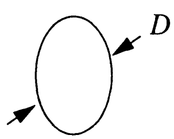
3
Capacitive sensor basics

Many of the different types of capacitive sensors use similar plate geometry and similar circuits and components. This chapter presents some of the different electrode configurations used to build various types of sensors.

3.1 BASIC ELECTRODE CONFIGURATION

Three different uses of capacitive sensors are to detect material properties, to sense motion or position, and to detect the proximity of conductive or dielectric objects. These applications all need specialized electrode configurations and circuit design.

The simplest electrode configuration, useful for proximity detection, is a single plate (repeated from Chapter 2) (Figure 3.1).

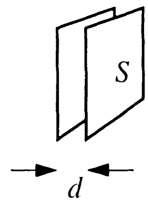


$$C = 0.354D$$

Figure 3.1 Single plate

This assumes vacuum (or air) dielectric. With D in cm, C, the capacitance to an equivalent ground potential very far away, is in pF. A 1 cm plate will have a capacitance of 0.354 pF. As conductive objects approach the plate, this capacitance increases.

The most useful configuration (also repeated from Chapter 2) is two parallel plates (Figure 3.2).



$$C = 0.08854 \times \frac{S}{d}$$

Figure 3.2 Two parallel plates

With dimensions in cm, and an air dielectric, C is in pF. Neglecting fringe effects, the capacitance with 1 cm^2 plate area and 0.1 cm spacing is 0.8 pF. This configuration is useful for measuring dielectric material properties and measuring motion, where either the spacing d is changed or the common area is changed by the transverse motion of one of the plates.

3.2 MOTION SENSING PLATE CONFIGURATIONS

Several more complex plate configurations which optimize linearity or range are used for motion sensing applications.

3.2.1 Spacing variation

For spacing variation motion sensors (Figure 3.3), the capacitance is dependent on the average plate spacing, or more accurately, the integration of $\varepsilon/d \cdot dS$ over the common plate area (assuming no fringing effects), where dS is an elementary area and d is the plate spacing. About 10% change in capacitance is produced by a 10% spacing change, so with small spacing this system is very sensitive to spacing changes. The nonlinear relationship between spacing and capacitance change is a problem if capacitance is measured directly, but the output is linear if capacitive impedance is measured instead.

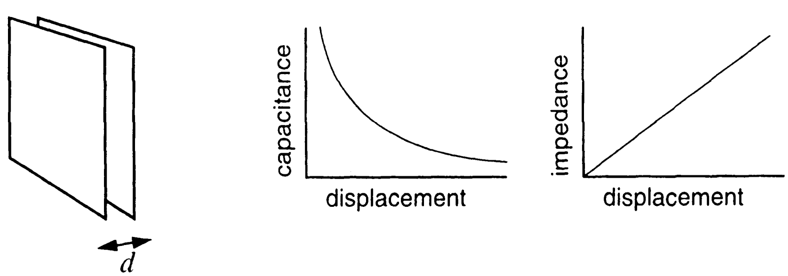


Figure 3.3 Motion sense with spacing variation

This geometry, with both plates equal in size, creates an undesired sensitivity to motion in unwanted axes which is repaired by overlapping or underlapping all edges (Figure 3.4).

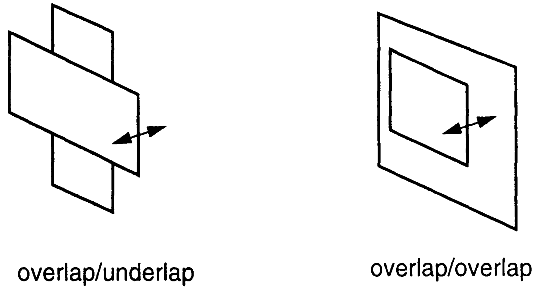


Figure 3.4 Underlap/overlap

The sensitivity of the system to mechanical disturbance in undesirable axes and to circuit drift can be further improved by using an additional electrode in a bridge circuit (Figure 3.5).

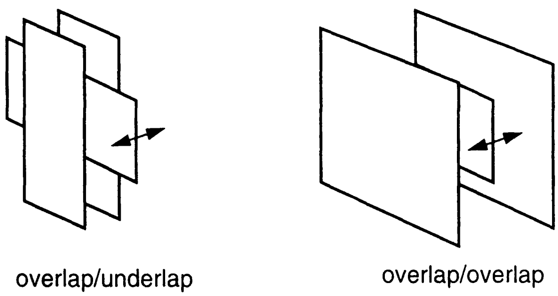


Figure 3.5 Three-plate bridge

The detecting circuit measures the ratio of the center plate's capacitance to each of the side plates. The advantage of this configuration is that the capacitance can be unaffected by translational motion in the two unwanted axes and can also be relatively insensitive to tilt in any of the three tilt axes. Another advantage of the bridge is that no absolute capacitance reference is needed, and two airgap capacitances in a bridge circuit tend to track quite accurately. The output signal is a ratio rather than an absolute value, and thus can be made to be insensitive to variations of power supply voltage, dielectric constant, and most other circuit and system variables.

