4. PIEZOELECTRIC MATERIALS AND PIEZOELECTRIC DISPLACEMENT SENSOR

4.1 Piezoelectric materials

Piezoelectricity is the property of some crystalline solids to generate electrical charges on their surfaces following a mechanical stress that induces a deformation. Specifically, charges of opposite polarity on opposite sides of the crystal are generated and can be determined by measuring the voltage between electrodes attached to the surfaces. This form of energy conversion, from mechanical forces to electric potential, is called the **direct piezoelectric effect** (Figure 4.1). This effect is reversible: when the piezoelectric material is subjected to an external electric field (e.g., by applying a voltage between two electrodes deposited on opposite surfaces) so that it becomes polarized, the response is a mechanical deformation of the material. This form of energy conversion, from electric potential to mechanical deformation is called the **inverse piezoelectric effect** (Figure 4.1).

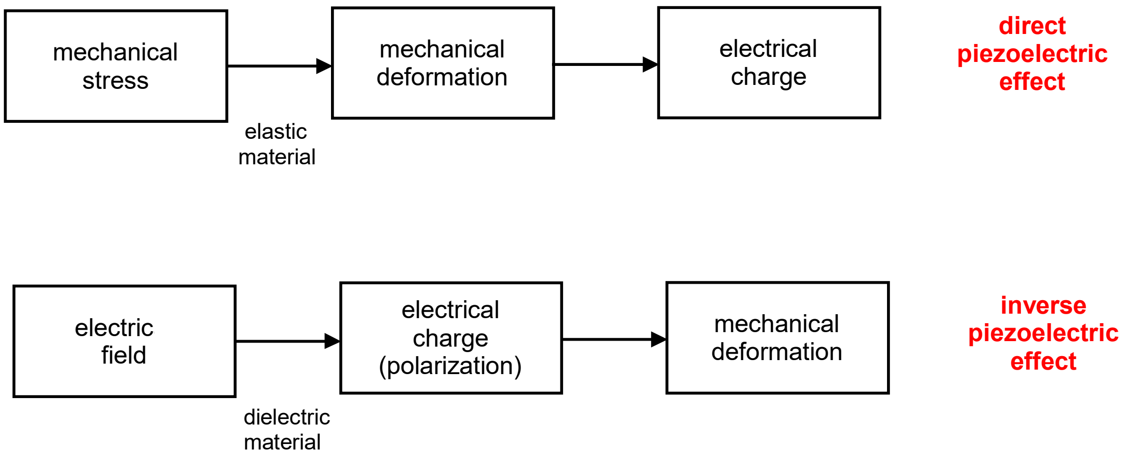

Figure 4.1 Schematic of the direct and inverse piezoelectric effect.

This electromechanical energy-conversion principle is applied usefully in both directions. The mechanical-input/electrical-output direction is the basis of many instruments for measuring acceleration, force and pressure. The electrical-input/mechanical-output direction is applied in ultrasound systems, to generate mechanical waves (sound waves).

The piezoelectric property derives from an asymmetric charge distribution in the unit cell of the crystal lattice. Unlike amorphous solids, characterized by spatial disorder of the particles (atoms or molecules), the crystalline solid is characterized by periodic and repetitive spatial order of the particles, forming the crystal lattice. The crystal lattice consists of the repetition of a structural unit (unit cell or elementary cell) having a simple geometric shape. The unit cell of a *non-piezoelectric* material is characterized by symmetrical charge distribution as exemplary shown in Figure 4.2a. In this case, the unit cell contains four atoms, two positively charged and two negatively charged, arranged in a diamond pattern. The average location of the negative charges matches the average location of the positive charges. When the crystal is mechanically deformed (and so also the unit cell) the average locations of the charges do not change. This material shows no electrical response to a mechanical force and thus is not piezoelectric. Conversely, the unit cell of a *piezoelectric material* is characterized by an asymmetric atomic charge distribution, as exemplary shown in Figure 4.2b. In unperturbed condition, the average location of the negative charges matches the average location of the positive charges. However, when the cell is deformed the average locations of the charges become different, and each unit cell behaves as a small electrical dipole. When an entire plate of piezoelectric material, which is a regularly order collection of these unit cells, is deformed, charges of opposite polarity arise at the surfaces (charges of opposite polarity internal to material cancel out, and only surface charges remain), and an electrical field is generated between the surfaces (see Figure 4.3). Similarly, when an electrical field is applied externally to the material, a charge separation occurs at the level of the single unit cell (i.e., each cell becomes a dipole) and this is accompanied by a structural deformation of the cell. Because of the ordered spatial disposition of the unit cells in the crystalline lattice, the entire material deforms.

