Semiconductor Sensors:

Ch4: Capacitive Sensors

Lecturer: Dr. N. A. Sheini
Shahid Chamran University of Ahvaz

Base of operation:

Capacitive sensors operate based on changes in electrical capacitance.

Capacitive sensors based on their sensing mechanisms:

- *Spacing variation*: varying the space or distance between plates;
- *Area variation*: varying the overlap area between plates;
- *Dielectric material property change*: changing properties of the dielectric media;
- *Electrode property change*: changing conductivity, charges, mass, or other physical or chemical properties of the electrodes;

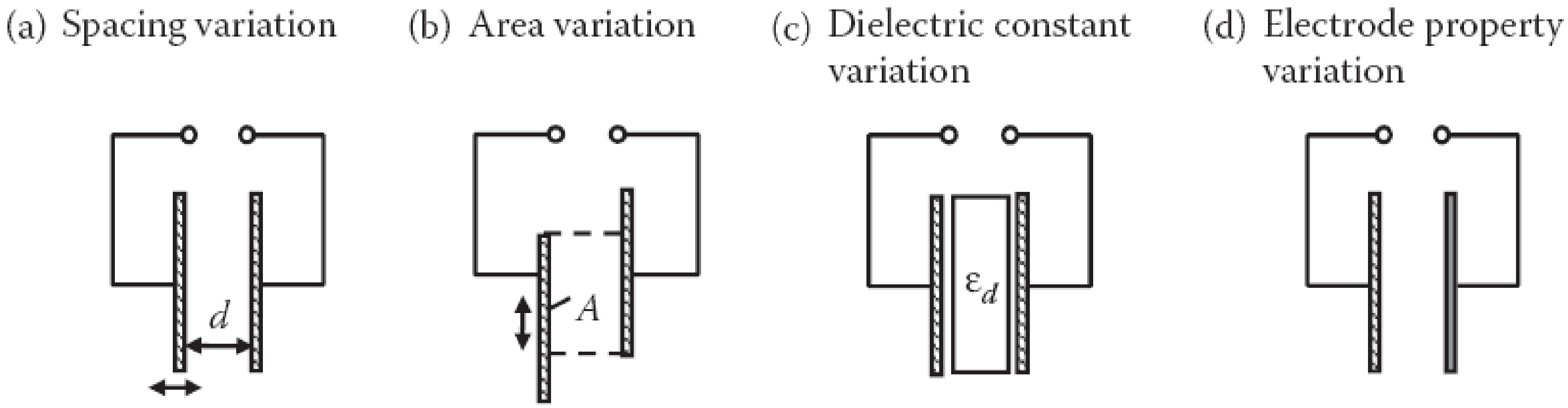


FIGURE 3.7 Four basic principles underneath the parallel capacitive sensor design.

انواع خازن:

Based on Structures

Parallel (flat) configuration and their array
Cylindrical (coaxial) configuration
Spherical (concentric) configuration

Based on Dielectric Materials

Air gap	Paper
Ceramic	Polyester
Mica	Polystyrene
Mylar	Polycarbonate
Glass	Teflon

Based on Capacitance Values

Fixed (constant)
Variable (adjustable)
Super

Based on Polarization

Polarized
Nonpolarized

Based on Electrodes

Electrostatic
Electrolytic
Multielectrode

Based on Applications

Energy storage
Power conditioning
Signal processing
Sensing
Memory

Based on Packaging

Through-hole
Surface mount

W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

گذردهی نسبی در دی الکتریکهای مختلف:

RDP of Common Materials at Room Temperature

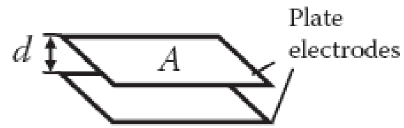
Material	RDP, ε_r	Material	RDP, ε_r	Material	RDP, ε_r
Air, vacuum	1	Paper	3.5	Mica	6
Clay	1.8–2.8	Silica glass	3.7	Rubber	7
Teflon	2	Silicon dioxide	3.9	Marble	8
Soft rubber	2.5	Nylon	4–5	Silicone	11–12
Wood	2.7	Porcelain	4.4	Alcohol	16–31
Silicone rubber	2.8	Diamond	5.5–10	Fresh water	80
Ice	3–4	Glass	5	Sea water	81–88

Source: *Dielectric Constants of Materials*, Clipper Controls, Inc., San Francisco, California, USA, 2011. With permission.

Dielectric constant ε_r (usually determined empirically) is the ratio of the permittivity of a substance ε_p to the permittivity of free space ε_0 (i.e., $\varepsilon_r = \varepsilon_p/\varepsilon_0$).

ظرفیت خازنی در آرایشهای مختلف:

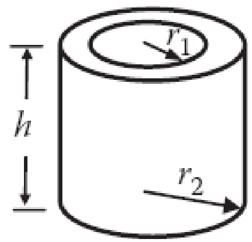
Parallel-(flat) plate capacitor



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

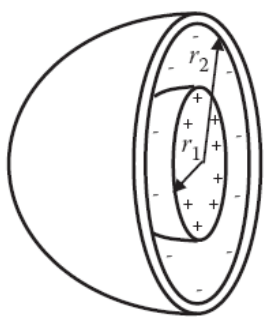
Ratio A/d is called the *geometry factor* for a parallel-plate capacitor.

Cylindrical (coaxial) capacitor



$$C = \frac{2\pi \varepsilon_0 \varepsilon_r h}{\ln(r_2/r_1)} \qquad (h \gg r_2)$$

Spherical (concentric) capacitor

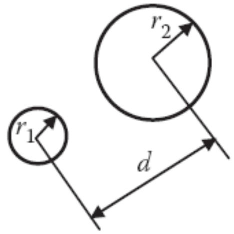


$$C = \frac{4\pi \varepsilon_0 \varepsilon_r r_1 r_2}{r_2 - r_1}$$

Ratio $4\pi r_1 r_2/(r_2 - r_1)$ is the *geometry factor* for a spherical capacitor.