A drawback with some amplifier types is the parabolic relationship between motion and capacitance and the limited range of motion which can be measured. The maximum useful linear range for spacing-variation motion detection is usually a small fraction of the plate diameter.

3.2.2 Area variation

For transverse motion which varies area with constant spacing (Figure 3.6), motion and capacitance are linearly related and a long range of motion can be measured, but the sensitivity is less, as 10% change in capacity is produced by a transverse displacement of 10% of the large plate diameter dimension rather than 10% of the small spacing dimension. Area-variation motion sensors can have an unwanted sensitivity to spacing and tilt, especially the two-plate version shown above, but these effects can usually be handled with correct electrode geometry and circuit design.

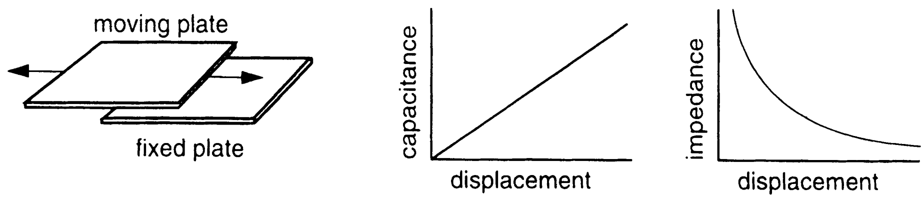


Figure 3.6 Area variation motion sense

Rotary motion

All of the electrode configurations above are shown as linear motion sensors, but they can be easily converted to rotary motion sensors using the familiar x - y to ρ - θ coordinate transform. Rectangular plate shapes will be transformed to pie-shaped sectors.

Moving shield

A configuration which is less sensitive to motion in unwanted axes is the moving shield, which interposes a grounded moving plate between a pair of fixed capacitor plates (Figure 3.7). The capacitance is proportional to the unshielded area of the plates.

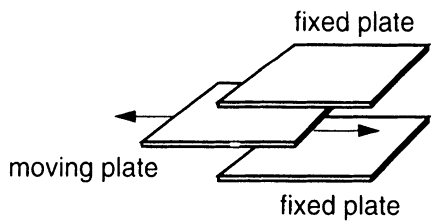


Figure 3.7 Moving shield motion sense

The plate geometries above will almost always need to be protected from external fields with an overall shield or a driven guard electrode, which also serve to control stray capacitance and improve linearity as shown in "Guards and shields" in Section 3.3.3.

3.3 MATCHING THE CIRCUIT TO THE SENSOR

3.3.1 Spacing variation with low-Z amplifier

For the simple parallel-plate spacing sensor used in sensitive capacitive micrometers (Figure 3.8), the output current *Iout*, with A the plate area in meters, x the spacing in meters, vacuum dielectric X_c and the capacitive reactance, in ohms and C, in farads, is

$$I_{out} = \frac{V_I}{X_c} = V_I \omega C = V_I \omega \cdot 8.854 \cdot 10^{-12} \cdot \frac{A}{x} \qquad 3.1$$

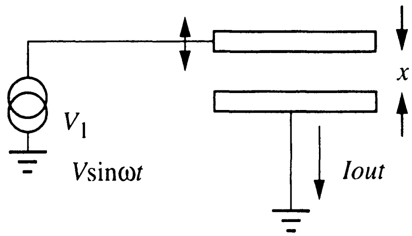


Figure 3.8 Spacing variation, low-Z amplifier

Adding a third plate produces a more stable ratiometric output signal (Figure 3.9).

