CAPACITANCE MEASUREMENT

Capacitance is the property that exists between two charged electrodes separated by a dielectric material. The capacitance C is equal to the ratio of the absolute value of the charge Q to the absolute value of the voltage between charged bodies as

$$C = Q/V \tag{1}$$

where C is the capacitance in farads (F), Q is charge in Coulombs (C) and V is voltage (V).

The unit of capacitance is the Farad, which is a very large unit; therefore, practical capacitors have capacitances of microfarads (μF or 10^{-6} F), nanofarads (nF or 10^{-9} F), and picofarads (pF or 10^{-12} F).

In general, the capacitance can be determined by using Laplace's equations $\nabla^2 V(x, y, z) = 0$ with appropriate boundary conditions. The boundary conditions specify the electrode voltages V_1 and V_2 of the plates. For two electrodes, Laplace's equation yields the voltage $V(x, y, z)$ and the electric field $E(x, y, z) = -\nabla V(x, y, z)$. The charge of each electrode can also be obtained by integration of the flux density over each electrode surface as

$$Q = \int \epsilon(x, y, z) \boldsymbol{E}(x, y, z)\, \mathrm{d}\boldsymbol{A} \tag{2}$$

If the capacitor is made from two parallel plates, as shown in Fig. 1, the capacitance value in terms of dimensions may be expressed by

$$C = \epsilon A/d = \epsilon_r \epsilon_0 A/d \tag{3}$$

where ϵ is the dielectric constant or permittivity, ϵ_r is the relative dielectric constant (in air $\epsilon_r = 1$), ϵ_0 is the dielectric constant of vacuum (8.854188×10^{-12} F/m or $10^{-9}/36\pi$ F/m), d is the distance between the plates in m, and A is the effective area of the plates in m^2.

As can be seen in Eq. (3), the value of the capacitance is largely dependent on the permittivity of the dielectric material used. The permittivity of commonly used materials in the construction of capacitors, is listed in Table 1.

The capacitance C depends on the size and shape of charged bodies and their positioning relative to each other as shown in Table 2. In many electric and electronic systems, it is necessary to deal with the useful capacitances as well unwanted components. In many circuits, stray capacitances are introduced externally or internally at various stages. Cables and other external components introduce additional capacitances that need to be dealt with for desirable performance of the system. In these cases, Table 1 is useful to identify and analyze possible sources of additional capacitances where charged bodies are involved.

Characteristics of Capacitors

Capacitors are characterized by dielectric properties, breakdown voltages, temperature coefficients, insulation resistances, frequency and impedances, power dissipation, and quality factors: reliability, aging, etc.

The dielectrics of capacitors can be made from polar or nonpolar materials. Polar materials have dipolar characteristics; that is they consist of molecules whose ends are oppositely charged. This polarization causes oscillations at certain frequencies resulting in high losses at those frequencies.

Dielectric absorption and leakage currents occur due to properties of dielectric materials. Absorption introduces a time lag during the charging and discharging of capacitors, thus reducing the capacitance values at high frequencies and causing unwanted time delays, particularly in pulse circuits. The leakage current, on the other hand, prevents indefinite storage of energy in the capacitor. An associated parameter of leakage currents is leakage resistance, which is measured in megohms but is usually expressed in megohm-microfarads or ohms-farads. The leakage resistance and capacitance introduce time constants which can vary from a few days for polystyrene to several seconds in some electrolytic capacitors. The leakage current is not only dependent on the properties of the dielectric materials but also on the construction and structure of the capacitors, and this is particularly true for capacitors having values less than 0.1 μF with very thin dielectric material between the electrodes.

If the capacitor is subjected to high operating voltages, the electric field in the dielectric exceeds the breakdown value and damages the dielectric permanently. The dielectric strength depends on the temperature, the frequency, and the applied voltage. An example of this dependence on the applied voltage is given in Fig. 2. It is commonly known that the use of capacitors below their rated values increases the reliability and their expected life time. The standard voltage ratings of most capacitors are quoted by the manufacturers as 50, 100, 200, 400, and 600 V. Tantalum and electrolytic capacitors have ratings of 6, 10, 12, 15, 20, 25, 35, 50, 75, 100 V, and higher.

Usually, values of surge voltages are given to indicate the ability of capacitors to withstand high transients. Typically, the surge voltages for electrolytic capacitors are 10% above the rated voltage, 50% for aluminum capacitors, and about 250% for ceramic and mica capacitors. The rated reverse voltages of electrolytic capacitors are limited to 1.5 V and, in some cases, to 15% of the rated forward voltages.

The temperature characteristics of capacitors are largely dependent on the temperature properties of the dielectric materials used, as given in Fig. 3. The temperature coefficients of glass, teflon, mica, polycarbonate, etc. are very small, whereas in ceramic capacitors, they can be very high.

The insulation resistance of capacitors is important in many circuits. The insulation resistance is susceptible to temperature and humidity. Particularly, unsealed capacitors show large and rapid changes against temperature and humidity. For most capacitors, at high temperatures, the change in insulation resistance is an exponential function of temperature ($R_{T1} = R_{T2} e^{K(T1-T2)}$). The temperature dependence of insulation resistance of common capacitors is shown in Fig. 4.

Power Dissipation and Quality Factors. An ideal capacitor should have entirely negative reactance, but losses and inher-

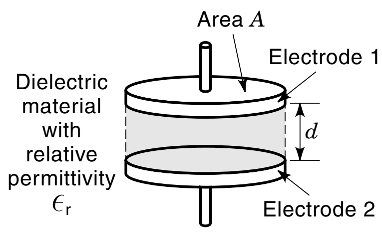


Figure 1. A typical capacitor made from two parallel plates. The capacitance between two charged bodies depends on the permittivity of the medium, distance between the bodies, and the effective area. It can also be expressed in terms of the absolute values of the charge and the absolute values of the voltages between bodies.

ent inductances prevent ideal operation. Depending on the construction, every capacitor resonates at certain frequencies due to equivalent resistance and inductances. A typical impedance characteristic of a capacitor is depicted in Fig. 5.

The electric equivalent circuit of a capacitor consists of a pure capacitance (C_p), plate inductances (L_1, L_2), plate resistances (R_1, R_2), and a parallel resistance R_p which represents the resistance of the dielectric or leakage resistance as shown in Fig. 6. The capacitors that have high leakage currents flowing through the dielectric have relatively low values for R_p. Very low leakage currents are represented by extremely large values of R_p. Examples of these two extremes are electrolytic capacitors that have high leakage current (low R_p), and plastic film capacitors which have very low leakage current (high R_p). Typically, an electrolytic capacitor might easily have $R_p < 1$ MΩ, giving several microamperes of leakage current, while a plastic film capacitor could have a resistance greater than 100,000 MΩ.

In some cases, it is usual to represent a low leakage capacitor (high R_p) by a series RC circuit, while those with high leakage (low R_p) are represented by a parallel RC circuit. However, when the capacitor is measured in terms of the series C and R quantities, it is usually desirable to convert them into the parallel equivalent circuit quantities. This is because the (parallel) leakage resistance best represents the quality of the capacitor dielectric.

An ideal capacitor stores energy without dissipating any power. However, due to equivalent resistances, R_{eq}, some power will be dissipated. The power factor of a capacitor may be expressed as

$$\mathrm{PF} = \cos\theta = R_{eq}/|Z_{eq}| \tag{4}$$

Table 1. Permittivity (Dielectric Constants) of Materials Used in Capacitors

Material	Permittivity
Vacuum	1.0
Air	1.0006
Polythene etc.	2.0 to 3.0
Impregnated paper	4.0 to 6.0
Glass and Mica	4.0 to 7.0
Ceramic (low K)	to 20.0
Ceramic (medium K)	80.0 to 100.0
Ceramic (high K)	1000.0 up

where θ is the phase angle, and Z_{eq} is the equivalent total impedance.

One important characteristic, the dissipation factor of capacitors, is expressed as

$$\mathrm{DF} = \tan\delta = R_{eq}/X_{eq} \tag{5}$$

where δ is the angle of loss, and X_{eq} is the equivalent reactance.

The dissipation factor is dependent on the frequency. Capacitors are designed such that this dependence is minimal. The measurement of the dissipation factor δ is made at 1 kHz and 1.0 Vrms applied to the capacitor. A typical dissipation factor curve is depicted in Fig. 7.

CAPACITIVE REACTANCE

Capacitors are used as two terminal elements, shown in Fig. 8(a), with the current voltage relationship given by

$$i(t) = C\,\mathrm{d}v(t)/\mathrm{d}t \tag{6}$$

From the $v(t)$, $i(t)$ relationship, the instantaneous power of this element is then

$$p(t) = v(t)i(t) \tag{7}$$

The stored energy in the capacitor at time t seconds may be calculated as

$$\begin{aligned} w(t) &= \textstyle\int Cv(t)\{\mathrm{d}v(t)/\mathrm{d}t\}\,\mathrm{d}t \\ &= [Cv^2(t)]/2 \end{aligned} \tag{8}$$

Hence, the energy stored in the capacitor in the time interval t_1, t_2 will be equal to

$$W = (1/2)C[v^2(t_2) - v^2(t_1)] \tag{9}$$

If $v(t_2) = v(t_1)$, the energy stored in the capacitor in this time interval is equal to zero. This implies that the energy stored in the capacitor is returned to the circuit during the time interval; that is, the capacitor transforms the energy without dissipation.