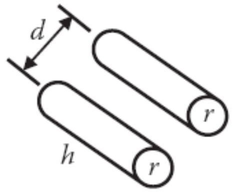
ظرفیت خازنی در آرایشهای مختلف:

Two spheres [4]



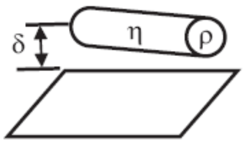
$$C = \frac{4\pi\varepsilon_0\varepsilon_r}{\frac{r_1+r_2}{r_1 r_2} - \frac{1}{d}}$$

Two parallel cylinders [4]



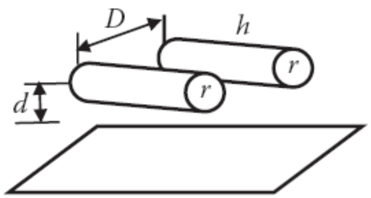
$$C = \frac{\pi\varepsilon_0\varepsilon_r h}{\ln\left(\frac{d+\sqrt{d^2-4r^2}}{2r}\right)}$$

One cylinder and one plate [4]



$$X = \frac{2\pi\varepsilon_0\varepsilon_\rho \eta}{\ln\left(\frac{\delta+\sqrt{\delta^2-\rho^2}}{\rho}\right)}$$

Two cylinders and one plate [4]



$$C = \frac{\pi\varepsilon_0\varepsilon_r h \cdot \ln\left(1+\frac{2d}{D}\right)}{\ln\left(\frac{2d}{r}\right)^2} \quad (2d \gg r)$$

W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

انواع خازن:

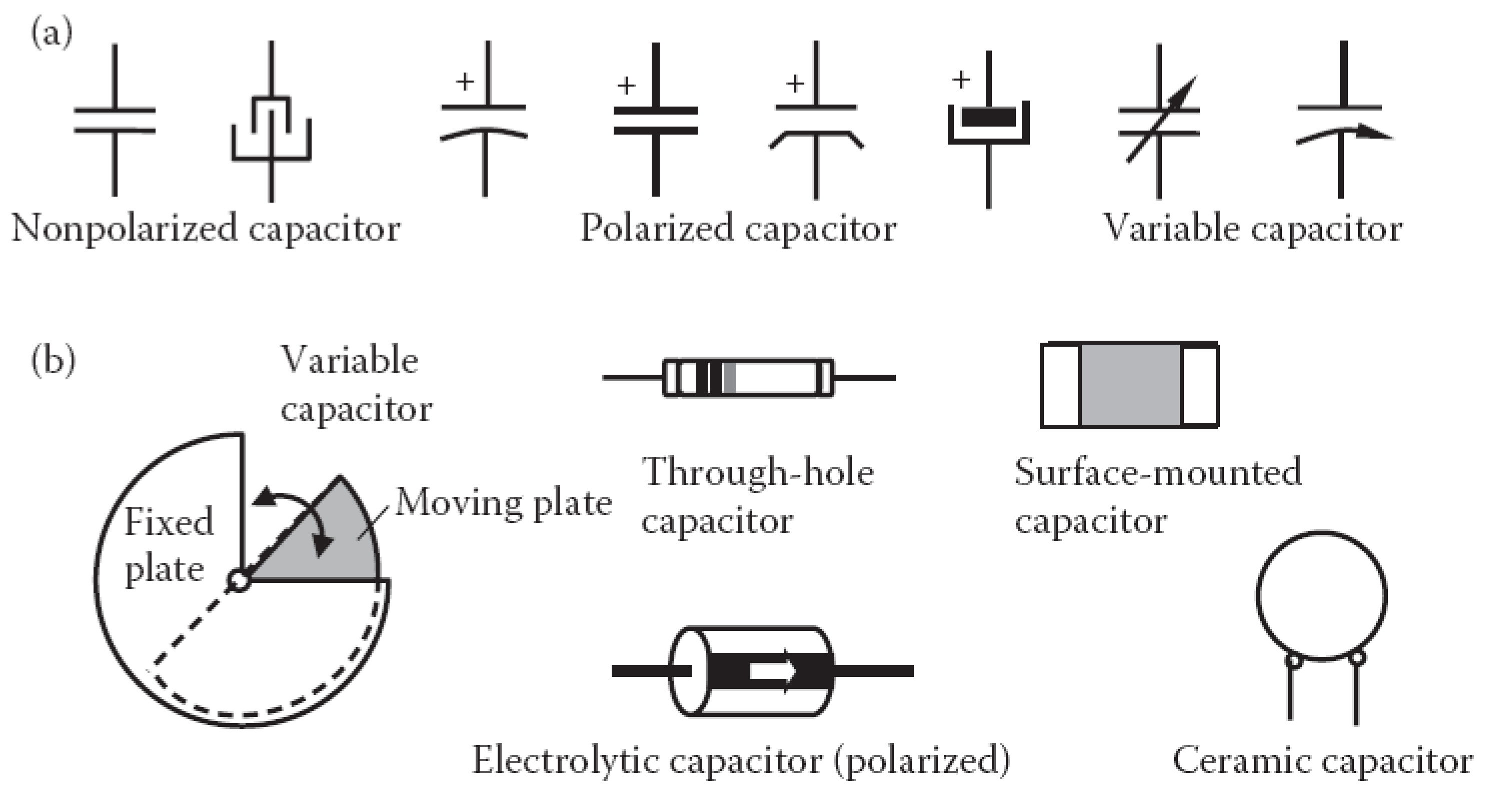


FIGURE 3.1 (a) Circuit symbols of capacitors; (b) certain types of capacitors.

Advantages:

- The most precise of all electrical sensors (including resistive and inductive sensors)
- Extremely high sensitivity
- High resolution (e.g.,0.01 nm)
- Broad bandwidth (e.g., 1 ~ 100 kHz)
- Robustness
- Long-term stability and durability
- Drift-free character
- Simple structures
- Low cost
- Noncontact detection

❖ Most capacitive sensors are immune to humidity, temperature, target material, and stray electric field variations.

❖ Some can be integrated into a printed circuit board (PCB) or embedded into a microchip or a nanodevice to provide excellent accuracy and nearly infinite resolution, higher reliability, less weight, and lower power consumption.

Coulomb's Law

Coulomb's law describes the force *F* between any two charges *Q*1 and *Q*2 separated by a distance *d*:

$$F = \frac{Q_1 Q_2}{4\pi\varepsilon_0\varepsilon_r d^2}$$

Gauss's Law for Electric Field

Gauss's law is one of Maxwell's four fundamental equations for electricity and magnetism. It states that the total electric flux out of a closed surface, Φ_E, is equal to the total charge enclosed $\sum Q_i$ divided by the permittivity in free space ε_0 [4]:

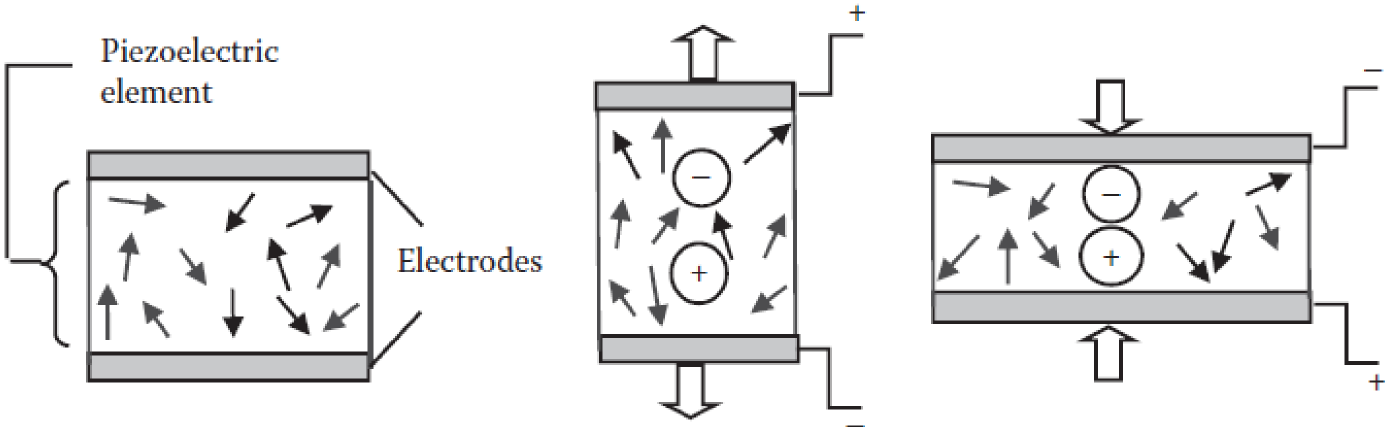
$$\Phi_E = \frac{\sum Q_i}{\varepsilon_0} \tag{3.17}$$