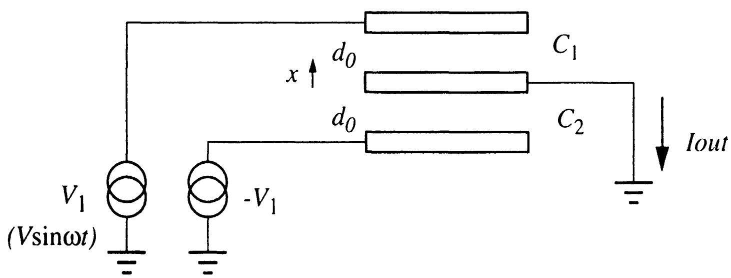


Figure 3.9 Spacing variation, three plates, low-Z amplifier

With the outer plates fixed at a spacing of $2d_0$, when the center plate is moved a distance x the output current is

$$I_{out} = V_I\omega(C_1 - C_2) = V_I\omega \cdot 8.854 \cdot 10^{-12} \cdot A \cdot \frac{2x}{d_0^2 - x^2} \qquad 3.2$$

For small displacements, this becomes

$$I_{out} \approx V_I\omega \cdot 8.854 \cdot 10^{-12} \cdot A \cdot \frac{2x}{d_0^2} \qquad 3.3$$

3.3.2 Spacing variation with high-Z amplifier

If the center plate feeds a high impedance (high-Z) or feedback amplifier, as in Figure 3.13 on page 44, instead of a low impedance amplifier as above, a voltage output is produced. With a voltage output instead of a current output, the response is no longer nonlinear, the electrostatic force is zero, and the dependence on dielectric constant and area disappears

$$V_{out} = 2V_I\left(\frac{X_{C2}}{X_{C1} + X_{C2}}\right) - V_I = \frac{V_I x}{d_0} \qquad 3.4$$

3.3.3 Area variation with low-Z amplifier

A useful area-variation three-electrode geometry for sensing linear displacement is shown in Figure 3.10.

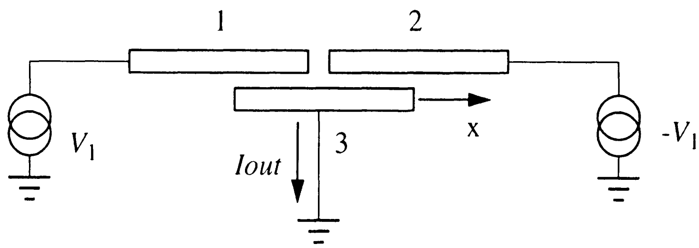


Figure 3.10 Area variation, high-Z amplifier

Here, if electrode 3 is moved to the right a distance x, neglecting fringe effects the inter-electrode capacitance C_{13} will decrease linearly with x while C_{23} increases. *Iout* is

$$I_{out} = C_{13}\frac{dV_I}{dt} - C_{23}\frac{dV_I}{dt} = (C_{13} - C_{23})\frac{dV_I}{dt} \qquad 3.5$$

and will linearly measure displacement x.

Guards and shields

Fringe fields will corrupt the measurement of position: as the edge of electrode 3 in Figure 3.10 nears the gap between electrodes 1 and 2, the fringe field will make the measurement nonlinear. Also, stray electric fields can be picked up by the signal electrode 3. One fix is to add a guard electrode which surrounds the pickup and moves with it (Figure 3.11).

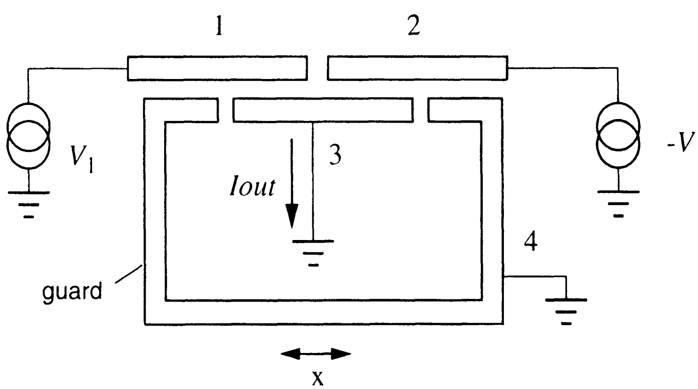
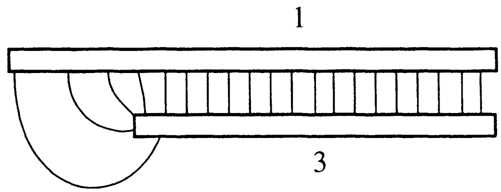
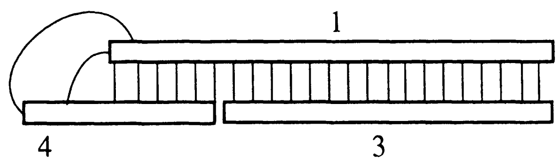


Figure 3.11 Guarded three-electrode displacement sensor

Now, electrode 4 changes the shape of the field lines at the edge of electrode 3 from



to



The field lines are distorted at the edge of the guard (electrode 4) where this distortion is unimportant, but uniform at the measuring electrode.

