Technology Brief 14
Capacitive Sensors

Capacitive sensors are used to convert information from the real world to a change in capacitance that can be detected by an electric circuit. Even though capacitors can assume many different shapes, the basic concepts can be easily explained using the shape and properties of the parallel plate capacitor, for which the capacitance C is given by

$$C = \frac{\varepsilon A}{d},$$

where ε is the permittivity of the material between the plates, A is the area of each plate, and d is the spacing between the plates. So, most capacitive sensors operate by measuring the change in one or more of these three basic parameters, in response to external physical stimuli. Let us examine each one of these three parameters separately and how it can be used to measure external stimuli.

Applications Based on Change in Permittivity ε

The electrical permittivity ε of a given material is an inherent property of that material; its value is dictated by the polarization behavior of that material's molecular structure, relative to the absence of polarizability (as in free space or vacuum). In free space, $\varepsilon = \varepsilon_0 = 8.854 \times 10^{-12}$ F/m, and for all other media, it is convenient to express the permittivity of a material relative to that for free space through the relative permittivity $\varepsilon_r = \varepsilon/\varepsilon_0$. **Table TT14-1** provides a list for various types of materials. We note that for plastic, glass, and most ceramics, ε_r is in the range between 2 and 4, which makes them different (electrically) from air ($\varepsilon_r = 1$ for air), but not markedly so. In contrast, water-based materials—such as biological materials or parts of the body—have an ε_r in the range of 60–80, making them electrically very different from both air and dry materials. This means that their presence can be easily detected by a capacitive sensor, which is the basis of capacitive touchscreens, fluid and moisture meters, and some proximity meters.

Table TT14-1: Relative permittivity ε_r of common materials.[a]

$\varepsilon = \varepsilon_r \varepsilon_0$ and $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m

Material	Relative Permittivity, ε_r
Vacuum	1
Air (at sea level)	1.0006
Low Permittivity Materials	
Styrofoam	1.03
Teflon	2.1
Petroleum oil	2.1
Wood (dry)	1.5–4
Paraffin	2.2
Polyethylene	2.25
Polystyrene	2.6
Paper	2–4
Rubber	2.2–4.1
Plexiglass	3.4
Glass	4.5–10
Quartz	3.8–5
Water	72–80
Biological Materials	40–70

[a]These are at room temperature (20 °C).

Capacitive Touch Buttons

An example of a capacitive touch sensor is shown in **Fig. TF14-1**. The capacitor has two conducting surfaces labeled ***sensor pad*** and ***ground hatch***. In general, the two conductors are separated either vertically or horizontally, and covered with a layer of glass or plastic. By applying a voltage source (supplied by the printed circuit board) between the conducting surfaces, electric field lines get established between them. When no finger (or a capacitive stylus) is present near the sensor pad, the electric field lines flow through the glass or plastic cover, but when in the proximity of a finger, the electric field lines pass partially through the finger, and since the finger has a relative permittivity comparable to that of water, its

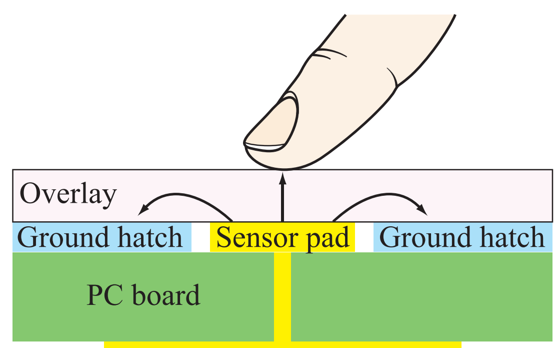

Figure TF14-1: A capacitive touch sensor uses the high permittivity of the finger to change the capacitance. The finger does not need to come in direct contact with the sensor in order to be detected.