The electric flux Φ_E (in volt · meter, V · m; or in newton meter square per coulomb, $N \cdot m^2 \cdot C^{-1}$) is defined as a surface integral of the electric field E over any closed surface A:

$$\Phi_E = \oint \vec{E} \cdot d\vec{A} \tag{3.18}$$

Piezoelectric Effect

A piezoelectric element will produce an electric charge when a mechanical stress (longitudinal, transverse, or shear) is applied. Conversely, mechanical deformation (e.g., shrinkage or expansion) occurs when an electric field is applied to a piezoelectric element.This effect is called *Piezoelectric effect*, discovered by the Curie brothers more than 100 years ago. They found that quartz changed its dimensions when subjected to an electrical field, and conversely, generated electrical charge when mechanically deformed.



Piezoelectric material without a stress—no voltage output

Piezoelectric material being stretched—a voltage output opposite to the polar axis

Piezoelectric material being compressed—a voltage output in the same direction to the polar axis

W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

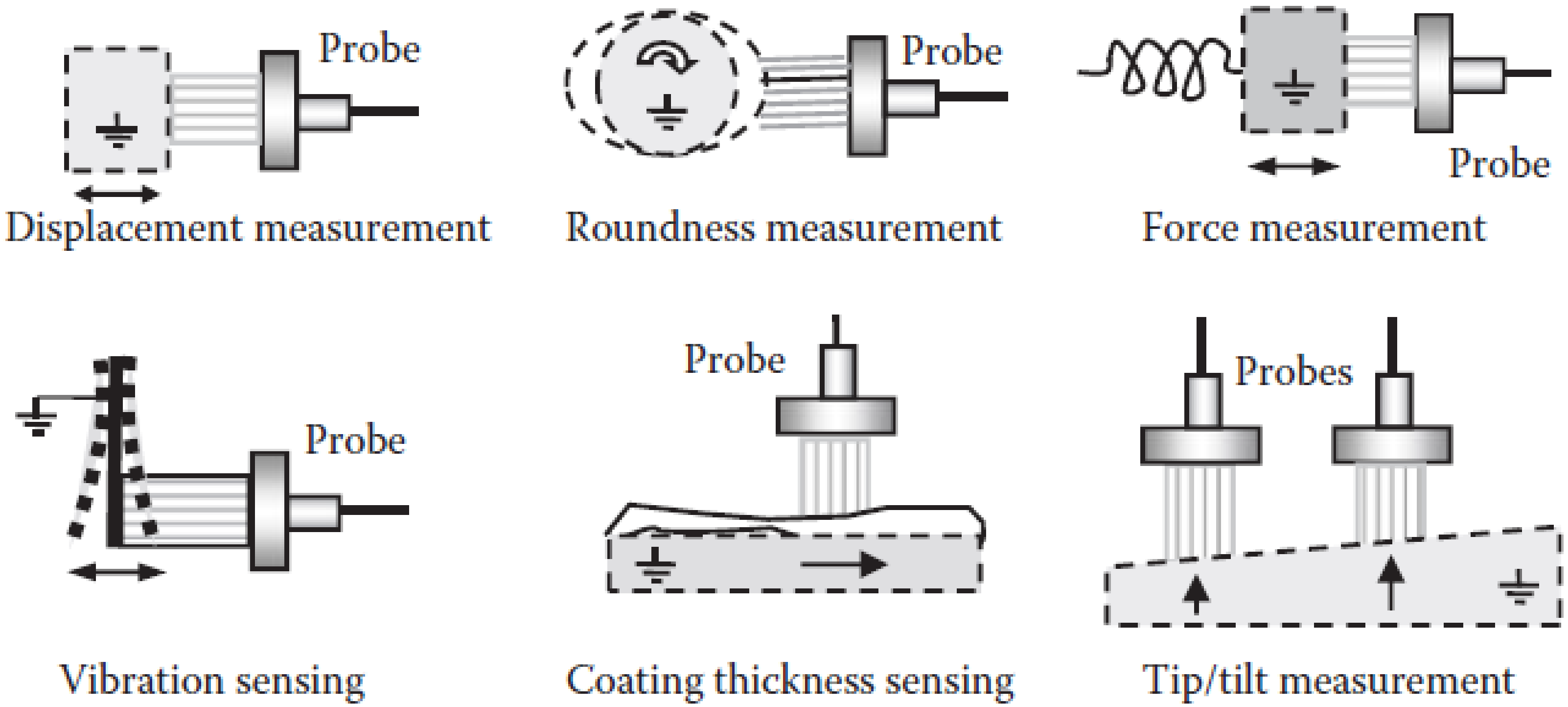
Effect of Excitation Frequencies

A capacitive sensor may require a high-frequency excitation, close to the resonance frequency of the circuit, so that the electrode impedance reaches its minimum and the sensitivity of the sensor reaches its maximum. The excitation frequency also affects the operating range of a capacitive sensor.

For example, a *ChenYang Technologies'* (in Germany) capacitive displacement sensor has a measurement range of 1 mm at the excitation frequency 28 kHz, but its measurement range can reach 4 mm at the resonance frequency of 30.4 kHz.