In circuits, capacitors form passive components. That is, if the voltage is known, the currents can immediately be determined by differentiation of the voltages. The Laplace transform gives the relationship

$$I(s) = sCV(s) \tag{10}$$

From this, the input-output relationship yields the impedance of the capacitor as

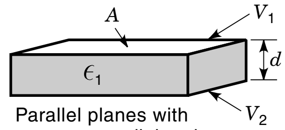
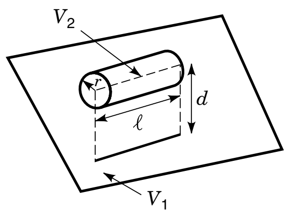
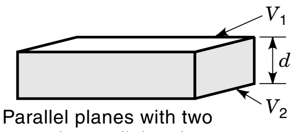
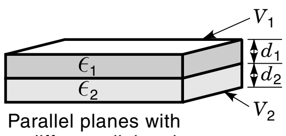
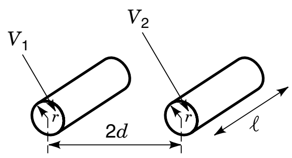
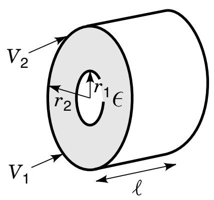
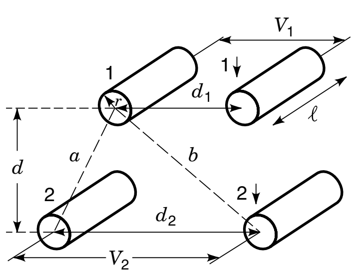
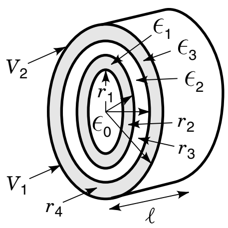
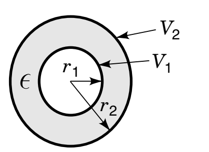
$$Z(s) = 1/sC$$

or

$$Y(s) = sC \tag{11}$$

In the stationary condition, $s \to 0$, $Z \to \propto$, and $Y \to 0$.

Table 2. Capacitances of Various Electrode Systems

Electrode system	Capacitance	Electrode system	Capacitance
 Parallel planes with homogeneous dielectric	$C = \frac{\epsilon A}{d'}$	 Cylinders parallel with plane	$C = \frac{\pi \epsilon l}{\ln\left[\frac{d}{r} + \sqrt{\left(\frac{d}{r}\right)^2 - 1}\right]} = \frac{2\pi\epsilon l}{\cosh^{-1}\left(\frac{d}{r}\right)}$
 Parallel planes with two constituent dielectrics	$C = \frac{(\epsilon_1 r + \epsilon_2)A}{(1 + r)d}$ where r value is the volumetric ratio		
 Parallel planes with two different dielectrics	$C = \frac{\epsilon A}{\frac{d_1}{\epsilon_1} + \frac{d_2}{\epsilon_2}}$	 Parallel cylinders with equal radius	$C = \frac{\pi \epsilon l}{\ln\left[\frac{d}{r} + \sqrt{\left(\frac{d}{r}\right)^2 - 1}\right]} = \frac{2\pi\epsilon l}{\cosh^{-1}\left(\frac{d}{r}\right)}$
 Coaxial cylinders with single dielectric	$C = \frac{4\pi\epsilon l}{\ln(r_2/r_1)}$	 Mutual capacitance	$C_{11} = \frac{\pi\epsilon l}{\ln(d_1/r)} + \frac{\pi\epsilon}{2}\frac{\ln(b/a)}{[\ln(a/r)]\ln(b/r)}$; $C_{21} = C_{12} = \frac{\pi\epsilon l}{2}\frac{\ln(b/a)}{[\ln(a/r)]\ln(b/r)}$
 Coaxial cylinders with three dielectrics	$C = \frac{2\pi\epsilon_0 l}{\ln\left[\left(\frac{r_2}{r_1}\right)^{\frac{\epsilon_0}{\epsilon_1}} \times \left(\frac{r_3}{r_2}\right)^{\frac{\epsilon_0}{\epsilon_2}} \times \left(\frac{r_4}{r_3}\right)^{\frac{\epsilon_0}{\epsilon_3}}\right]} = \left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right)^{-1}$	 Concentric spheres	$C = \frac{4\pi\epsilon r_1 r_2}{r_2 - r_1}$

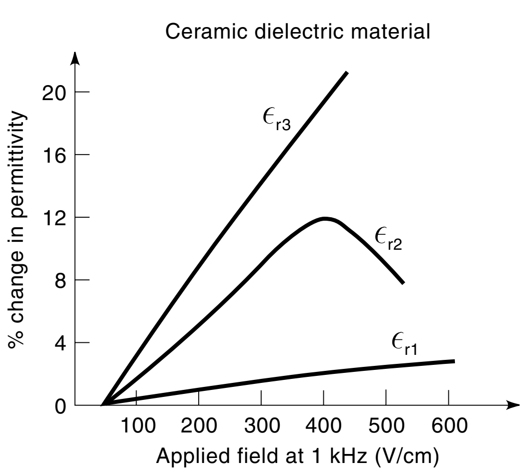


Figure 2. Changes in relative permittivity against field strength. The dielectric strength depends on the temperature, frequency, and applied voltage. Increases in the applied voltage cause higher changes in the dielectric strength. If the capacitor is subjected to higher operating voltages, the electric field in the dielectric exceeds the breakdown value which can damage the dielectric permanently.

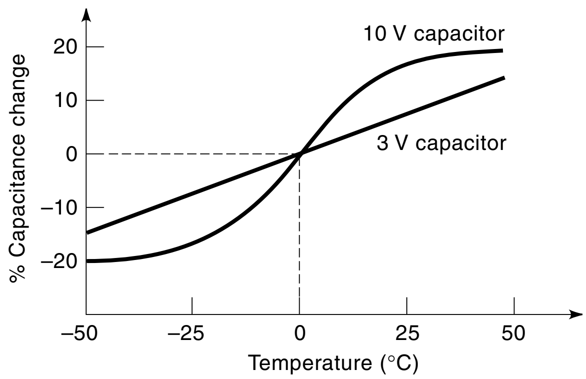


Figure 3. Temperature dependence of capacitors. The temperature characteristics of capacitors are largely dependent on the temperature properties of the dielectric materials used. The variations in capacitance due to temperature also depend on the type of capacitor and the operational voltage. The temperature coefficient of glass, teflon, mica and polycarbonate are very small, whereas in ceramic capacitors, they are relatively high.

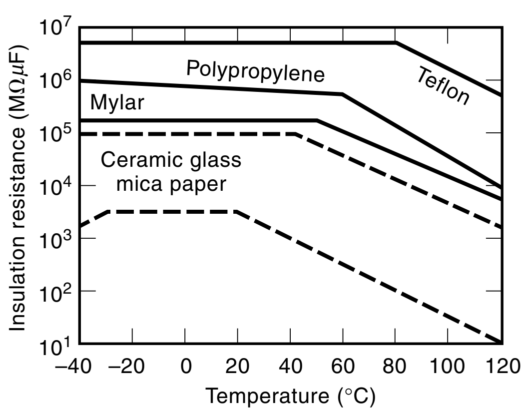


Figure 4. Temperature dependence of insulation resistance. The insulation resistance of many capacitors is not affected at low temperatures. However, under high temperature conditions, the change in insulation resistance may be approximated by an exponential relation. The insulation resistance is also susceptible to variations in humidity.

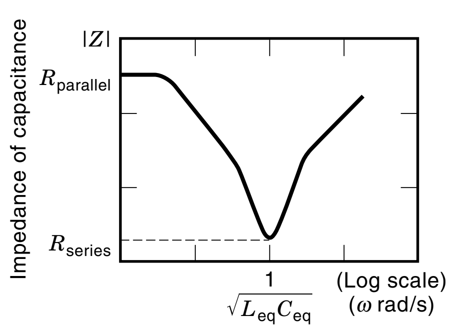


Figure 5. Frequency and impedance relation of capacitors. The losses and inherent inductance affects the ideal operation of capacitors, and the capacitance impedance becomes a function of frequency. Depending on their construction, all capacitors will resonate at a certain frequency.

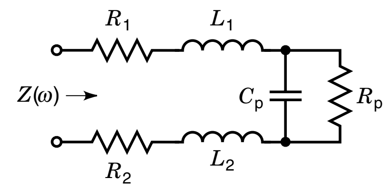


Figure 6. Capacitor equivalent circuit. A practical capacitor has resistances and inductances. Often, the electrical equivalent circuit of a capacitor can be simplified by a pure capacitance C_p and a parallel resistance R_p by neglecting resistances R_1, R_2 and inductances L_1, L_2. In low leakage capacitors where R_p is high, the equivalent circuit may be represented by a series *RC* circuit.