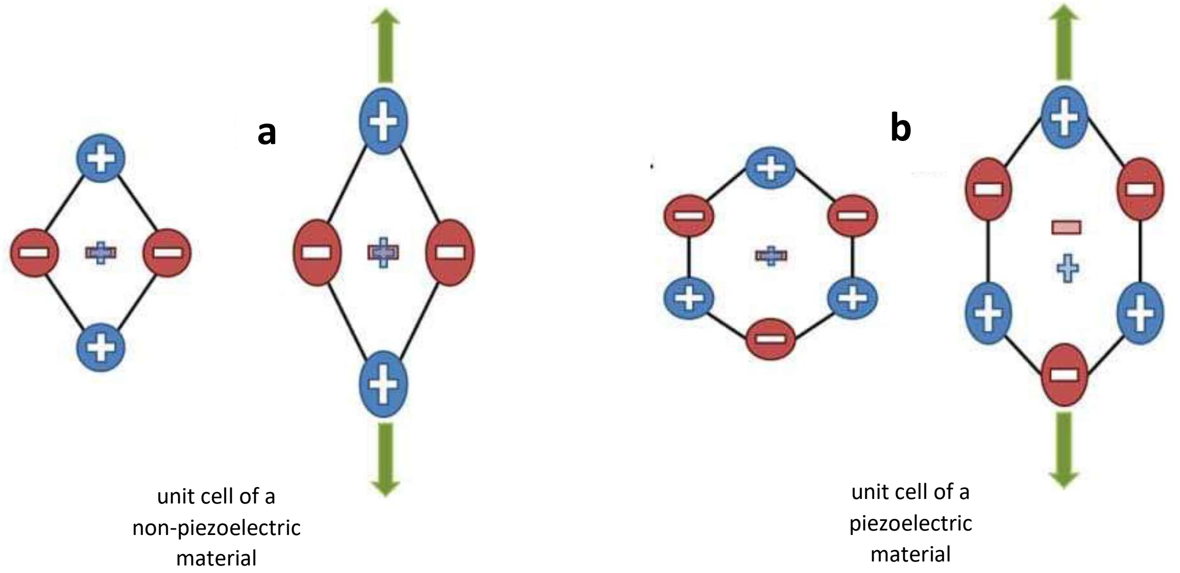

Figure 4.2 *Panel a*: Unit cell characterized by symmetrical charge distribution. When the cell is deformed, the average locations of the positive and negative charges remain the same and no electric dipole is formed. *Panel b*: Unit cell characterized by an asymmetrical charge distribution. When the cell is deformed, the average locations of the positive and negative charges are separated and the unit cell behaves as a small electrical dipole. The symmetry/asymmetry can be demonstrated by drawing an arrow to any of the atoms with starting point in the center of the unit cell, and then drawing the same arrow in the opposite direction. If they point to the same/different type of atom, the unit cell is symmetrical/asymmetrical.