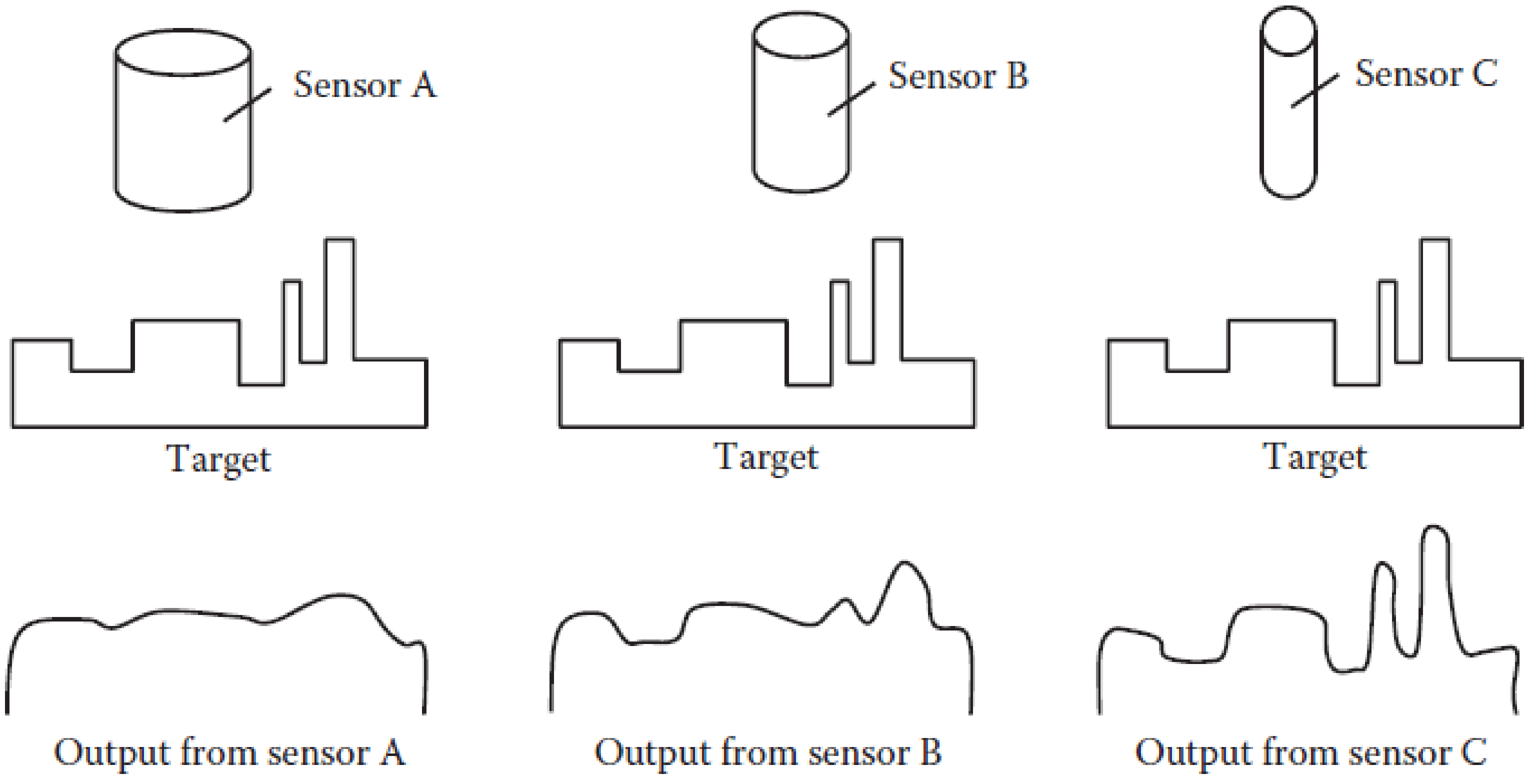
حسگرهای خازنی- مثالهای کاربردی از نوع تک صفحه ایی:

The application examples of single-plate sensors:



W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

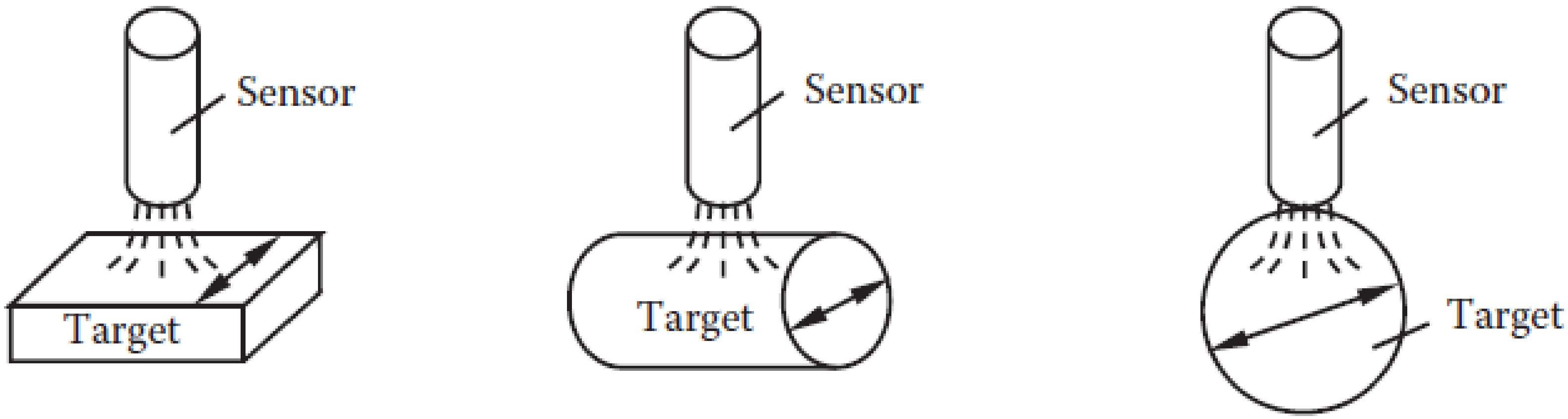
The sensor's size effect:



W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.

حسگرهای خازنی- راهنما برای انتخاب قطر حسگر:

Selection guidelines for the maximum sensor size:



Flat surface:
Maximum sensor diameter = 0.6 × Minimum target detecting surface dimension

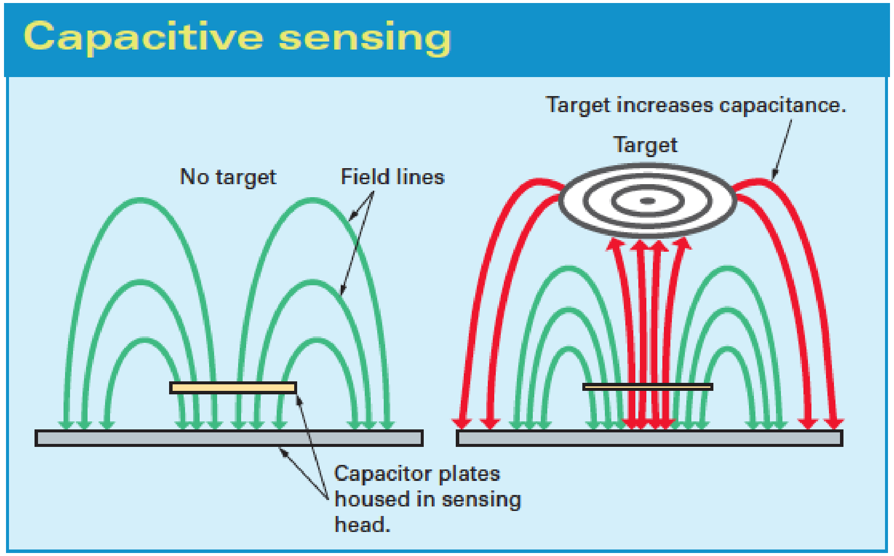
Cylindrical surface:
Maximum sensor diameter = 0.25 × Minimum target dimension

Spherical surface:
Maximum sensor diameter = 0.2 × Minimum target dimension

Common diameters range for capacitive proximity sensor is from 12 to 60 mm in shielded and unshielded mounting versions.