In the sinusoidal condition, $s = j\omega = 2\pi f$, where f = frequency, and hence,

$$Z(j\omega) = 1/\{j\omega C\} \\ = -j/\{\omega C\} \tag{12}$$

and

$$Y(j\omega) = j\omega C \tag{13}$$

The capacitor can then be characterized, under the sinusoidal condition, by a reactance of $X_c = 1/\omega C$, measured in ohms. The current leads the voltage by 90° as shown in the phasor diagram in Fig. 8(b).

In sinusoidal operations, the instantaneous power $p(t) = v(t)\, i(t)$ can be calculated as

$$v(t) = V_{\max}\cos\omega t = \sqrt{2}V\cos\omega t \tag{14}$$

By using the relationship given by Eq. (6), the current can be written as

$$i(t) = C\,\mathrm{d}v/\mathrm{d}t = -\omega C\sqrt{2}V\ \sin\omega t \tag{15}$$

giving

$$p(t) = v(t)i(t) = -2\omega CV^2\ \sin\omega t\cos\omega t = V^2\sin 2\omega t/X_c \tag{16}$$

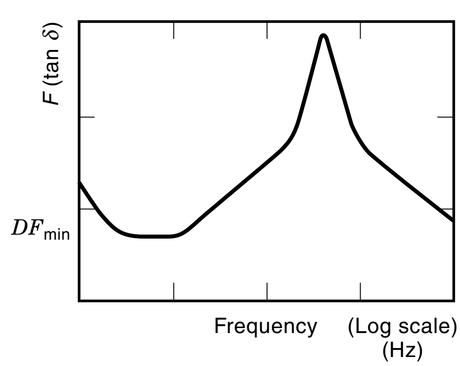


Figure 7. Power dissipation factors. In ideal operation, capacitors should store energy without dissipating power. Nevertheless, due to resistances, some power will be dissipated. The dissipation depends on frequency. The standard measurement of the dissipation factor δ is determined by applying 1.0 Vrms at 1 kHz.

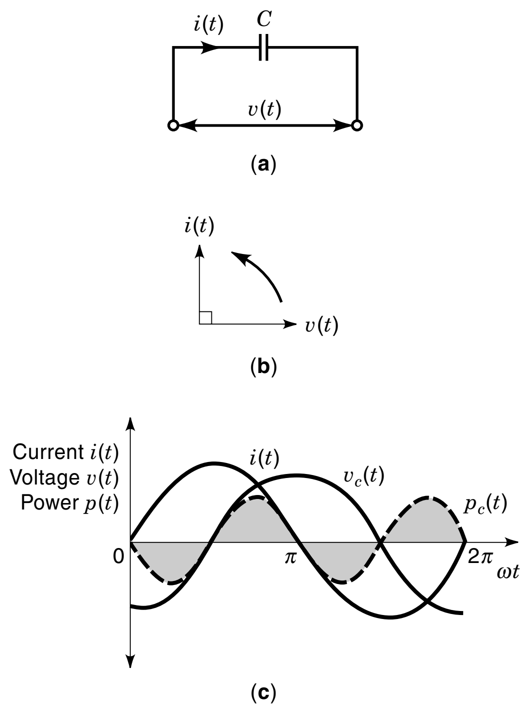


Figure 8. A capacitor as a two-terminal circuit element: (a) connection of a capacitor in electrical circuits, (b) current voltage relationship under sinusoidal operations, and (c) the power, voltage, and current relationships. The power has positive and negative values with twice the frequency of applied voltage.

This indicates that the average power is zero because of the sin $2\omega t$ term, but there is a periodic storage and return of energy, and the amplitude of that power is V^2/X_c. The power, voltage, and current relationship in a capacitor is shown in Fig. 8(c).

Series and Parallel Connection of Capacitors

The formulas for series and parallel connections of capacitors, as shown in Fig. 9(a) and 9(b), respectively, can be obtained from a general consideration of series and parallel connections of impedances. For the series connection, the impedances are added such that

$$1/sC = 1/sC_1 + 1/sC_2 + \ldots + 1/sC_n \tag{17}$$

where C_1, C_2, . . . C_n are the capacitances of the capacitors connected in series as in Figure 9(a). The equivalent capacitance is then given by

$$C = \{1/C_1 + 1/C_2 + \ldots + 1/C_n\}^{-1} \tag{18}$$

That is, in series connection, the final capacitance value will always be smaller than the smallest value of the capacitance in the circuit.

In a similar way, the equivalent capacitance of parallel connected capacitors is

$$C = C_1 + C_2 + \ldots + C_n \tag{19}$$

and the final value of C is always larger than the largest capacitance in the circuit.

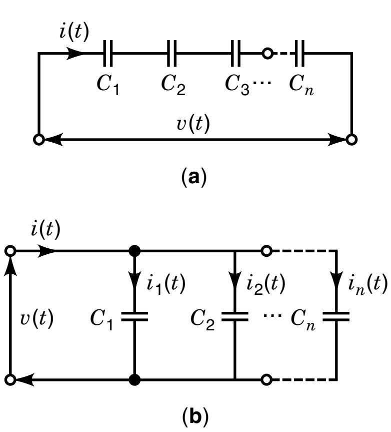


Figure 9. Series and parallel connection of capacitors: (a) series connection, and (b) parallel connection. In series connection, the final capacitance value will always be smaller than the smallest value of the capacitor as the circuit element, whereas in parallel connection, the final value is greater than the largest capacitance.

STANDARD CAPACITORS

Commonly used fixed capacitors are constructed with paper, mica, polymeric, and ceramic dielectric materials. Variable capacitors are generally made of air or ceramic dielectric materials. Capacitors can broadly be classified as electrolytic, ceramic, polymer, mica, variable, and integrated circuit capacitors.

Paper Capacitors

Usually, paper capacitors are made with thin (5 μm to 50 μm thickness) wood pulp. A number of sheets are used together to eliminate possible chemical and fibrous defects that may exist in each sheet. The paper sheets are placed between thin aluminum foils and convolutely wound, as shown in Fig. 10. The moisture of the paper is removed by high temperature vacuum drying before the capacitor is vacuum impregnated with oil, paraffin, or wax. When impregnated with silicon oil, they can withstand voltages up to 300 kV.

Electrolytic Capacitors

This implies any capacitors in which the dielectric layer is formed by an electrolytic method. Electrolytic capacitors in

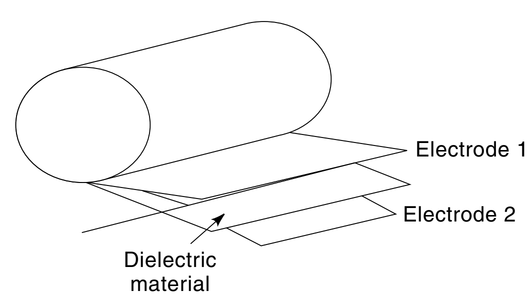


Figure 10. Construction of a typical capacitor. Dielectric sheets are placed between electrode foils and convolutely wound. The moisture of the dielectric material is removed at high temperatures by vacuum drying before the capacitor is impregnated with oil, paraffin, or wax.

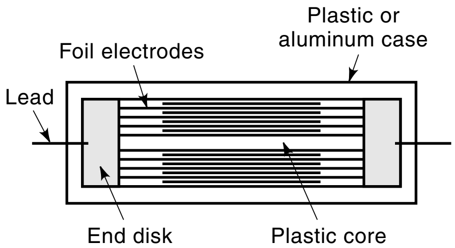


Figure 11. Construction of an electrolytic capacitor. The two foil layer electrodes are separated by an impregnated electrolyte paper spacer and rolled together on a plastic core. Usually, a flexible metallized dielectric film is used as one of the plates and an ordinary foil is used for the other. The capacitor is then hermetically sealed in an aluminum or plastic can.

dry foil form may be similar in construction to paper film capacitors; that is, two foil layers separated by an impregnated electrolyte paper spacer are rolled together. In this case, one of the plates is formed by metallization of one side of a flexible dielectric film. A foil, for example aluminum, is used as the other plate. The capacitor is then hermetically sealed in an aluminum or plastic can, as shown in Fig. 11. These capacitors can be divided into two main subgroups:

Tantalum Electrolytic. The anode consists of sintered tantalum-powder, and the dielectric is Ta_2O_5, which has a high value of ϵ_r. A semiconductor layer MnO_2 surrounds the dielectric. The cathode made from garaphite is deposited around the MnO_2 before the capacitor is sealed. These capacitors are highly stable and reliable with good temperature ranges, and they are suitable in high frequency applications.

Aluminum Electrolytic Capacitors. Aluminum-foil is oxidized on one side as Al_2O_3. The oxide layer is the dielectric, having a thickness of about 0.1 μm and a high electric field strength (7×10^5 Vmm^{-1}). A second layer acting as a cathode made from ecthed Al-foil is inserted. The two layers are separated by a spacer; then, the layers are rolled and mounted.

Electrolytic capacitors must be handled with caution, since in these capacitors, the electrolyte is polarized. That is, the anode should always be positive with respect to the cathode. If not connected correctly, hydrogen gas will form, which damages the dielectric layer causing a high leakage current or blow-up. These capacitors may be manufactured to values up to 10,000 μF.

Ceramic and Glass Capacitors

The dielectric is a ceramic material with deposited metals. They are usually rod or disk shaped. They have good temperature characteristics and are suitable in many high frequency applications. There are many different types, such as

(1) *Low K ceramic:* These capacitors are made with materials that contain a large fraction of titanium dioxide (TiO_2). The relative permittivity of these materials varies from 10 to 500, with negative temperature coefficients. The dielectric is $TiO_2 + MgO + SiO_2$, suitable in high frequency applications in filters, tuned circuits, coupling and bypass circuits, etc.