The guard electrode also serves as a shield to screen electrode 3 from extraneous fields. Note that the guard electrode does not need to be at the same potential as the signal electrode to be effective [Heerens, pp. 897–898]. It can be at any DC or uncorrelated AC voltage and the same results will be achieved. This is difficult to prove by constructing field lines and applying Poisson's equation, as the field lines will be distorted by the new voltage, but easy to prove using superposition and an equivalent circuit, as in "Multielectrode capacitors" in Section 2.3.1.

3.3.4 Area variation with high-Z amplifier

The previous linear sensor system (Figure 3.11) can be modified to show another way to use the guard electrode (Figure 3.12).

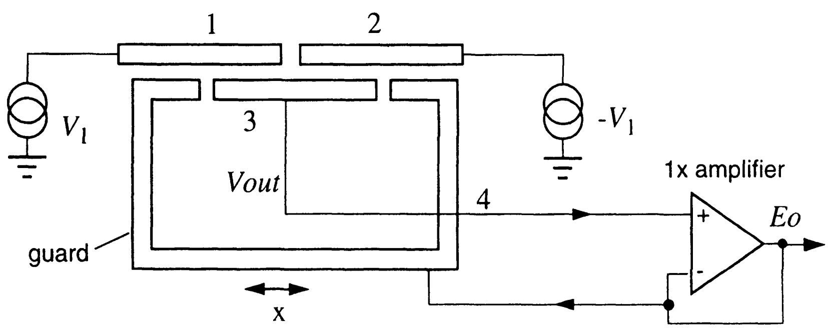


Figure 3.12 Guarded displacement sensor, high impedance amplifier

The output voltage *Eo* is

$$Eo = V_I\left[\frac{C_{13} - C_{23}}{C_{13} + C_{23}}\right] \qquad 3.6$$

Note that this and many other circuits are shown without a way to control the DC voltage at the operational amplifier input; see Section 4.3.4 for more guidance. Without the guard, the use of a high impedance amplifier would mean that stray capacitance from electrode 3 to local grounds would have attenuated the signal, but with the bootstrapped guard these strays are now unimportant. The previous circuit (Figure 3.11) measured $C_{13} - C_{23}$ by amplifying the output current or output charge, using a low input impedance amplifier. This circuit measures $C_{13} - C_{23}$ by amplifying voltage with a high input impedance amplifier. Each circuit has equivalent performance with respect to rejecting the effects of stray capacitance and rejecting external electric fields, but the circuit of Figure 3.12 has a very important advantage of spacing insensitivity. With the current-output circuit of Figure 3.11, the output with $x = 0$ is zero and is insensitive to spacing, but the maximum output level (and hence the gage factor) is a direct function of spacing. For example, at the maximum-output position with the sense electrode 3 directly opposite electrode 2, the output current is proportional to C_{23}, or inversely proportional to the plate spacing; this is a benefit if the plate spacing is the parameter to be measured, but not for the current task of measuring linear displacement orthogonal to the spacing axis. With the high impedance amplifier circuit (Figure 3.12), the output level is ratiometric rather than absolute response, it is sensitive to V_1 instead of dV_1/dt, and it is totally insensitive to spacing, except for second order effects due to unguarded amplifier input capacitance and fringe fields. The output level is, unfortunately, sensitive to rotation in the axis through the paper, but we will find ways around this in later chapters.

3.3.5 Area variation with feedback amplifier

A third arrangement is similar to the high-Z amplifier above, except the feedback is taken around the driven electrodes (Figure 3.13).

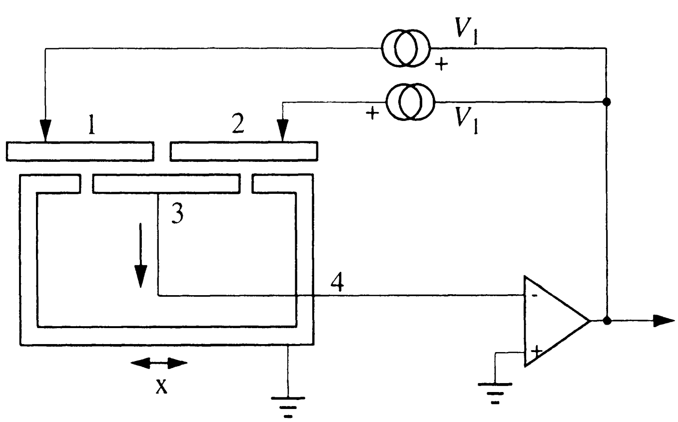


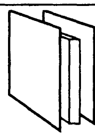
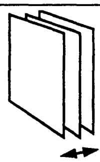
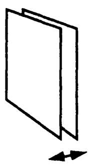
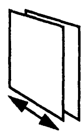
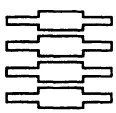
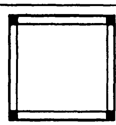
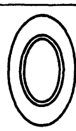
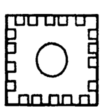
Figure 3.13 Guarded displacement sensor, feedback circuit

The performance of this circuit is very similar to the high impedance amplifier, and it can be made more resistant to stray capacitance. The circuit is similarly insensitive to spacing, as the spacing-variable capacitances C_{13} and C_{23} are inside the feedback loop and in series with the high input impedance of the amplifier. It is discussed further in the next chapter.