حسگرهای خازنی- نوع پروکسی متر:

Proximity sensors detect the presence or absence of objects using electromagnetic fields, light, and sound. There are many types, each suited to specific applications and environments.



As a ferrous or nonferrous target enters the sensing zone, capacitance increases; circuit natural frequency shifts towards the oscillation frequency, causing amplitude gain.

Capacitive proximity sensors can detect both metallic and non-metallic targets in powder, granulate, liquid, and solid form. This, along with their ability to sense through nonferrous materials, makes them ideal for sight glass monitoring, tank liquid level detection, and hopper powder level recognition.

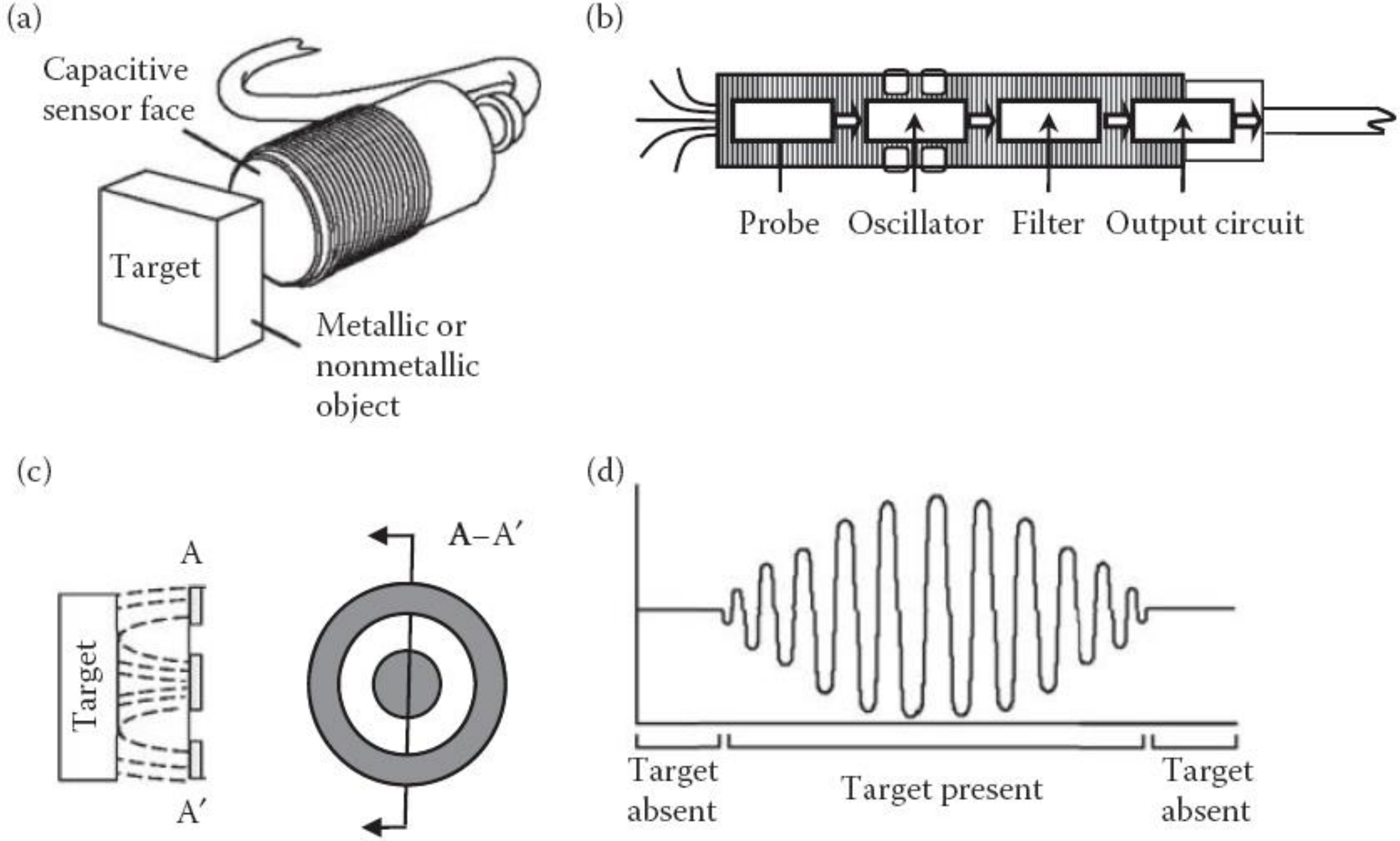
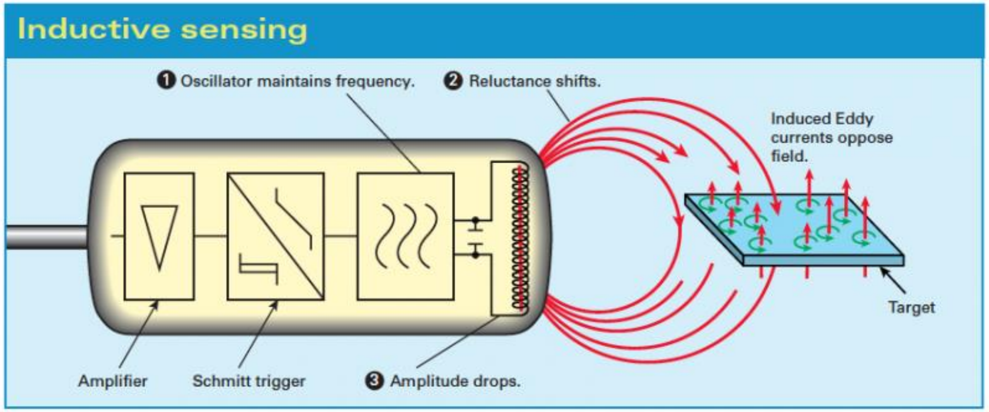
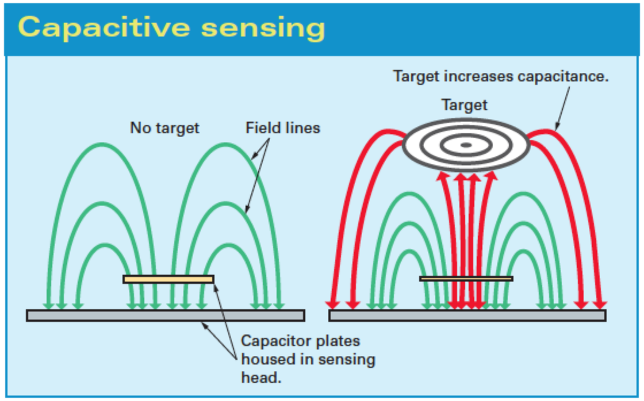


FIGURE 3.29 Example of a capacitive proximity sensor design and sensing. (After Capacitive proximity sensors: Theory of operation, Siemens online course. www.automationmedia.com/Port1050%5CSiemensFreeCourses%5Csnrs_3.pdf.)