(2) *High K ceramic:* The dielectric contains a large fraction of barium titanate, $BaTiO_3$, mixed with $PbTiO_3$ or $PbZrO_3$ giving relative permeabilities of 250 to 10,000. They have high losses and also have high voltage time dependence with poor stability.

(3) *Miniature ceramic capacitors:* These are used in critical high-frequency applications. They are made in the ranges of 0.25 pF to 1 nF.

(4) *Dielectric ceramic capacitors:* The material is a semiconducting ceramic with deposited metals on both sides. This arrangement results in two depletion layers which make up the very thin dielectric. In this way, high capacitances can be obtained (22 nF to 100 nF). Due to thin depletion layers, only small dc voltages are allowed. They are used in small and lightweight equipment such as hearing aids.

Glass capacitors are made with dielectric glass materials. The properties of dielectric glass are similar to ceramic materials.

Polymer Capacitors

Various polymers such as polycarbonate, polystyrol, polystyrene, polyethylene, polypropylene, etc. are used as the dielectric. The construction is similar to that of paper capacitors. Polystyrene capacitors, in particular, are very stable and are virtually frequency independent. They have low voltage rating and are used in transistorized applications as tuning capacitors.

Mica Capacitors

A thin layer of mica, usually muscovite mica ($\geq$0.003 mm), is stapled with Cu-foil or coated with a layer of deposited silver. It is then vacuum impregnated and coated with epoxy. The field strength of these capacitors is very high (10^5 Vmm^{-1}), and their resistivity is $\rho = 10^6$ to 10^{15} Ωm. These capacitors are available in values from 1.0 pF to several microfarad for high voltage (from 100 V to 2000 V) and high frequency applications. They have tolerances between $\pm$20 to $\pm$0.5%.

Variable Capacitors

These capacitors usually have air as the dielectric and consist of two assemblies of space plates positioned together by insulation members, such that one set of plates can be rotated, as shown in Fig. 12. Their main use is in adjustment of the reso-

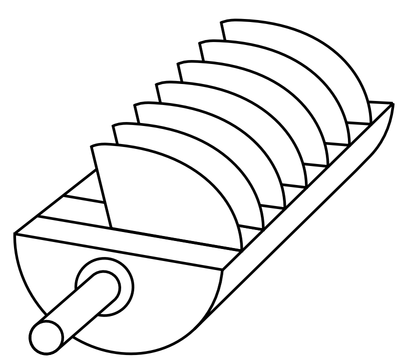


Figure 12. A variable capacitor. It consists of two assemblies of spaced plates positioned together by insulation members such that one set of plates can be rotated. The majority of variable capacitors have air as the dielectric. They are used mainly in adjustment of resonance frequency of tuned circuits in receivers and transmitters. By shaping the plates suitably, they can be made to be linear or logarithmic.

nance frequency of tuned circuits in receivers and transmitters, filters, etc. By shaping the plates, various types of capacitances can be obtained, such as linear capacitance, in which capacitance changes as a linear function of rotation, and logarithmic capacitance.

Variable capacitors may be grouped as precision types, general-purpose types, transmitter types, trimmer types, and special types such as phase shifters.

Precision type variable capacitors are used in bridges, resonant circuits, and many other instrumentation systems. The capacitance swing can be from 100 pF to 5000 pF. They have good long term stability with very tight tolerances.

General-purpose type variable capacitors are used as tuning capacitors in radio and other broadcasting devices. They are available in many laws such as straight line frequency, straight line wavelength, etc. The normal capacitance swing is from 400 pF to 500 pF. In some cases, a swing of 10 to 600 pF is available.

Transmitter type variable capacitors are similar to general-purpose variable capacitors, but they are specially designed for high voltage operations. The swing of these capacitors can go from as few picofarads up to 1000 pF. The most common laws are liner frequency and straight line capacitances. In some cases, oil filling or compressed gases are used to increase operating voltages.

Trimmer capacitors are used for coil trimming at intermediate radio frequencies. They can be air spaced rotary types (2 pF to 100 pF), compression types (1.5 pF to 2000 pF), ceramic-dielectric rotary types (5 pF to 100 pF), and tubular types (up to 3 pF).

INTEGRATED CIRCUIT CAPACITORS

There are many types of capacitors in IC technology. The most commonly used are depletion capacitors and thin-film capacitors. Junction capacitors are the easiest to form in integrated circuits and are primarily used as decoupling and bypass capacitors. The typical value of a junction capacitor is about 300 pF/mm^2. Capacitors of the order of picofarads occupy large areas.

The thin-film capacitors are made mostly within MOS integrated circuits, as monolayer capacitors containing tantalum or other suitable deposits. The plates of integrated circuit capacitors are generally formed by two heavily doped polysilicon layers formed on a thick layer of oxide. The dielectric is usually made from a thin layer of silicon oxide. Important parameters for IC capacitors are the tolerances, voltage coefficients, temperature coefficients, and capacitance values. These capacitors are largely temperature stable with a temperature coefficient of about 20 ppm/°C. The voltage coefficients are usually less than 50 ppm/V. Integrated circuit capacitive sensors are achieved by incorporating a dielectric sensitive to physical variables. Typical values of these capacitors are 1 pF to 27 nF for temperature compensating ceramic, 100 pF to 3000 pF for tantalum oxide, 390 pF to 0.47 μF for general purpose ceramic, and 0.1 μF to 10 μF for tantalum electrolyte. Operating voltages range from 25 V to 200 V for ceramic, 12 V to 35 V for tantalum electrolyte, and 12 V to 25 V for tantalum oxide.

Integrated circuit capacitors are adapted for use in microelectronic circuits. They include some miniature ceramic capacitors, tantalum oxide solid capacitors, and tantalum electrolyte solid capacitors. The ceramic and tantalum oxide chips are not encapsulated and are fitted with end caps for direct surface mounting onto the circuit board. Ceramic chip capacitors are most suitable for RF applications. Many different types of high-Q, multi-layer ceramic chip capacitors are offered by different manufacturers. They are available from 0.5 pF to 1000 pF, with voltage ratings from 100 V to 500V dc, depending on capacitance value.

The thin film integrated circuit computable capacitor may contain many capacitors with typical values of up to 1, 2, 4, 8, and 16 pF capacitance. Binary ratios starting at 0.25 pF are also available. In many designs, a common back metallization layer forms one plate of the capacitor, individual contacts form the other plate, and silicon dioxide dielectric features high Q over a wide temperature range. These capacitors are commonly used in circuits involving active filters, such as the Chebyshev or Butterworth filter (multiple feedback design) for high pass, low pass, or band pass applications.

CAPACITIVE MEASUREMENTS

Capacitive measurement techniques are extensively used in industrial and scientific applications. They are based on changes in capacitances in response to physical property variations. These sensors find many diverse applications from humidity and moisture to displacement measurements.

Capacitive Displacement Measurements

The measurement of distances or displacements is an important aspect of many industrial, scientific, and engineering systems. Capacitive displacement sensors have high linearity and have wide ranges from a few centimeters to a few nanometers.

The basic sensing element of a typical displacement sensor consists of two simple electrodes with capacitance C. The capacitance is a function of the distance d (cm) between the electrodes of a structure, the surface area A (cm^2) of the electrodes, and the permittivity ϵ (=8.85 pF/m for air) of the dielectric between the electrodes; therefore

$$C = f(d, A, \epsilon) \tag{20}$$

There are three basic methods for realizing a capacitive displacement sensor, that is, by varying d, A, or ϵ as discussed below.

Variable Area Displacement Measurements

Alternatively, the displacements may be sensed by varying the surface area of the electrodes of a flat plate capacitor, as illustrated in Fig. 13. In this case, the capacitance is

$$C = \epsilon_r \epsilon_0 (A - wx)/d \tag{21}$$

and the transducer output is linear with displacement x. This type of sensor is normally implemented as a rotating capacitor for measuring angular displacement. The rotating capacitor structures are also used as output transducers for measuring electric voltages as capacitive voltmeters.

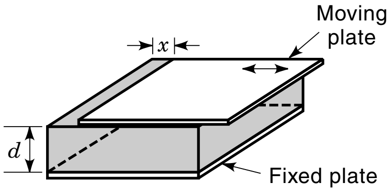


Figure 13. A variable area capacitive displacement sensor. The sensor operates on the variation in the effective area between the plates of a flat plate capacitor. The transducer output is linear with displacement x. This type of sensor is normally implemented as a rotating capacitor for measuring angular displacement.

Variable Distance Displacement Measurements

If a capacitor is made from two flat coplanar plates separated by a variable distance x, ignoring fringe effects, the capacitance can be found by

$$C(x) = \epsilon A/x = \epsilon_r \epsilon_0 A/x \tag{22}$$

where ϵ is the dielectric constant or permittivity, ϵ_r is the relative dielectric constant (in air and vacuum, $\epsilon_r \approx 1$), $\epsilon_0 = 8.854188 \times 10^{-12}$ F/m ($10^{-9}/36\ \pi$ F/m) is the dielectric constant of vacuum, x is the distance of the plates in m, and A is the effective area of the plates in m^2.