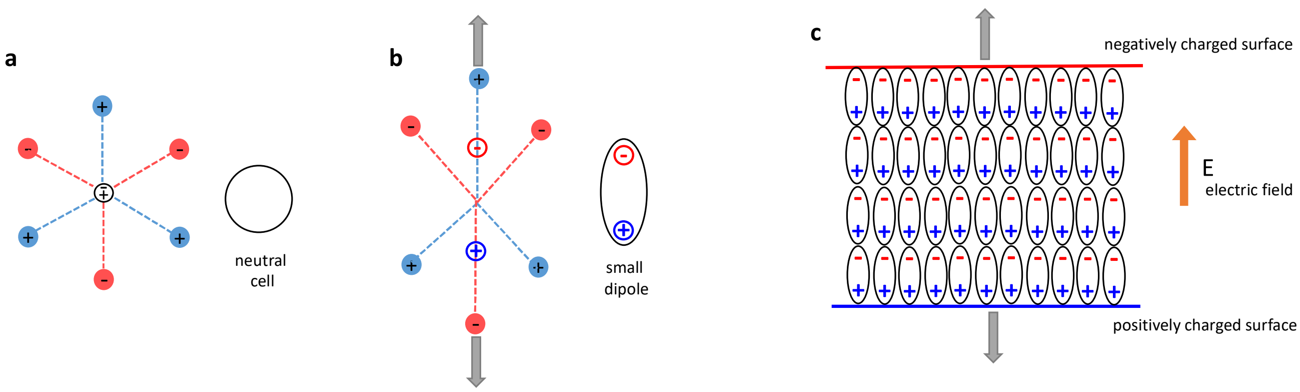

Figure 4.3 *Panel a*: Unperturbed unit cell of a piezoelectric material. *Panel b*: The deformed unit cell due to a force application: the unit cell behaves as a small dipole (the average locations of the positive and negative charges are separated). *Panel c*: When the force is applied to the entire material, each unit cell behaves as a dipole and charges with opposite polarity are generated at opposite surfaces, inducing an electric field.

The materials that exhibit a significant and useful piezoelectric effect fall into three main groups: natural crystals (e.g. quartz, Rochelle salt), synthetic crystals (e.g. lithium sulfate, ammonium dihydrogen phosphate), and polarized ferroelectric ceramics (e.g. barium titanate, lead zirconate titanate). The latter are characterized by strong piezoelectric effect.

There are various modes of operations of piezoelectric materials depending on the specific material and on how the slab is cut relative to the geometrical structure of the crystal lattice. That is, the piezoelectric effect can be made to respond to (or cause) mechanical deformation in different modes, including thickness expansion, transverse expansion, thickness shear and face shear (see Figure 4.4). Metal electrodes are plated onto selected faces of the piezoelectric material so that lead wires can be attached for bringing in or leading out electric charge. The piezoelectric effect is direction-sensitive in that stress in one direction (e.g. inducing expansion) produces a given charge polarity (and so a given voltage polarity across the surfaces), while stress in the other direction (e.g. inducing compression) produces the opposite polarity. The inverse piezoelectric effect (conversion from electric to mechanical energy) is direction-sensitive, too.

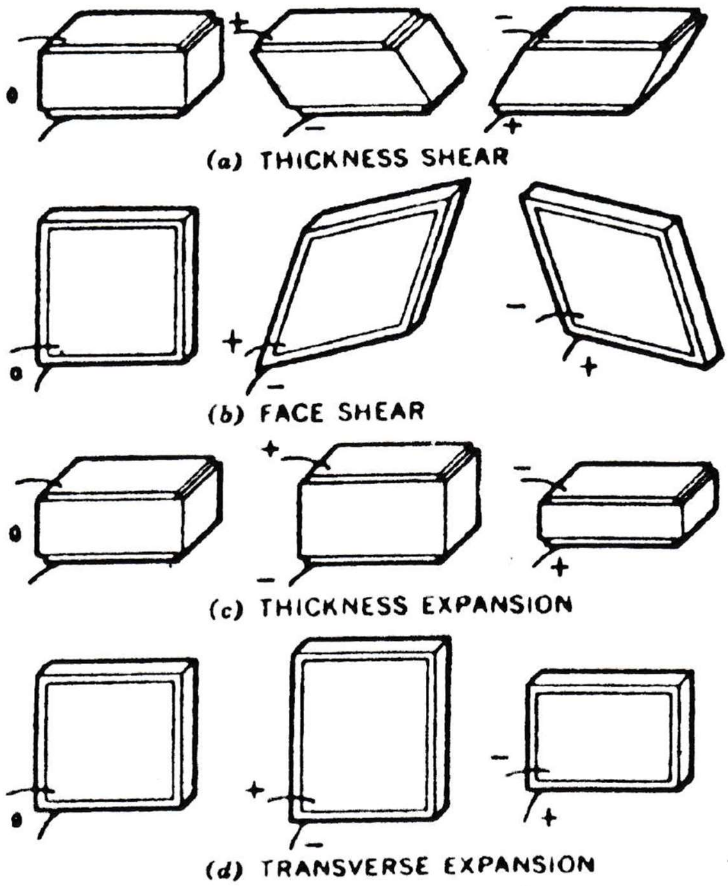

Figure 4.4 Basic operation modes of piezoelectric slabs. It is interesting to observe that the piezoelectric effect is direction-sensitive.

