bare electrode section, current passes only through the detected material to the tank wall, completing the detection circuit. This technique works even if the material dries out and becomes non-conductive, because the measurement is RF capacitive. BI International refers to this special electrode as a “driven-shield” type (Figure 5).

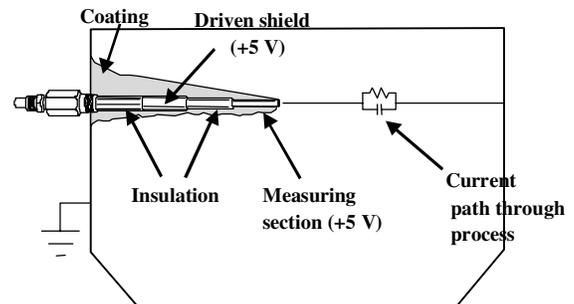


FIGURE 5 -- BI Driven-shield Anti-coating Technique

B. Continuous Level Measurement

Various methods are used to minimize the coating error, including proper electrode selection, higher frequency measurements, phase shifting, and conductive-component subtraction circuits.

Coating error is illustrated by the diagram shown in Figure 6. The submerged portion of the electrode generates nearly a pure capacitive susceptance. Since the electrode is insulated, a conductive component is virtually non-existent. However, the upper section of the electrode, coated with conductive material, generates an error signal consisting of a capacitive susceptance and a conductive component. The result is an admittance component that is 45° out of phase with the main level signal. A study of transmission line theory is

required to prove this phenomenon. An equivalent circuit for the coated section is shown as a ladder network producing the phase shifted error signal.

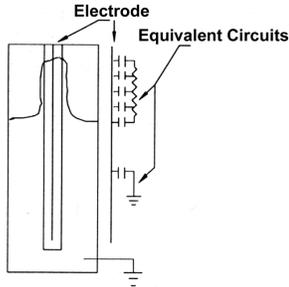


FIGURE 6 -- Phase-shifted Coating Error

One way to cancel the error signal is to measure the conductive component (c) shown in Figure 7, Method A. Since the 45° relationship exists, the capacitive error component (e) is the same magnitude and can be subtracted from the total output signal, thus effectively canceling the error signal.

Another cancellation method used by BI is to introduce a 45° phase shift to the entire measurement as shown in Figure 7, Method B. This automatically cancels the coating error portion because the conductance component (c) still has the same magnitude as the error component (e),

resulting in the appropriate level signal.

Instruments that incorporate these techniques are known as “admittance” types.

The coating error can also be reduced by increasing the capacitive susceptance. This is accomplished by increasing the frequency of measurement and/or decreasing the electrode insulation wall thickness.

It should be noted that none of these techniques can perfectly cancel the coating effect, but each reduces the error. For all of the preceding reasons, RF continuous level instruments are not used in inventory control applications. These are process control devices that require careful evaluation of the listed considerations to provide satisfactory results.

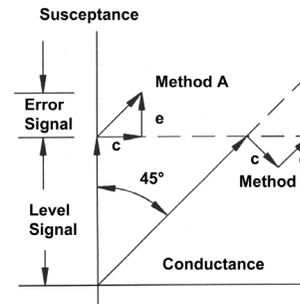


FIGURE 7 - Admittance Vector Diagram

TABLE A -- Capacitance Values (pF per foot)

| BI Level Sensor Type | Non-conductive Materials/Distance from Vessel Wall | | | | | | | | | Conductive Material (Saturation Capacitance) |
|------------------------|----------------------------------------------------|--------|--------|-----------------|--------|--------|-----------------|--------|--------|----------------------------------------------|
| | Dielectric = 2 | | | Dielectric = 20 | | | Dielectric = 80 | | | |
| | 1 in. | 24 in. | 96 in. | 1 in. | 24 in. | 96 in. | 1 in. | 24 in. | 96 in. | |
| General Purpose: | | | | | | | | | | |
| TFE Teflon-insulated | 15 pF | 4 pF | 2 pF | 63 pF | 39 pF | 34 pF | 73 pF | 62 pF | 58 pF | 76 pF |
| Polyethylene-insulated | 16 pF | 6 pF | 3 pF | 123 pF | 57 pF | 46 pF | 167 pF | 120 pF | 117 pF | 189 pF |
| PVDF-insulated | 18 pF | 7 pF | 4 pF | 178 pF | 68 pF | 50 pF | 280 pF | 169 pF | 142 pF | 350 pF |
| Enhanced Performance: | | | | | | | | | | |
| PFA Teflon-insulated | 23 pF | 5 pF | 3 pF | 147 pF | 160 pF | 48 pF | 187 pF | 128 pF | 114 pF | 207 pF |
| Polyethylene-insulated | 22 pF | 8 pF | 5 pF | 260 pF | 78 pF | 58 pF | 410 pF | 210 pF | 165 pF | 518 pF |
| PVDF-insulated | 25 pF | 10 pF | 8 pF | 330 pF | 80 pF | 60 pF | 640 pF | 260 pF | 205 pF | 950 pF |