The capacitance is a nonlinear function of the distance x, and has the characteristics of a hyperbolic transfer function. The sensitivity of capacitance to changes in plate separation may be found as

$$dC/dx = -\epsilon_r \epsilon_0 A/x^2 \tag{23}$$

Equation (23) indicates that the sensitivity increases as x decreases. Nevertheless, using Eqs. (22) and (23), it can be proved that the percent changes in C are proportional to the percent changes in x which can be expressed as

$$dC/C = -dx/x \tag{24}$$

This type of sensor is often used for measuring small incremental displacements without making contact with the displaced object.

Differential Capacitive Measurements

These sensors are basically three terminal capacitors, as shown in Fig. 14. Slight variations of these sensors find many applications, including differential pressure measurements. In some versions, the central plate moves in response to physical variables with respect to the fixed plates. In others the central plate is fixed, and the outer plates are allowed to move. The output from the center plate is zero at the central position and increases as it moves left or right. The range is equal to twice the separation d. For a displacement d, we have

$$\begin{aligned} 2\delta C = C_1 - C_2 &= \epsilon_r \epsilon_0 lw/(d - \delta d) - \epsilon_r \epsilon_0 lw/(d + \delta d) \\ &= 2\epsilon_r \epsilon_0 lw \delta d/(d^2 + \delta d^2) \end{aligned} \tag{25}$$

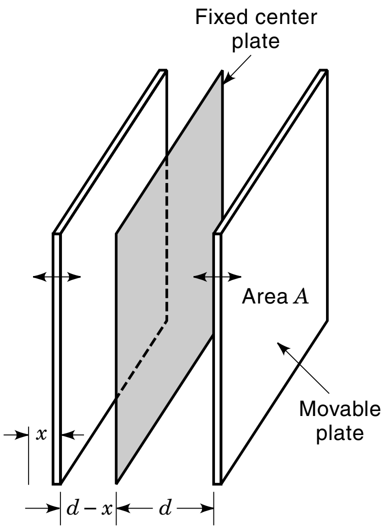


Figure 14. A differential capacitive sensor. This is a three terminal capacitor with one fixed center plate and two outer plates. Its response to physical variables is linear. In some versions, the central plate moves in response to physical variables with respect to two outer plates, and in the others, the central plate is fixed, and the outer plates are allowed to move.

and

$$\begin{aligned} C_1 + C_2 = 2C &= \epsilon_r \epsilon_0 lw/(d - \delta d) + \epsilon_r \epsilon_0 lw/(d + \delta d) \\ &= 2\epsilon_r \epsilon_0 lwd/(d^2 + \delta d^2) \end{aligned} \tag{26}$$

giving

$$\delta C/C = \delta d/d \tag{27}$$

This indicates that the device is inherently linear in contrast to the nonlinear response of the two-plate types. However, some nonlinearity can still be observed in practice due to defects in the structure.

Integrated Circuit Smart Capacitive Position Sensor

Figure 15 shows a typical microstructure capacitive displacement sensor. It has a 1 mm measuring range, 1 micron accuracy, and 0.1 s total measuring time. The specification corresponds to a possible range of 1 pF to 50 pF displacement.

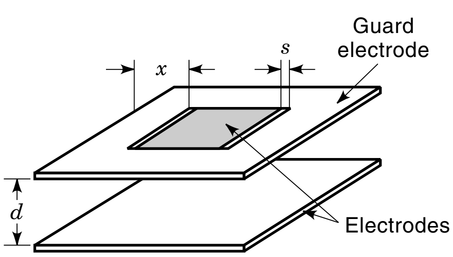


Figure 15. A typical smart capacitive position sensor. These types of microstructure position sensors contain three electrodes, two of which are fixed, and the third electrode moves infinitesimally relative to the others. Although the response is highly nonlinear, the integrated chip contains linearization circuits. They have a 0 to 1 mm measuring range with 1 μm accuracy.

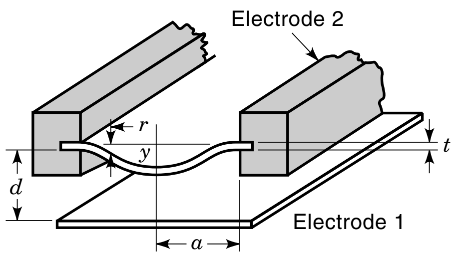


Figure 16. A capacitive pressure sensor. The pressure sensors are made from a fixed metal plate and a flexible diaphragm. The flat flexible diaphragm is clamped around its circumference. The bending of the flexible plate is proportional to applied pressure P. The deformation of the diaphragm results in changes in capacitance.

The relative deviation in the capacitance C_x between the two electrodes caused by the finite guard electrode can be expressed as

$$d < \epsilon^{-P\frac{x}{d}} \tag{28}$$

where x is the width of the guard, while d is the distance between the electrodes. Nonlinearity characteristics are exhibited in this deviation. Therefore, d is required to be less than 100 ppm.

In some special cases, the sensor capacitance C_x can be expressed as

$$C_x = \frac{\epsilon A_x}{d_0 + \Delta d} \tag{29}$$

where A_x is the area of the electrode, d_0 is the initial distance between them, ϵ is the dielectric constant, and Δd is the displacement to be measured.

Capacitive Pressure Sensors

A commonly used two-plate capacitive pressure sensor is made from one fixed metal plate and one flexible circular diaphragm as shown in Fig. 16. The flat circular diaphragm is clamped around its circumference, and is bent into a curve by an applied pressure P. The deflection y of this system at any radius r is given by

$$y = 3(1 - v^2)(a^2 - r^2)P/16Et^3 \tag{30}$$

where

a is the radius of diaphragm
t is the thickness of diaphragm
E is the Young's modulus and
v is the Poisson's ratio

Deformation of the diaphragm means that the average separation of the plates is reduced. Hence, the resulting increase in the capacitance ΔC can be calculated by

$$\Delta C/C = (1 - v^2)a^4P/16Et^3 \tag{31}$$

where d is the initial separation of the plates, and C is the capacitance at zero pressure.

Capacitive Accelerometers and Force Transducers

These accelerometers with capacitive sensing elements typically use the proof mass as one plate of the capacitor and the other plate as the base, as illustrated in Fig. 17. When the sensor is accelerated, the proof mass tends to move, and the voltage across the capacitor changes. This change in the voltage corresponds to the applied acceleration.

In Fig. 17, let $F(x)$ be the positive force in the x direction. Neglecting all losses (due to friction, resistance, etc.), the energy balance of the system can be written for an infinitesimally small displacement dx, electrical energy dE_e, and field energy dE_f of the electrical field between the electrodes as:

$$dE_m + dE_e = dE_f \tag{32}$$

in which

$$dE_m = F(x)\,dx \tag{33}$$

also

$$dE_m = d(QV) = Q\,dV + V\,dQ \tag{34}$$

If the supply voltage V across the capacitor is kept constant, it follows that $dV = 0$. Since $Q = VC(x)$, the Coulomb force is given by

$$F(x) = -V^2\frac{dC(x)}{dx} \tag{35}$$

Thus, if the movable electrode had complete freedom of motion, it would have assumed a position in which he capacitance is maximal, and also if C were a linear function of x, the force $F(x)$ would be independent of x.

Capacitive silicon accelerometers are available in a wide range of specifications and sizes. A typical light weight sensor will have a frequency range of 0 to 1000 Hz with a dynamic range of ± 2 to $\pm 500\,g$.

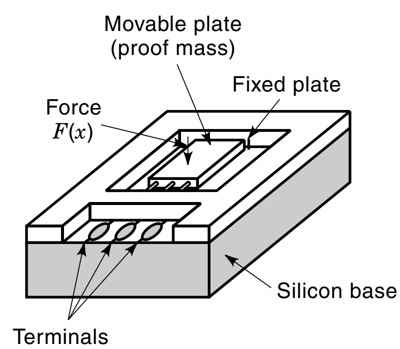


Figure 17. A capacitive force transducer. A typical capacitive micromachined accelerometer has one of the plates as the proof mass. The other plate is fixed, thus forming the base. When the sensor is accelerated, the proof mass tends to move, thus varying the distance between the plates and altering the voltage across the capacitor. This change in the voltage is made to be directly proportional to the applied acceleration.

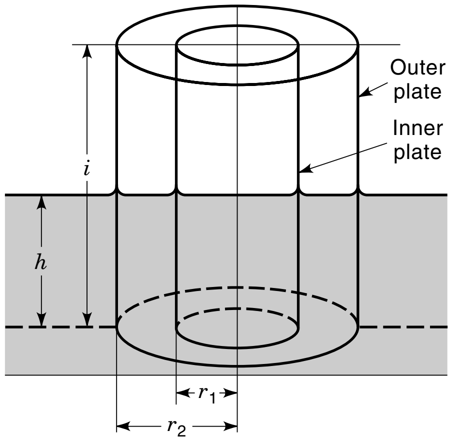


Figure 18. A capacitive liquid level sensor. Two concentric metal cylinders are used as electrodes of a capacitor. The value of the capacitance depends on the permittivity of the liquid and that of the gas or air above it. The total permittivity changes depending on the liquid level. These devices are usually applied in nonconducting liquid applications.