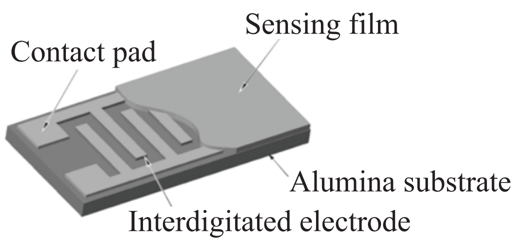

Figure TF14-2: Interdigitated humidity sensor. (Credit: Hygrometrix.)

proximity changes the overall capacitance of the circuit. The electric field starts on one of the conductors and ends on the other, basically making an arc between them. When the finger comes near either one or both of the two conductors, it changes this field (note the electric field arrow pointing straight up at the finger, which would not be there without the finger), and this in turn changes the capacitance. Another way to think about the process is in terms of the electric charge stored at the two conductors. The presence of the finger changes the effective permittivity of the medium through which the electric field lines flow, thereby changing the effective capacitance C. Since for any capacitor, $C = Q/V$—where Q is the charge on the conductor connected to the positive terminal of the voltage source and V is the voltage of the source—it follows that increasing C leads to an increase in Q (with V remaining constant). Hence, when the finger approaches the sensor pad, additional charge accumulates at the two conductors (with more $+Q$ at the sensor pad and a corresponding $-Q$ at the ground hatch).

Humidity Sensor

Another example of a capacitive sensor that also relies on measuring the change in permittivity is the humidity sensor featured in **Fig. TF14-2**. A sensing film absorbs moisture from the air, thereby changing the capacitance of the interdigitated line in proportion to the humidity in the air surrounding the sensor.

"Seeing" through Walls

The capacitive sensing technique also is used to "see" inside boxes, through walls, or through basically any low-conductivity low-permittivity material (paper, plastic, glass, etc.). An example is illustrated in **Fig. TF14-3**, in which a capacitive sensor on an assembly line is used to determine if a metal object is placed inside a box. The

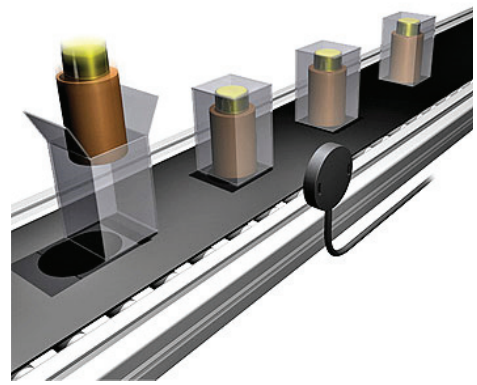

Figure TF14-3: Capacitive proximity sensors can "see" through low permittivity materials such as paper, cardboard, plastic, and glass and detect objects composed of a wide variety of materials including metals, fluids, etc. Here, a capacitive sensor detects the contents of a box. (Graphic courtesy of Balluff.)

object does not have to be metal, but its permittivity has to be significantly different from that of the paper or plastic enclosure. A similar application of capacitive sensors is to locate wooden studs through plaster walls.

Fluid Gauge

Capacitive sensors can serve as fluid gauges by measuring the height of a fluid in a tank or reservoir. Examples include gasoline and oil level gauges used in cars. If the tank is made of plastic or glass, metal strips on the outside of the tank can determine the height of the fluid without having to make contact with the fluid. This is very useful when the fluid is caustic or sterile. If the tank is metal, the strips must be placed inside. In either case, the sensor consists of two capacitors, one (C_2 in **Fig. TF14-4**) with metal plates separated by a reference fluid, and another (C_1) in which the fluid level is a variable. If the permittivity of the fluid is ε and the height of the fluid in the upper container in **Fig. TF14-4** is h, the ratio of the two capacitances is given by

$$\frac{C_1}{C_2} = ah + b,$$

where a and b are known constants related to ε and the dimensions of the two capacitors. Hence, by measuring the two capacitances with an external circuit, the sensor provides a direct measurement of the fluid height h.