When considering the conversion from mechanical to electric energy, a fundamental point to be considered is the following one. The piezoelectric materials are dielectric materials (insulator); hence, the electrodes deposited onto opposite surfaces of the piezoelectric also behave as the plates of a capacitor. Thus, a piezoelectric element used for converting mechanical input into electrical signals may be thought of as a charge generator and a capacitor. Mechanical deformation generates a charge Q; then, this charge results in a certain voltage appearing between the electrodes according to the usual law for capacitors $V = \frac{Q}{C_s}$, where C_s is the capacitance of the piezoelectric element.

In the following, we will consider only one common mode of deformation: thickness expansion/compression.

4.2 Piezoelectric displacement sensor

Now, we will consider a piezoelectric element as displacement sensor. The ultimate aim is generally to measure the force, pressure, or acceleration, but here we consider only the conversion from displacement to voltage (here for displacement we mean the displacement of one face of the piezoelectric as a consequence of the applied force, pressure or acceleration).

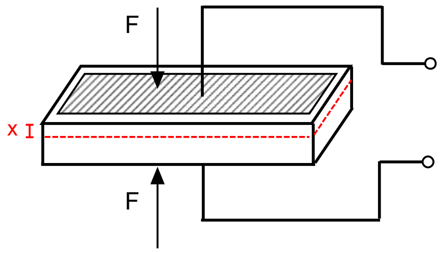

Figure 4.5 A piezoelectric slab subjected to a force inducing a face displacement x. The dashed area on the superior face indicates the metal electrode (the metal electrode is present also on the inferior face but not visible).

Consider the piezoelectric slab in Figure 4.5, subjected to a force that causes a face displacement x. Based on the above description (section 4.1, direct piezoelectric effect), the displacement, i.e. thickness deformation, induces a charge; the latter can be expressed as

$$Q = K_q x \tag{4.1}$$

where K_q (in C/cm, where C indicates coulomb) is a constant characteristic of the piezoelectric sensor, linking the generated charge to the applied displacement x. Since the piezoelectric together with the metal electrodes, behaves as a capacitor, the charge Q is converted into a voltage across the two faces:

$$V = \frac{Q}{C_s} = \frac{K_q}{C_s} x \tag{4.2}$$

C_s in (4.2) is the capacitance of the piezoelectric element.

Hence, the electrical behavior of the piezoelectric sensor can be represented by the electrical equivalent circuit in Figure 4.6a, consisting of a charge generator in parallel with a capacitor. The charge generator can be converted into a more familiar current generator, as displayed in Figure 4.6b, where the generated current is

$$i = \dot{Q} = K_q \dot{x} \tag{4.3}$$

(the point above the symbol indicates the time derivative). Based on the equivalent circuit in Figure 4.6b, the piezolectric sensor behaves like an ideal sensor, capable of providing an output (the voltage V) that perfectly reproduces the time course of the input (the displacement x). Indeed, the following differential equation holds

$$C_s \frac{dV(t)}{dt} = i(t) \tag{4.4}$$

and by integrating we obtain

$$V(t) = \frac{1}{C_s} \int i(t)\, dt = \frac{1}{C_s} \int K_Q \frac{dx(t)}{dt} dt = \frac{K_Q}{C_s} x(t) \tag{4.5}$$

[of course, we have obtained the same equation as (4.2), since the equivalent circuit derives from that equation and it must return the same result]. Thus, according to (4.5), if we apply a step input (the classic input used to test the dynamic performance of a measurement system), the output voltage perfectly reproduces the step input, and we would have a perfect sensor (see Figure 4.6b).

Actually, the previous one is not a complete description of the electric behavior of the piezoelectric sensor. Indeed, for a complete description, we have to take into account that the piezoelectric material has a finite *leakage resistance* R_s. In other words, the piezoelectric material is not an ideal dielectric material with zero conductivity (= infinite resistivity) and behaving as an ideal capacitor, but has a finite (although high) resistivity. The electrical equivalent circuit of the piezoelectric sensor, taking into account R_s, is shown in Figure 4.6c. Because of this resistance, the output voltage in response to a step input tends to decade with time (the charge accumulated on the capacitor discharges through the resistance). Value of the leakage resistance is usually very high (a few $G\Omega$ up to hundreds of $G\Omega$); thus, it may allow a quasi-static response (as in Figure 4.6c).