Capacitive Level Measurement

The level of a nonconducting liquid can be determined by capacitive techniques. This method is generally based upon the difference between the dielectric constant of the liquid and that of the gas or air above it. Two concentric metal cylinders are used for capacitance as shown in Fig. 18. The height of the liquid, l, is to be measured relative to the total height, h. Appropriate provision is made to ensure that the space between the cylindrical electrodes is filled by the liquid to the same height as the rest of the container. The usual operational conditions dictate that the spacing between the electrodes, s, should be much less than the radius of the inner electrode, r. Furthermore, the tank height should be much greater than r. When these conditions apply, the capacitance is approximately

$$C = \frac{\epsilon_1(l) + \epsilon_g(h-l)}{4.6\log[1-(s/r)} \qquad (36)$$

where ϵ_1 and ϵ_g are the dielectric constant of the liquid and gas (or air), respectively. The denominator of the above equation contains only terms that relate to the fixed system. A typical application is the measurement of the amount of gasoline in a tank in airplanes. The dielectric constant for most compounds commonly found in gasoline is approximately equal to 2, while that of air is approximately unity. These sensors are often incorporated with an ac deflection bridge.

Capacitive Humidity and Moisture Sensors

The permittivity of atmospheric air as well as of many solid materials is a function of moisture content and temperature. The capacitive humidity device is based on the changes in the permittivity of the dielectric material between the plates of capacitors. There are many types of capacitive humidity sensors. Aluminum types and tantalum types will be introduced here as examples.

Aluminum Type Capacitive Humidity Sensors. The majority of capacitive humidity sensors are aluminum oxide type sensors. In these sensors, high purity aluminum is chemically oxidized to produce a prefilled insulating layer of partially hydrated aluminum oxide which acts as the dielectric. A water permeable but conductive gold film is deposited onto the oxide layer, usually by vacuum-deposition, and forms the second electrode of the capacitor.

Another type of aluminum–aluminum oxide sensor has a pore structure as illustrated in Fig. 19. The oxide with its pore structure forms the active sensing material. Moisture in the air reaching the pores reduces the resistance and increases the capacitance. The decreased resistance can be thought of as being due to an increase in conduction through the oxide. An increase in capacitance can be considered to be due to an increase in the dielectric constant. The quantity measured can be either resistance, capacitance, or impedance. The high humidity end is best measured by capacitance, since resistance changes are very small in this region.

Tantalum Capacitive Humidity Sensors. In some versions of capacitive humidity sensors, one of the capacitor plates consists of a layer of tantalum deposited on a glass substrate. A layer of polymer dielectric is then added, followed by a second plate which is made from a thin layer of chromium. The chromium layer is under high tensile stress, so that it cracks into a fine mosaic structure which allows water molecules to pass into the dielectric. A sensor of this type has an input range of 0 to 100% relative humidity, RH. The capacitance is 375 pF at 0% RH and a linear sensitivity of 1.7 pF/%RH. The error usually is less than 2% due to nonlinearity and 1% due to hysteresis.

Capacitive humidity sensors enjoy wide dynamic ranges, from 0.1 ppm to saturation points. They can function in saturated environments for longer lengths of time, which would adversely affect many other humidity sensors. Their ability to function accurately and reliably extends over a wide range of temperatures and pressures. Capacitive humidity sensors also exhibit low hysteresis and high stability with little maintenance requirements. These features make capacitive humidity sensors viable for many specific operating conditions and ideally suitable for a system where uncertainty of unac-

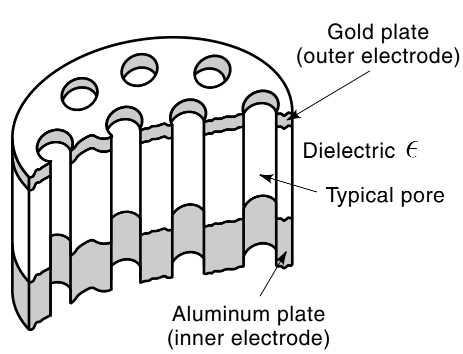


Figure 19. A typical capacitive humidity sensor. The sensors have pore or cracked mosaic structures for the moisture in air or gas to reach the dielectric material. The characteristics of the dielectric material change with the amount of water absorbed, thus reducing the resistance and increasing the capacitance. The quantity measured can be either resistance, capacitance, or impedance.

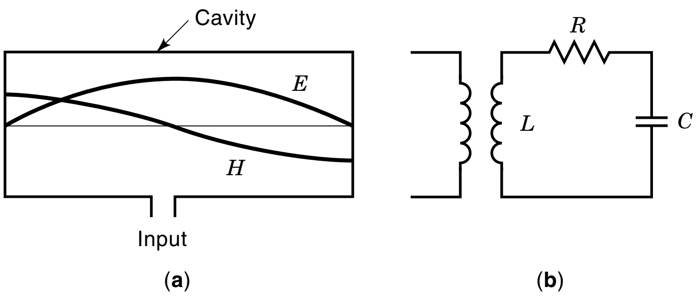


Figure 20. Cavity resonator and equivalent circuit. (a) A cavity resonator is a container confining electromagnetic energy in space. The resonant frequency is set by the particular field configuration and by the cavity dimensions. A resonance is obtained when the cavity length l is equal to the multiple of the half of the wavelength. (b) The energy is stored in electric and magnetic energy forms inside the cavity, largely determined by eqivalent capacitance, inductance, and resistance. In its simplest form, the equivalent circuit can be viewed as the inductive coupling supplyng the capacitor C.

counted conditions exists during the operations. However, in some applications, contaminants can block the flow of water vapor into the sensor material, thus affecting the accuracy of the instrument. Many sensors come with some form of casing to provide protection.

Capacitive Moisture Sensors

Measurements in capacitive moisture sensors are based on the changes in the permittivity of granular or powder type dielectric materials such as wheat and other grains containing water. Usually, the sensor consists of a large cylindrical chamber, for example 150 mm deep and 100 mm in diameter. The chamber is filled with samples under test. The variation in capacitance values with respect to water content is processed. The capacitor is incorporated as a part of an oscillatory circuit operating at a suitable frequency.

Capacitive moisture sensors need to be calibrated for samples made from different materials, as the materials, themselves, demonstrate different permittivity. Accurate temperature is necessary as the dielectric constant may be highly dependent on temperature. Most of these devices are built to operate at temperature ranges of 0°C to 50°C, supported by tight temperature compensation circuits.

CAVITY RESONATORS

Cavity resonators are enclosures that confine electromagnetic energy in space. Cavity resonators find extensive use in microwave and laser optic applications, since they can be configured with reasonable dimensions. The energy is stored in the form of electric and magnetic energy inside the cavity, largely determined by equivalent capacitance, inductance, and resistance, very similarly to circuits made from coil and capacitance combinations. The coupling of the cavity resonator is equivalent to the inductive coupling as shown in Fig. 20(b).

Cavity resonators come in many shapes, from rectangular to circular or semicircular. The most commonly used cavity resonators are rectangular types as shown in Fig. 20(a). The cavity shapes can be related to associated waveguide modes. With each mode, a resonant frequency may be determined by the particular field configuration involved and by the cavity dimensions. A given resonator has an infinite number of resonant modes which correspond to definite resonant frequencies. At resonant frequencies, the maximum amplitude of the standing wave occurs. The mode of the minimum resonant frequency is called the dominant mode and the higher resonant frequencies are called higher order modes. The modes in cavities are classified as transverse electric and transverse magnetic. In the case of rectangular prisms, if the wave is travelling in the l direction, resonance will be obtained whenever the multiple of half a wavelength is equal to the cavity length l.

The resonant frequency of a cavity resonator can be derived from Maxwell's equations for the electrical and magnetic fields within the resonator. In practical applications, the resonator is obtained first by constructing a resonator of convenient size and measuring the resulting resonant frequency for the construction. The ratio of the desired wavelength to the practical wavelength gives a scale factor that can be applied to every dimension of the test model. The resonant frequencies of a cavity resonator can be changed in a number of ways, such as (1) altering the mechanical dimensions, (2) changing the coupling reactance into the resonator, and (3) using copper paddles.

The Q factor of a cavity resonator is significant, as in the case of any other resonant circuits. The Q factor of a cavity resonator can be defined by

$$Q = 2\pi \frac{\text{Energy stored}}{\text{Energy loss per cycle}} \tag{37}$$

The energy stored is proportional to the square of the magnetic flux density integrated throughout the volume of the resonator. The energy loss is proportional to the skin depth and to the square of the magnetic flux density integrated over the surface of the cavity. As a result, the Q factor depends on the ratio of volume to surface area of the resonator.

CAPACITANCE MEASUREMENTS

Null Bridge Instruments and Resonance Methods

Bridges are used to make precise measurements of unknown capacitances and associated losses in terms of some known external capacitances and resistances. Most commonly used bridges are series-resistance-capacitance bridges, parallel-resistance capacitance bridges, Wien bridges, and Schering bridges.