حسگرهای خازنی- مقایسه نوع پروکسی متر خازنی با القایی:



Ferrous targets change the reluctance of the magnetic circuit; system oscillation frequency, which gets left behind when the natural frequency shifts, then loses amplitude.

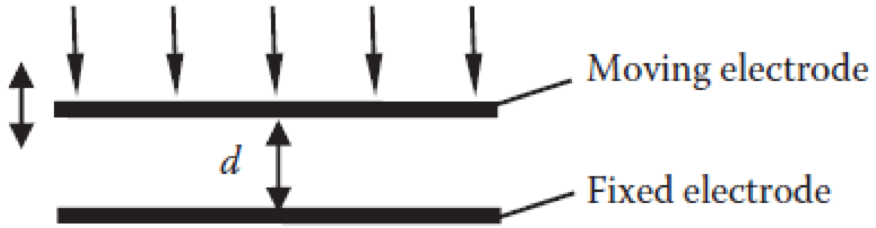


As a ferrous or nonferrous target enters the sensing zone, capacitance increases; circuit natural frequency shifts towards the oscillation frequency, causing amplitude gain.

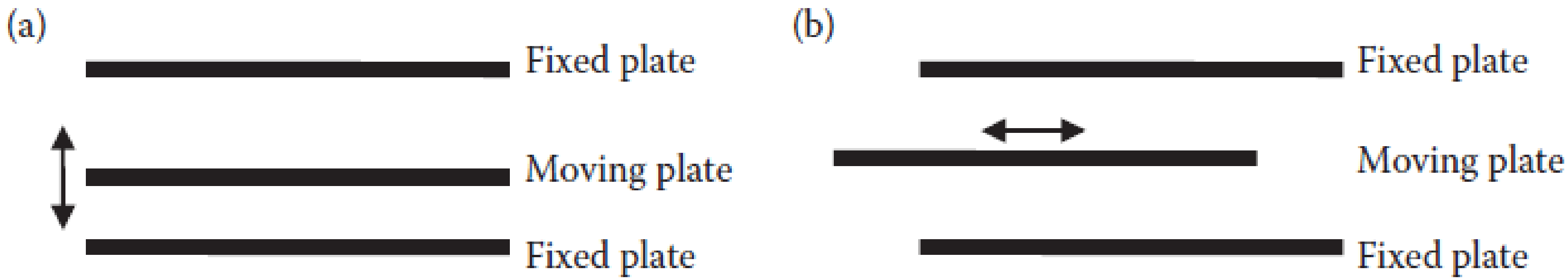
- Inductive sensors oscillate until the target is present and capacitive sensors oscillate when the target is present.
- Because capacitive sensing involves charging plates, it is somewhat slower than inductive sensing.
- Due to their ability to detect most types of materials, capacitive sensors must be kept away from non-target materials to avoid false triggering. For this reason, if the intended target contains a ferrous material, an inductive sensor is a more reliable option.

http://www.machinedesign.com/sensors/proximity-sensors-compared-inductive-capacitive-photoelectric-and-ultrasonic

حسگرهای خازنی- انواع بر اساس تعداد صفحات:

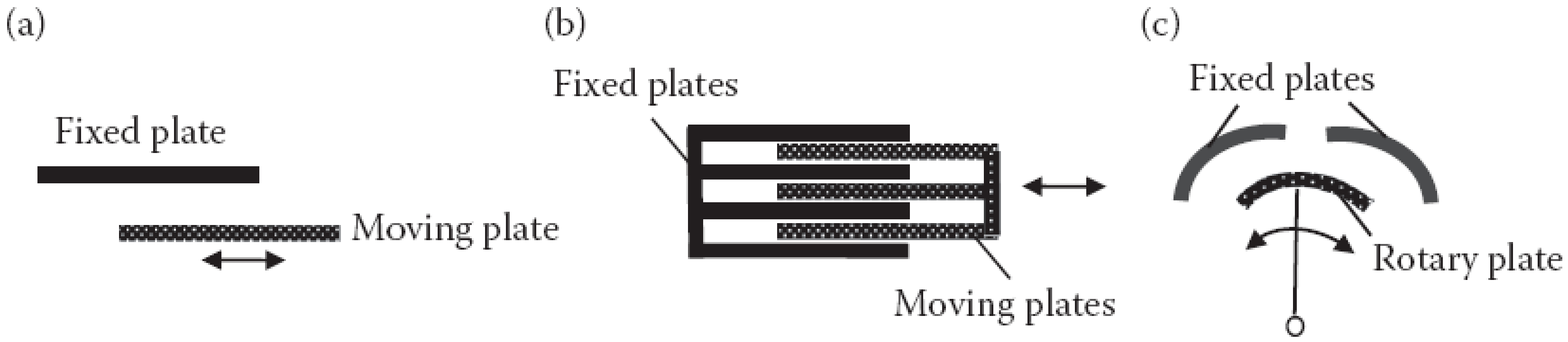


A dual-plate capacitive sensor design.



Three-plate configurations for (a) spacing-variation- and (b) area-variation based sensors.

One-pair or multi-pair, linear or rotary configurations:



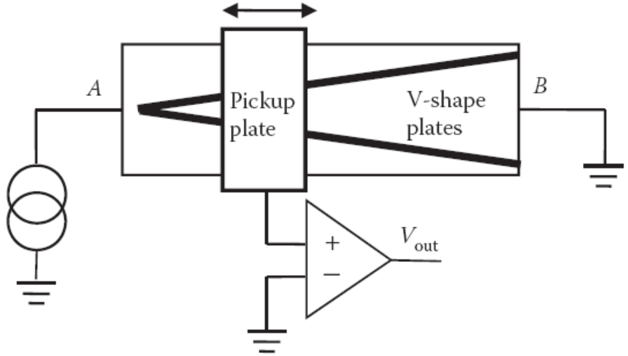


FIGURE 3.21 Chevron-shaped driven plate reducing tilt. (From Baxter, L.K., *Capacitive Sensors: Design and Applications*, 1st ed., IEEE Press, New York, 1997. With permission.)