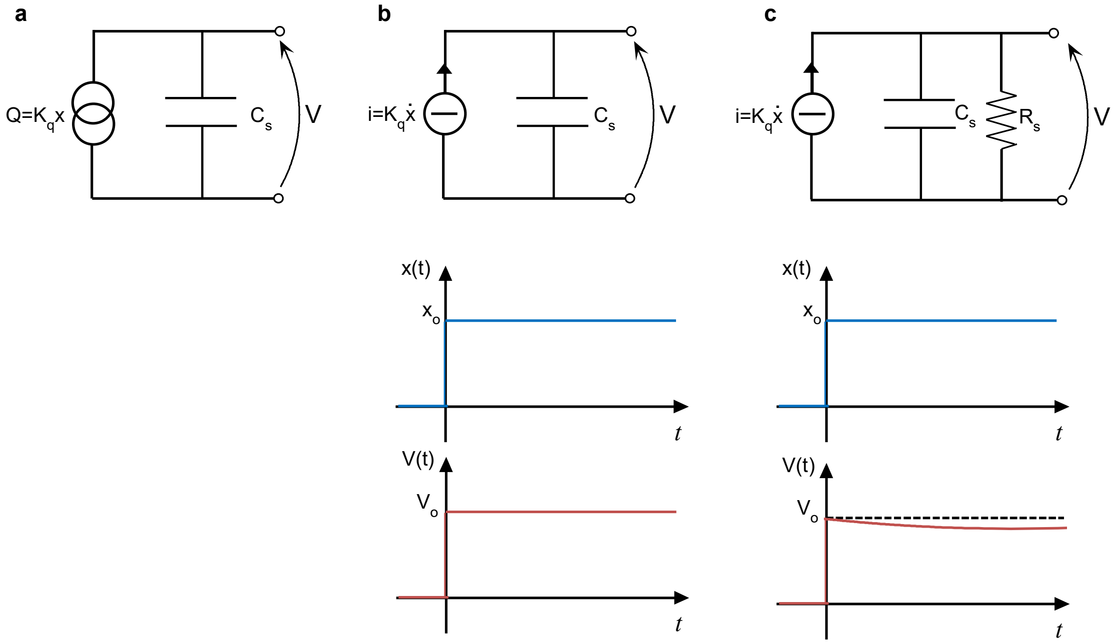

Figure 4.6 *Panel a*: Equivalent circuit of the piezoelectric displacement sensor, consisting of the charge generator in parallel to a capacitor. *Panel b*: Same as in panel a, where the charge generator has been converted into a current generator. The time plots below the circuit highlight that this equivalent circuit corresponds to a perfect sensor, where the output perfectly reproduces the step pattern of the input. *Panel c*: Equivalent circuit of the sensor accounting for the leakage resistance R_s of the piezoelectric material. Because of this resistance, the step response gradually decreases (a quasi-static response may be observed in case of very high R_s).

Connection to a voltage amplifier

The previous description covers only the sensor (the piezoelectric element with the electrodes). However, we have to consider that the sensor is also connected, via connecting cables, to a conditioning block. The latter can be a *voltage amplifier* (as in Figure 4.7a). The amplifier is characterized by its input resistance (R_{in}), which can be much less than the sensor leakage resistance R_s. Moreover, the cables introduce a parasitic capacitance (or stray capacitance) C_{cables}. The overall equivalent circuit is represented in Figure 4.7b and, by combining in parallel resistances and capacitances we obtain the circuit in Figure 4.7c. Note that the transfer function of the voltage amplifier linking $V_u(s)$ to $V(s)$ is constant on a very wide range of frequencies (here, equal to $1 + R_r/R_i$), and it does not influence the dynamics of the system.

From the circuit in Figure 4.7c, we can derive the transfer function of the system $G(s) = \frac{V(s)}{x(s)}$ linking the Laplace transform of the voltage $V(s)$ to the Laplace transform of the displacement $x(s)$:

$$V(s) = i(s)\frac{R}{1 + sRC} \tag{4.6}$$

$$i(s) = K_q s x(s) \tag{4.7}$$

Hence

$$G(s) = \frac{V(s)}{x(s)} = K_q \frac{sR}{1+sRC} = \frac{K_q}{C}\frac{s\tau}{1+s\tau} = K\frac{s\tau}{1+s\tau} \tag{4.8}$$

Based on (4.8), the system has a first-order high-pass frequency response, with passband gain (sensitivity) $K = \frac{K_q}{C}$ and cutoff angular frequency $\frac{1}{\tau} = \frac{1}{RC}$ (see Figure 4.8).