The Series *RC* Bridge. Figure 21 is a Series-Resistance Capacitance Bridge which is used for the comparison of a known capacitance with an unknown capacitance. The unknown capacitance is represented by C_x and R_x. A standard adjustable resistance R_1 is connected in series with a standard capacitor C_1. The voltage drop across R_1 balances the resistive voltage drop when the bridge is balanced. The additional resistor in series with C_x increases the total resistive component, so that small values of R_1 will not be required to achieve balance. Generally, the bridge balance is most easily achieved when capacitive branches have substantial resistive components. To obtain balance, R_1 and either R_3 or R_4 are alternately ad-

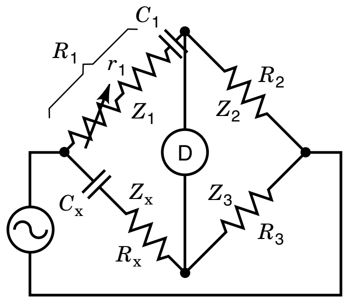


Figure 21. A series *RC* bridge. In these bridges, the unknown capacitance is compared with a known capacitance. The voltage drop across R_1 balances the resistive voltage drop in branch Z_2 when the bridge is balanced. The bridge balance is most easily achieved when capacitive branches have substantial resistive components. The resistors R_1 and either R_3 or R_4 are adjusted alternately to obtain the balance. This type of bridge is found to be most suitable for capacitors with a high-resistance dielectric, hence very low leakage currents.

justed. This type of bridge is found to be most suitable for capacitors with a high-resistance dielectric, hence very low leakage currents. At balance,

$$Z_1/Z_3 = Z_2/Z_4 \tag{38}$$

Substituting impedance values gives

$$\frac{(R_1 = j/\omega C_1)}{R_3} = \frac{R_x - j/\omega C_x}{R_4} \tag{39}$$

Solving for the real terms gives

$$R_x = R_1 R_4 / R_3 \tag{40}$$

and solving for the imaginary terms gives

$$C_x = C_1 R_3 / R_4 \tag{41}$$

An improved version of the series *RC* bridge is the substitution-bridge, which is particularly useful to determine the values of capacitances at radio frequencies. In this case, a series connected *RC* bridge is balanced by disconnecting the unknown capacitance and resistance C_x and R_x and replacing it by an adjustable standard capacitor C_s and adjustable resistor R_s. After having obtained the balance position, the unknown capacitance and resistance C_x and R_x are connected in parallel to the capacitor C_s. The capacitor C_s and resistor R_s are adjusted again for the rebalance of the bridge. The changes in the ΔC_s and ΔR_s lead to unknown values as

$$C_x = \Delta C_s \quad \text{and} \quad R_x = \Delta R_s (C_{s1}/C_x)^2 \tag{42}$$

where C_{s1} is the value of C_s in the initial balance.

Parallel-Resistance-Capacitance Bridge. Figure 22 illustrates a parallel-resistance capacitance bridge. In this case, the unknown capacitance is represented by its parallel equivalent circuit, C_x in parallel with R_x. The Z_3 and Z_4 impedances are pure resistors where either or both may be adjustable. The Z_2 impedance is balanced by a standard capacitor C_1 in parallel with an adjustable resistor R_1. The bridge balance is achieved by adjustment of R_1 and either R_3 or R_4. The parallel-resistance capacitance bridge is found to be most suitable for capacitors with a low resistance dielectric, hence relatively high leakage currents. At balance,

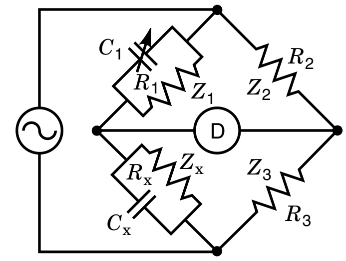


Figure 22. A parallel-resistance-capacitance bridge. The unknown capacitance is represented by its parallel equivalent circuit: C_x in parallel with R_x. The bridge balance is achieved by adjustment of R_1 and either R_3 or R_4. The parallel-resistance capacitance bridge is found to be most suitable for capacitors with a low resistance dielectric, hence relatively high leakage currents.

$$\frac{1/\{1/R_1 + j\omega C_1\}}{R_3} = \frac{1/\{1/R_x + j\omega C_x\}}{R_4} \tag{43}$$

Solving for real terms gives

$$R_x = R_1 R_4 / R_3 \tag{44}$$

and solving for the imaginary terms gives

$$C_x = C_1 R_3 / R_4 \tag{45}$$

The Wien Bridge. Figure 23 shows a Wien bridge. This is a special resistance-ratio bridge which permits two capacitances to be compared once all the resistances of the bridge are known. At balance, it can be proven that the unknown resistance and the capacitance are

$$R_x = R_3(1 + \omega^2 R_1^2 C_1^2)/(\omega^2 R_1 R_2 C_1^2) \tag{46}$$

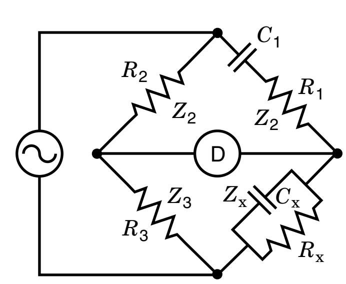


Figure 23. The Wien bridge. This bridge is used to compare two capacitors directly. It finds applications, particularly in determining the frequency in *RC* oscillators. In some cases, capacitors C_1 and C_x are made equal and ganged together, so that the frequency at which the null occurs varies linearly with capacitances.

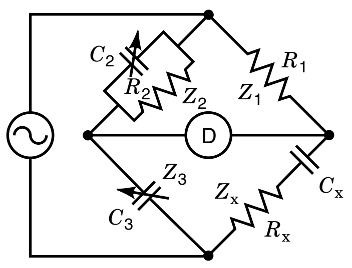


Figure 24. The Schering bridge. This bridge is particularly useful for measuring the capacitance, associated dissipation factors, and the loss angles. The unknown capacitance is directly proportional to the known capacitance C_1. The Schering bridge is frequently used as a high-voltage bridge with a high-voltage capacitor as C_1.

and

$$C_x = C_1 R_2/[R_3(1+\omega^2 R_1^2 C_1^2)] \tag{47}$$

It can also be shown that

$$\omega^2 = 1/R_1 C_1 R_x C_x \tag{48}$$

As indicated in Eq. (48), the Wien bridge has an important application in determining the frequency of RC oscillators. In frequency meters, C_1 and C_x are made equal, and the two capacitors are joined together so that the frequency at which the null occurs varies linearly with capacitances.

The Schering Bridge. Figure 24 illustrates the configuration of a Schering bridge. This bridge is used for measuring the capacitance, the dissipation factors, and the loss angles. The unknown capacitance is directly proportional to the known capacitance C_1. That is, the bridge equations are

$$C_x = C_1 R_2/R_3 \quad \text{and} \quad R_x = C_2 R_3/C_1 \tag{49}$$

A Schering bridge is frequently used as a high-voltage bridge with a high-voltage capacitor as C_1. It is also used as a high frequency bridge, since variable capacitors may be used for both adjustments.

Resonance Methods

Capacitors can be connected in parallel or series with inductors to form LC networks. In a series LC network, as the frequency, ω, increases the impedance of the circuit decreases. The decrease in the impedance reaches a point where the reactance becomes zero. That is

$$\omega_0 L - 1/\omega_0 C = 0 \qquad \text{or} \qquad \omega_0 = 1/\sqrt{LC} \tag{50}$$

The frequency ω_0 is called the resonant frequency of the circuit. The value of ω_0 is specified entirely in terms of the parameters of the energy storing elements of the circuit. In many instances, the unknown value of a capacitance is determined once the resonance frequency and the inductance are known.

ACCURACY AND SIGNAL PROCESSING

Generally, capacitive type measurements require relatively more complex circuitry in comparison to many other type of sensors, but they have the advantage of mechancal simplicity. They are also sensitive with minimum mechanical loading effects. For signal processing, these sensors are usually incorporated either in ac deflection bridge circuits or oscillator circuits. In practice, capacitive sensors are not pure capacitances but have associated resistances representing losses in the dielectric. This has an important influence in the design of circuits, particularly in oscillator circuits. Here, the most commonly used circuit based on charge amplifier is discussed.

Operational Amplifiers and Charge Amplifiers

One method of eliminating the nonlinearity in the relationship between the physical variable, for example two plate displacement sensors, and capacitance C is by the use of operational amplifiers, as illustrated in Fig. 25. In this circuit, if the input impedance of the operational amplifier is high, the output is not saturated, and the input voltage is small, it is possible to write

$$1/C_f = \int i_f \, dt = e_{ex} - e_{ai} = e_{ex} \tag{51}$$

$$1/C_x = \int i_x \, dt = e_0 - e_{ai} = e_0 \tag{52}$$

$$i_f + i_x - i_{ai} = 0 = i_f + i_x \tag{53}$$

Manipulation of these equations gives

$$e_0 = -C_f e_{ex}/C_x \tag{54}$$

Substituting the value of C_x

$$e_0 = -C_f x e_{ex}/\epsilon A \tag{55}$$

Equation (55) shows that the output voltage is directly proportional to the plate separation x, thus giving linearity for all variations in motion.

However, a practical circuit requires a resistance across C_f to limit output drift. The value of this resistance must be greater than the impedance of C_f at the lowest frequency of interest.