3.3.6 Electrode configuration table

Table 3.1 shows the various types of plate and circuit configurations for different applications.

Table 3.1 Capacitive sensor configurations

Application	Plate geometry	Amplifier (Chapter 4)	Circuit	Excitation	See Chap.
Material properties		Low-Z	Single ended or bridge	Variable frequency	10
Micrometer high sensitivity		Low-Z	Bridge	Sine wave	5
Micrometer small movement		Low-Z	Single ended	Square wave 0°/ 180°	5
Motion detect large movement		High-Z or feedback	Single ended	Square wave 0° / 180°	6, 7
Motion detect analog/digital		High-Z or feedback	Sin/cos or tracking	Square wave 0°/ 180°	8
Motion detect 2-axis		High-Z or feedback	Single ended	Square wave 0°/ 90°	19
Proximity detector		Low-Z	Single ended or bridge	Square wave or pseudo-random	6
Silicon sensors		High-Z or feedback	Bridge	Square wave	11, 15

3.4 LIMITS TO PRECISION

3.4.1 Noise

One limit to measurement precision in a capacitive sensor may be the number of charged particles associated with the capacitance. If a test voltage of 1 V is applied to a 1 cm disk, the capacitance of 0.354 pF accumulates a charge $Q = CV$ of 0.354×10^{-12} C. With 6.242×10^{18} electrons/C, we have 2.27×10^{6} electrons (or holes) on the disk. In systems where the charges are quantized so that fractional charges are not allowed, as for an isolated electrode, this limits precision to several parts per million. Certainly, the quantization of electron charge will not be a problem for most systems, and fractional charges are usually allowed except for currents through semiconductor junctions or electrodes which are completely floating.

Another limit is the input current noise of the amplifier circuit. With the high impedances of capacitive sensors, current noise is usually more important than voltage noise. With 10 V p-p AC excitation at 100 kHz, the reactance of 0.354 pF is 45 kΩ and the signal current is 10 V/45 kΩ or 2 μA. Bipolar amplifiers with input current noise of 1 pA in a 1 Hz bandwidth would generate 100 pA in a 10 kHz bandwidth and degrade signal to noise ratio to 4000:1. But FET-input operational amplifiers are available with current noise of less than a femtoamp (10^{-15} A) in 1 Hz, so the signal-to-noise ratio measured in a narrow 1 Hz bandwidth can be greater than $20 \times 10^{-6}/10^{-15}$ or 20×10^{9}. Apparently, current noise is not much of a limiting factor either, except for very small capacitive reactance or large bandwidth.

Actual resolution may be several orders of magnitude worse than this, depending on circuit design; shot noise effects, excess noise in semiconductor junctions, and thermal noise in resistors can be larger than amplifier input noise. But careful design can produce current sensors with noise of just a few thousand noise electrons per second. Systems with a sensitivity of 0.01 aF (0.01×10^{-18} F) have been reported [Jones and Richards, 1973]. Chapter 12 has a more detailed discusson of noise problems with capacitive sensor circuits.

3.4.2 Stability

Environmental

The environmental stability of air-dielectric capacitors is quite good. The dielectric constant of dry air at 0°C and 760 mm pressure is 1.000590, and that of gaseous water (steam) at 110°C is 1.00785, so the effects of temperature and humidity are minimal; Section 12.5 considers these effects in more detail. But absolute capacitance measurement is difficult to do accurately, as stray capacitances must be considered; careful grounding and shielding are needed. If stray capacitances are well guarded, the variation of capacitance due to dielectric constant variation and fringe fields can usually be ignored.

Mechanical

The mechanical stability of the supporting structure can be a concern. For spacing-variation micrometers discussed in Chapter 5, structural stability to μm dimensions is critical, but for area-variation systems or systems with carefully designed reference capacitors, ratiometric bridge amplifiers, and spacing-insensitive circuit design, structural stability is not so much of a problem.

Electrical

With ratiometric circuits, the output is sensitive only to a ratio of capacitances. Very precise components are not needed, and correct circuit design mitigates or cancels the effects of power supply variation and component variation.