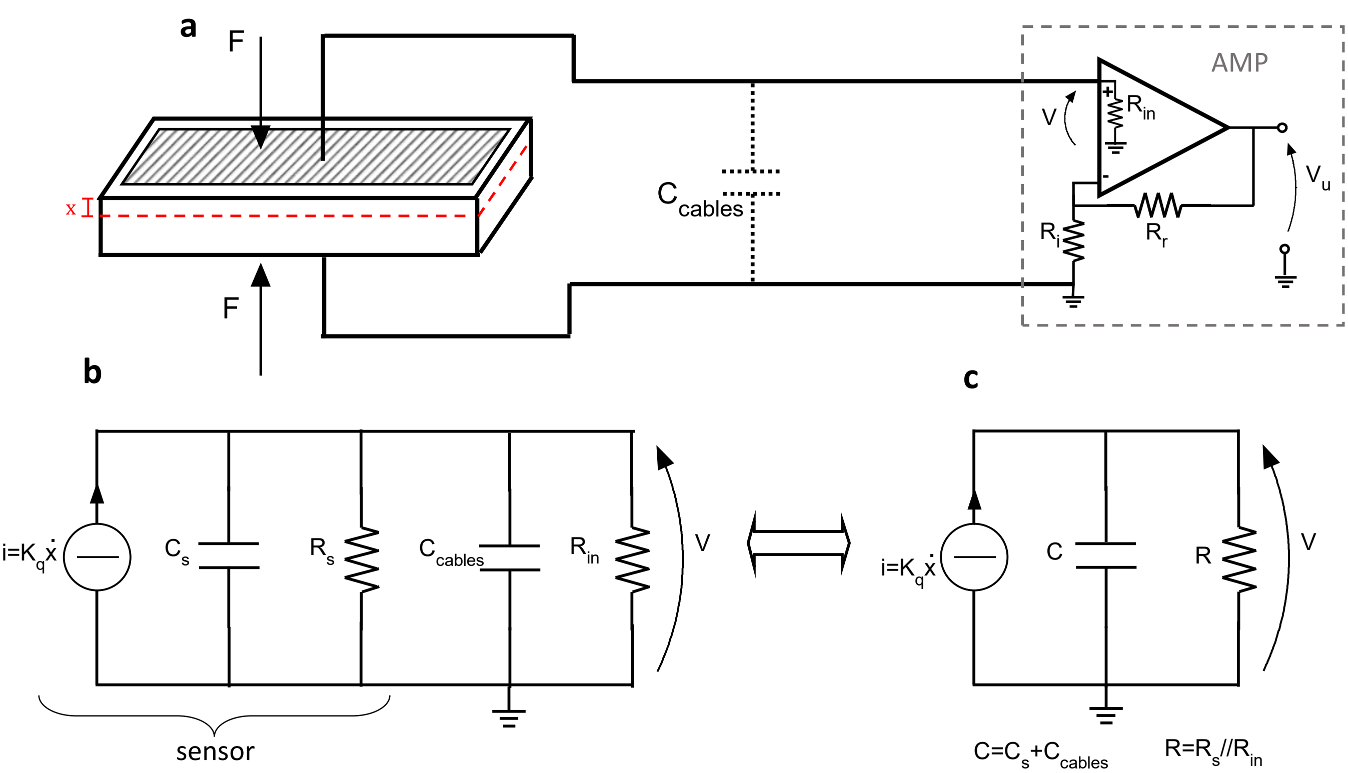

Figure 4.7 *Panel a*: Connection of the piezoelectric sensor to a voltage amplifier with input resistance R_{in}, (here a non-inverting configuration has been considered). The cables connecting the sensor to the amplifier introduce a parasitic capacitance C_{cables}. *Panel b*: Equivalent circuit of the piezoelectric sensor + cables + voltage amplifier. *Panel c*: Same as in panel b, where resistances and capacitances in parallel are combined. R is the parallel between R_{in} and R_s ($R_{in}//R_s$) and in case $R_{in} \ll R_s$, we have $R \cong R_{in}$.