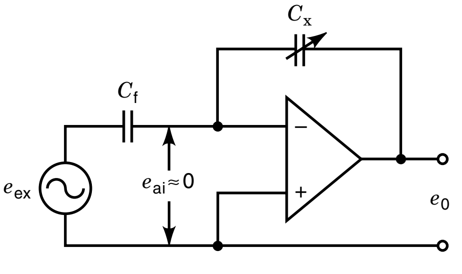


Figure 25. An operational amplifier signal processor. This method is useful to eliminate the nonlinearity in the signals generated by capacitive sensors. By this type of arrangement, the output voltage can be made to be directly proportional to variations in the signal representing the nonlinear operation of the device.

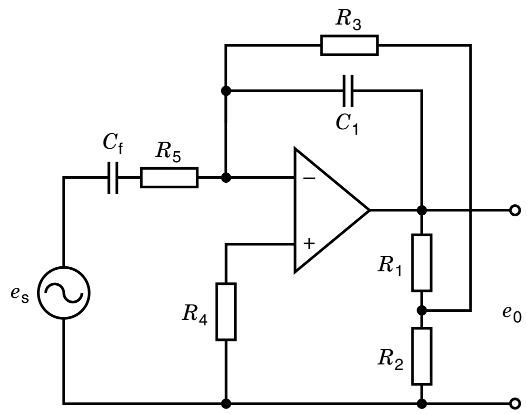


Figure 26. A practical charge amplifier. The effective feedback resistance is a function of other resistances. It is possible to reduce the output drift substantially by selecting the resistors suitably. The accuracy of this circuit can be improved further by cascading two or more amplifiers substantially, improving the signal-to-noise ratio.

A practical charge amplifier circuit is presented in Fig. 26. In this case, the effective feedback resistance R_{fef} is given by

$$R_{fef} = R_3(R_1 + R_2)/R_2 \tag{56}$$

It is possible to reduce the output drift substantially by suitably selecting the resistors. The accuracy of this circuit can be improved further by cascading two or more amplifiers. In this way, a substantial improvement in the signal-to-noise ratio can also be achieved.

In many applications, the resultant change in capacitance of capacitive transducers is measured with a suitable ac bridge, such as a Wien bridge or a Schering bridge. However, in a majority of cases, improvised versions of bridges are used as oscillator circuits for capacitive signal processing. The transducer is configured as part of the oscillatory circuit that causes changes in the frequency of the oscillations. This change in frequency is scaled to be a measure of the magnitude of the physical variable.

SELECTION, RELIABILITY, ACCURACY, AND STANDARDS OF CAPACITORS

Selection of Capacitors

The capacitors used in electronic circuits can be classified as low-loss, medium-loss, and high-tolerance capacitors. The low-loss capacitors have good capacitance stability, such as mica, glass, low-loss ceramic, and low-loss plastic film capacitors. These capacitors are expensive and used for precision applications, for example, telecommunication filters. Medium-loss capacitors are paper, plastic film, and medium-loss ceramic capacitors. Their applications include coupling, decoupling, bypass, energy storage, and some power electronic applications, for example, motor starting, lighting, power line applications, and interference suppressions. High tolerance capacitors, such as aluminum and tantalum electrolytic capacitors, deliver high capacitances. Although their sizes are relatively greater, they are reliable and have longer service life. They are used in polarized voltage applications, radio, television, other consumer goods as well as military equipment and harsh industrial environmental usage.

The values of general-purpose capacitors tend to be grouped closely together in a bimodal distribution manner within their tolerances. Usually, the tolerances of standard capacitors are 5, 10 and 20% of their rated values. Nevertheless, tolerances of precision capacitors are much tighter in the range of 0.25, 0.5, 0.625, 1, 2, and 3% of their rated values. These capacitors are much more expensive than those in the standard range.

For capacitors in the small pF range, the tolerances can be given as ±1.5, ±1, ±0.5, ±0.25, and ±0.1 pF. Usually, low tolerance ranges do not include additional values; the capacitors' values simply have tighter distribution.

Capacitors and capacitive sensors are offered by many manufacturers, and some examples are listed in Table 3.

Reliability and Accuracy of Capacitors

Experience shows that a substantial part of component failures in electronic equipment is due to capacitors. The major cause of this is the improper selection and inappropriate application of capacitors. The following factors are, therefore, important criteria in the selection of capacitors in circuit applications: (1) The capacitance values and tolerances are determined by operating frequencies or by the value required for timing, energy storage, phase shifting, coupling, or decoupling. (2) The type and nature of the sources, such as ac, dc, transient, surges, and ripples determine the applied voltages. (3) The stability is determined by operating conditions like temperature, humidity, shock, vibration, and life expectancy. (4) Life expectancy, leakage current, dissipation factor, impedance, and self-resonant frequency determine electrical properties. (5) Types and construction, for example, size, configuration, and packaging determine mechanical properties.

Some of the common causes of capacitor failure are due to voltage and current overloads. The voltage overload produces an excessive electric field in the dielectric that results in its breakdown and destruction. The current overload caused by rapid voltage variations results in current transients. If these currents are of sufficient amplitude and duration, the dielectric can be deformed or damaged, resulting in drastic changes in capacitance values, thus leading to equipment malfunction. Overheating and high temperatures accelerate dielectric aging. This causes the plastic film to be brittle and also introduces cracks in the hermetic seals. Moisture and humidity due to a severe operating environment causes corrosion, reduces the dielectric strength, and lowers insulation resistances.

Standards and Computable Capacitors

Standards of Capacitors. Standard capacitors are constructed from interleaved metal plates using air as the dielectric material. The area of the plates and distance between them are determined and constructed with precision. The National Bureau of Standards maintains a bank of primary standard air capacitors that can be used to calibrate secondary and working standards for laboratories and industry. Generally, smaller capacitance working standards are obtained from air capacitors, whereas larger working standards are made from solid dielectric materials. Usually, silver–mica capacitors are selected as working standards. These capacitors are very stable, have very low dissipation factors, small temperature coefficients, and very little aging effect. They are available in decade mounting forms.

Computable Capacitors. Another form of standard capacitors is the Thompson-Lampard calculable cross-capacitor. Thompson has shown that in cylindrical capacitors, the capacitance per unit length may be computed with good accuracy. The cylindrical cross-capacitor of Lampard and Thompson and the modified versions find wide use in many standards laboratories. There are many other types of standard calculable capacitors. For example, recently, new types of capacitors have been added to the classical-Kelvin parallel plates and coaxial cylindrical–calculable standards. Also, cubical capacitors, for which the direct capacitance between opposite faces can be estimated with high accuracy, are used as an independent check of the farad as established by means of a cross-capacitor.

The calculable capacitor is capable of determining the value of a 0.5 pF capacitor to within 2.2 parts in 10^8. There are several computer-based models available that can be used to investigate the effect of changing the lengths and diameters of capacitors and their frequency dependence.

Table 3. List of Manufacturers

ANALITE Inc. 24-T Newtown Plaza Plainview, NY 11803 Tel: 1-800-229 3357	Magnetek 902 Crescent Avenue Bridgeport, CT 06607 Tel: 1-800-541 9997 Fax: 203-335 2820
Chenelex Barr Road, P.O. Box 82 Norwich, NY 13815 Tel: 607-344 3777 Fax: 607-334 9076	Maxwell Laboratories Inc. 8888 Balboa Avenue San Diego, CA, 92123 Tel: 619-576 7545 Fax: 619-576 7545
Comet North America Inc. 11 Belden Avenue Norwalk, CT 06850 Tel: 203-852 1231 Fax: 203-838 3827	Metuchen Capacitors Inc. 139 White Oak Lane Old Bridge, NJ 08857 Tel: 908-697 3366 or 1-800-679 0514 Fax: 1-800-679 9959
CSI Capacitors 810 Rancheros Drive San Marcos, CA 92069-3009 Tel: 619-747 4000 Fax: 619-743 5094	Murata Electronics Marketing Communications 2200 Lake Park Drive Smyrna, Georgia 30080 Tel: 1-800-394 5592 Fax: 1-800-4FAXCAT
FSI/FORK Standards Inc. 668 Western Avenue Lombard, IL 60148-2097 Tel: 708-932 9380	NWL Capacitors 204 Caroline Drive, PO Box 97 Snow Hill, NC 28580 Tel: 919-747 5943 Fax: 919-747 8979
Gordon Engineering Corp. 67 Del Mar Drive, Brookfield, CT 06804 Tel: 203-775 4501	Okaya Electric America Inc. 503 Wall Street, Valparaiso, Indiana 46383 Tel: 219-477 4488 Fax: 219-477 4856
Hecon Corp. 15-T Meridian Rd, Eatontown, NJ 07724 Tel: 1-800-524 1669	
Kistler Instrumentation Corp. Amherst, NY 14228-2171 Tel: 716-691 5100 Fax: 716-691 5226	Rechner Electronic Industries Inc. 8651 Buffalo Avenue, Box 7 Niagara Falls, NY 14304 Tel: 1-800-544 4106
Locon Sensor Systems, Inc. 1750 S. Eber Road, PO Box 789 Holland, Ohio 43526 Tel: 419-865 7651 Fax: 419-865 7756	RDP Electrosense, Inc. 2216-Dept. B Pottstown, PA Tel: 1-800-334 5838

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CAPACITANCE MEASUREMENT. See BRIDGE CIRCUITS; PHOTONIC CRYSTALS.