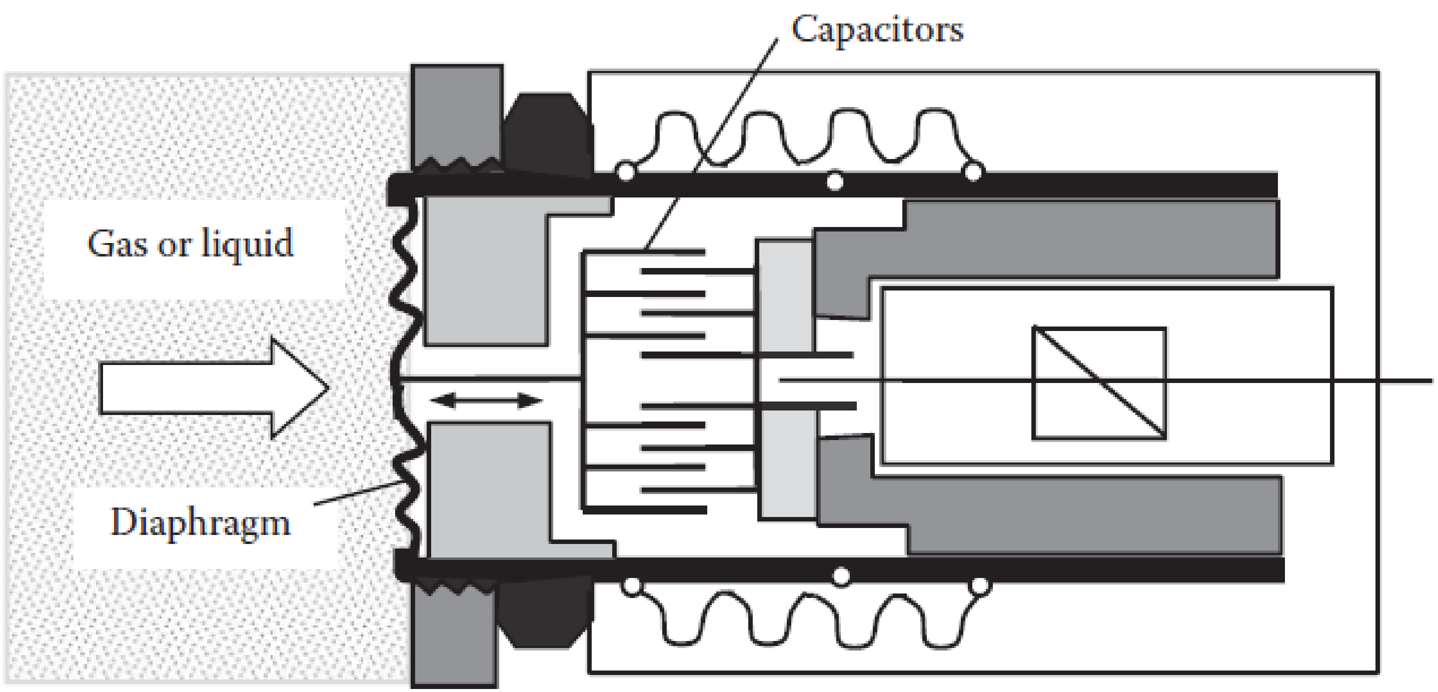
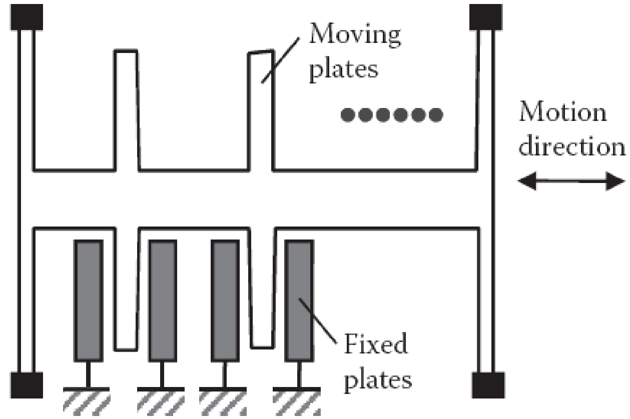
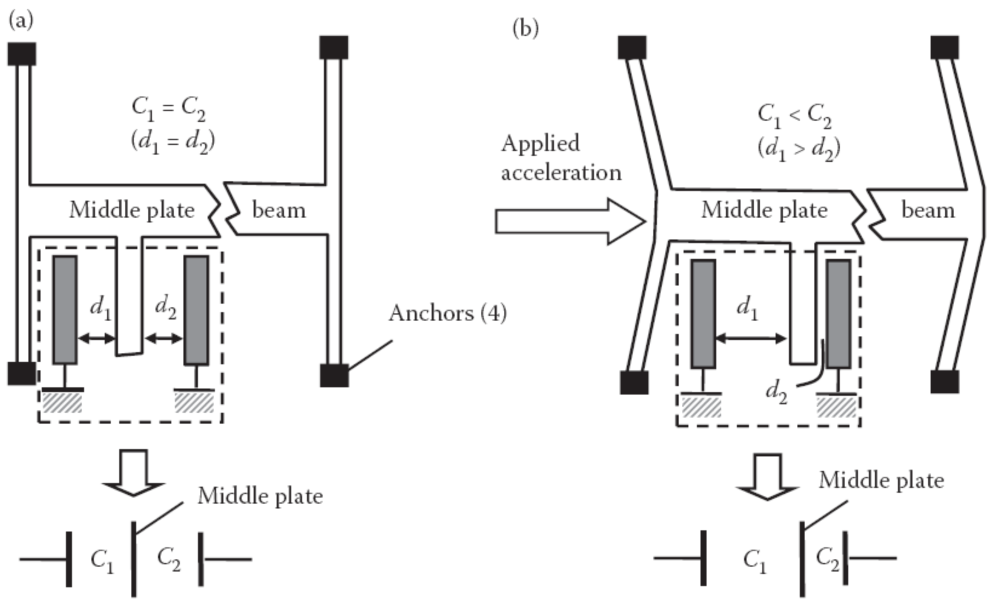
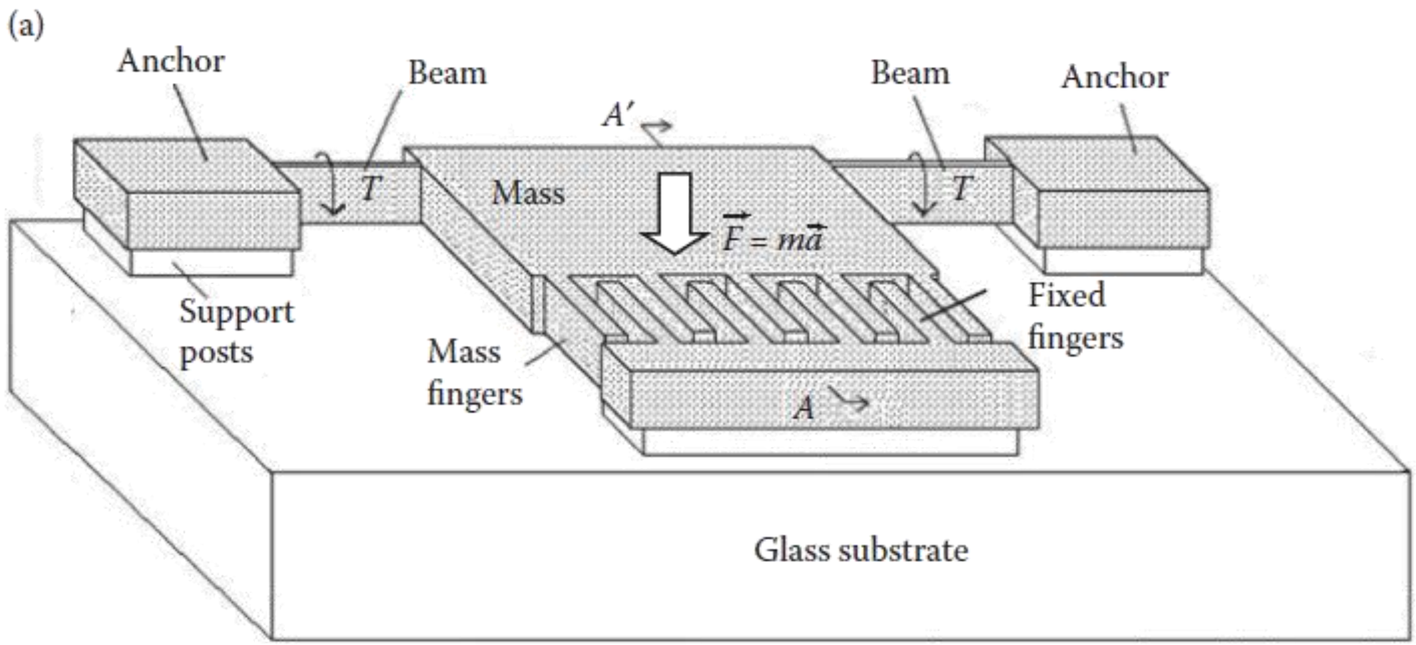