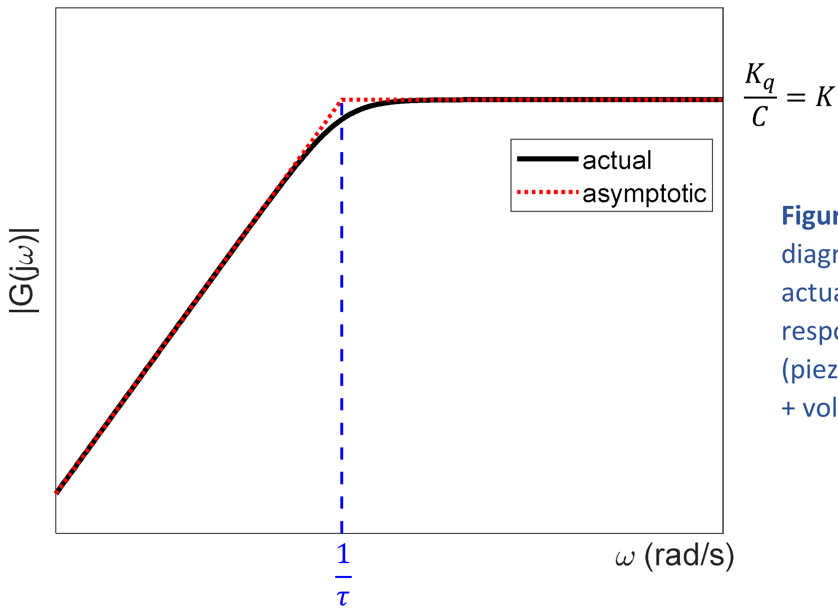

Figure 4.8 Bode magnitude diagram (asymptotic and actual) of the frequency response of the system (piezoelectric sensor + cables + voltage amplifier)

We can better illuminate the dynamic behavior of the system by deriving the response (as a function of time) to the input displacement shown in Figure 4.9a (step input of duration T). Both $x(t)$ and $V(t)$ are zero for $t < 0$. The differential equation corresponding to the transfer function in (4.8) is

$$\tau \frac{dV(t)}{dt} + V(t) = K\tau \frac{dx(t)}{dt} \tag{4.9}$$

where $x(t)$ (the input) is the forcing function.
Since $x(t) = L\ (constant)$ for $0 < t < T$ (and thus its time derivative is zero), in this interval (4.9) becomes

$$\tau \frac{dV(t)}{dt} + V(t) = 0 \qquad 0 < t < T \tag{4.10a}$$

The displacement x exhibits a sudden change, increasing from 0 at $t = 0^-$ to L at $t = 0^+$. Due to the high-pass behavior of the system (with high-frequency gain = K), the voltage V reproduces this sudden increase assuming value $V = KL$ at $t = 0^+$. Hence, the initial condition for the differential equation (4.10a) is

$$V(0^+) = KL \tag{4.11}$$

Solving (4.10a) with initial condition (4.11), we have

$$V(t) = KL\, e^{-\frac{t}{\tau}} \qquad 0 < t < T \tag{4.12}$$

Based on (4.12), in that interval $V(t)$ decreases exponentially towards 0 starting from the value KL, with time constant τ. Equation (4.12) still holds at $t = T^-$ and $V(T^-) = KL\, e^{-\frac{T}{\tau}}$. Then, the displacement x suddenly changes, decreasing from L at $t = T^-$ to 0 at $t = T^+$; this causes voltage V to suddenly drop by KL from its value at $t = T^-$. Therefore,

$$V(T^+) = V(T^-) - KL = KL\, e^{-\frac{T}{\tau}} - KL \tag{4.13}$$

In the interval $t > T$, $x(t) = 0\ (constant)$; in this interval equation (4.9) becomes

$$\tau \frac{dV(t)}{dt} + V(t) = 0 \qquad t > T \tag{4.10b}$$

Equation (4.10b) must be solved with initial condition (4.13), obtaining the solution

$$V(t) = \left(KLe^{-\frac{T}{\tau}} - KL \right) e^{-\frac{t-T}{\tau}} \qquad t > T \tag{4.14}$$

Based on (4.14), for $t > T$, $V(t)$ tends to 0 starting from the value $KLe^{-\frac{T}{\tau}} - KL$, according to an exponential pattern with time constant τ.
Figure 4.9b shows the temporal pattern of the response for three different values of the time constant.