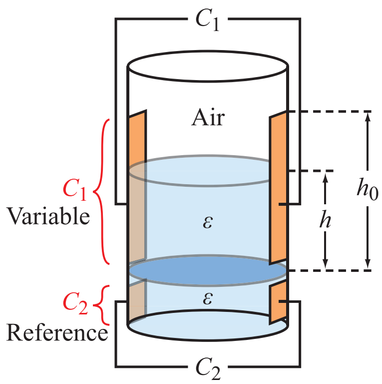

Figure TF14-4: Fluid height can be measured from the outside of a plastic or glass tank using a pair of parallel plate capacitors on the outside of the tank.

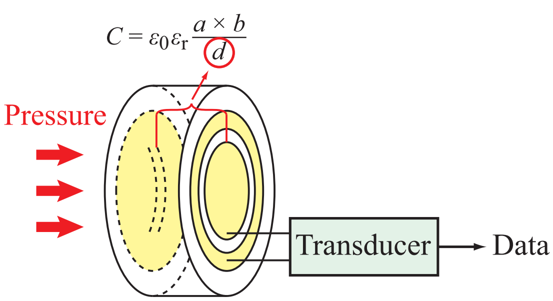

Figure TF14-5: Capactive transducer responding to pressure from a sound wave.

Applications Based on Change in Inter-Conductor Distance d

As noted earlier, the capacitance C is inversely proportional to the distance d between the two conductors. This dependence can be used to measure pressure, as illustrated by the diagram in **Fig. TF14-5**. We call such a sensor an electrical ***transducer*** because it converts one type of energy (mechanical) into another (electrical). The capacitor has one stationary conducting plate on the back side and a flexible conducting membrane on the side exposed to the incident pressure carried by an acoustic wave. The sound wave causes the membrane to vibrate, thereby changing the capacitance, which is measured and processed by an external circuit. This type of capacitive transducer is used in numerous industrial applications.

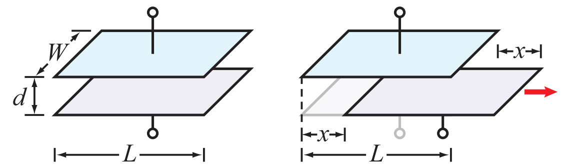

Figure TF14-6: Capacitance is proportional to overlap area $A = W(L - x)$, so when plates slide past each other the capacitance decreases in proportion to the shifted distance x.

Applications Based on Change in Area A

The change in the effective area common to the two conducting surfaces can also change the capacitance C. If one plate is slid past the other in **Fig. TF14-6**, the effective area A changes as a function of the shifted distance x. The capacitance is maximum when they are perfectly lined up, corresponding to $x = 0$, and changes approximately linearly as $(L - x)$. This can be used to align two objects, or to determine any other manual displacement in either one or two directions. The MEMS capacitive vibration sensor shown in **Fig. TF14-7** uses two interdigital electrodes, one static and another moveable. When mounted in a car, for example, car acceleration or deceleration causes the moveable electrode to respond accordingly, which changes the capacitance between the two electrodes, thereby providing the means to measure acceleration. Such a sensor is called an ***accelerometer***.

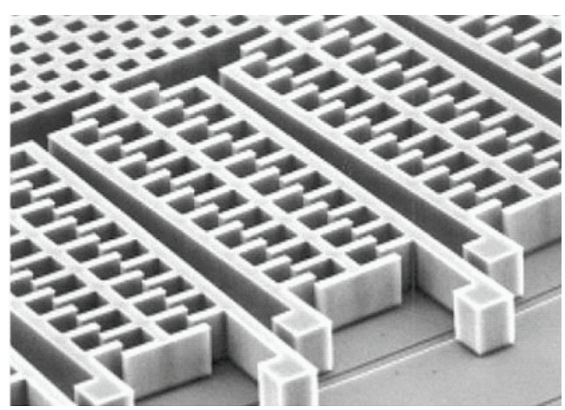

Figure TF14-7: Microelectromechanical system (MEMS) vibration sensor using interdigitated static and movable electrodes. (Credit: STMicroelectronics.)