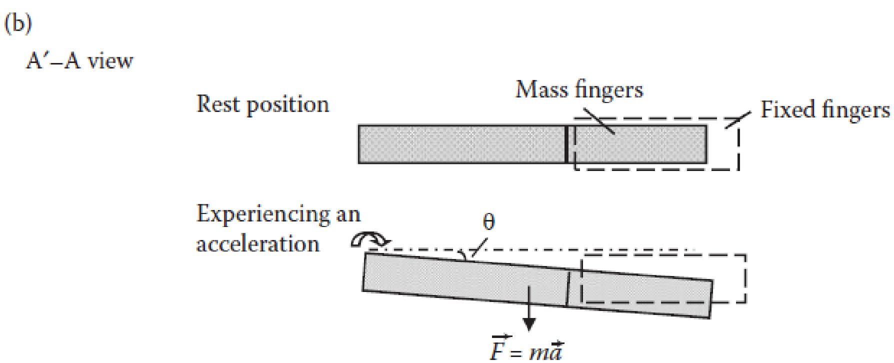
FIGURE 3.23 Capacitive pressure sensor with area variation. (Modified based on original drawing from *VEGA Technique*, France.)



A multiplate capacitive sensor.



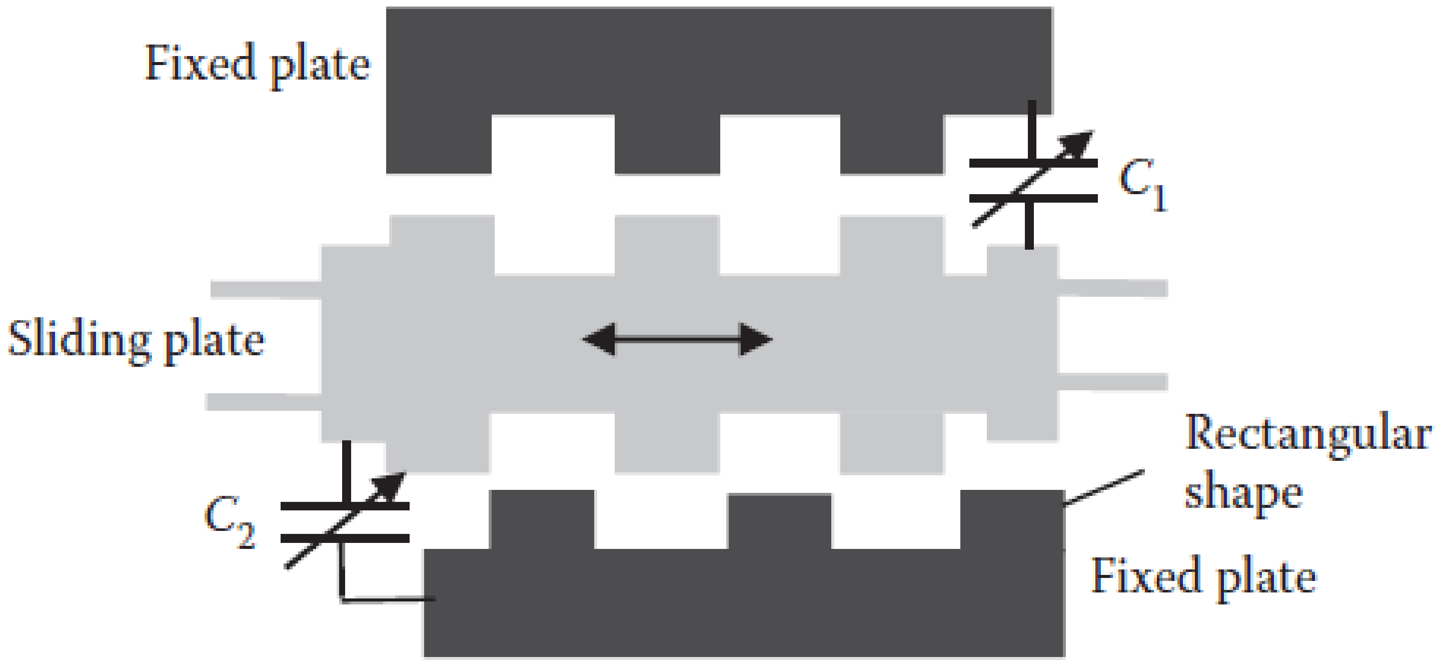




Geometry Parameters of a Torsional Accelerometer

Mass length l_m: 1000 µm	Beam length l_b: 150 µm
Mass width w_m: 750 µm	Beam width w_m: 5 µm
Mass thickness t_m: 12 µm	Finger length l_f: 500 µm
Total moving mass M: 2.446 × 10^{-3} g	Finger width w_m: 10 µm
Etch pit depth d': 15 µm	Inter finger gap d_f: 5 µm
	Total number of moving fingers n: 25

Position Sensor: حسگرهای خازنی- مثال کاربردی- مکان سنج:



W. Y. Du "*Resistive, capacitive, inductive, and magnetic sensor technologies*", CRC Press, 2014.