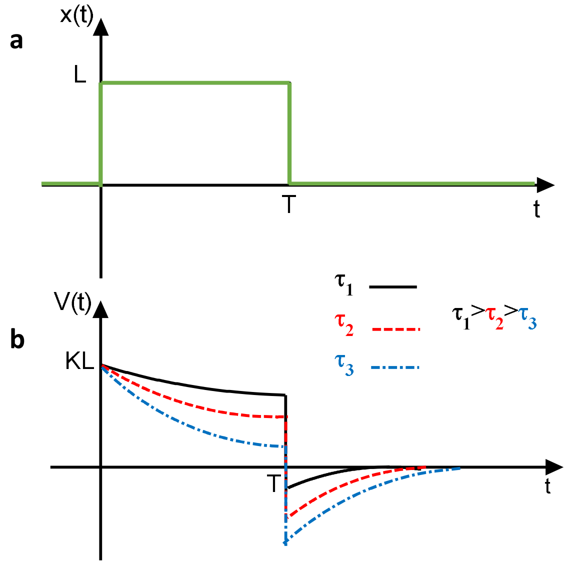

Figure 4.9 *Panel a*: Time pattern of the displacement applied in input (step input with duration T).
Panel b: Time pattern of the output voltage in response to the step input, for three different values of the time constant τ.

It is clear that a large value for the time constant τ is desirable for a faithful reproduction of $x(t)$. An increase in the time constant corresponds to a decrease in the cutoff frequency of this high-pass measurement system, improving the response at low frequencies.

If an increase in τ is required for a specific application, this may be achieved by increasing either C or R or both R and C.

An increase in C can be obtained by connecting an external capacitor across the sensor terminals as represented in Figure 4.10a. Indeed, the capacitors in parallel add directly. The equivalent circuit is represented in Figure 4.10b. The transfer function of the system is of the same type as in (4.8):

$$G(s) = K' \frac{s\tau'}{1 + s\tau'} \tag{4.15}$$

where $\tau' = RC'$, $C' = C_s + C_{par} + C_{cables}$ and $K' = \frac{K_q}{C'}$. Hence, time constant τ' is larger than in the original configuration (Figure 4.7) thanks to addition of C_{par}. The price to be paid is a loss in sensitivity, since the value of the capacitance is at the denominator in the expression of sensitivity (K' in configuration of Figure 4.10 is less than K in the original configuration of Figure 4.7).

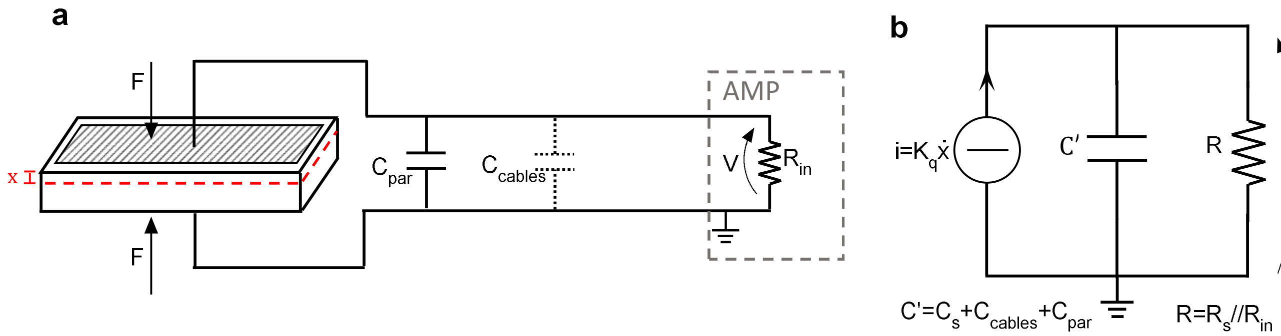

Figure 4.10 *Panel a*: The piezoelectric sensor is connected to an amplifier having input resistance R_{in} (for brevity, only the input resistance is represented rather than the overall amplifier). A capacitor C_{par} is connected in parallel to the sensor to increase the time constant of the system. *Panel b*: Electrical equivalent circuit. The equivalent circuit of the piezoelectric sensor includes the current generator in parallel with the capacitance C_s and resistance R_s. The capacitances and resistances in parallel are combined together. The overall capacitance C' is larger than in the original configuration (Figure 4.7) thanks to the addition of C_{par}.

An increase in R can be obtained by changing the amplifier and using an amplifier with greater input resistance. An alternative solution, useful in case the voltage amplifier has a low R_{in} ($R_{in} \ll R_s$) and we have not the possibility to change the amplifier, consists in connecting a resistance in series with the input of the amplifier (as in Figure 4.11a). This solution increases the time constant without the need of using a different amplifier, but is associated with a decrease in sensitivity. Indeed, considering the equivalent circuit in Figure 4.11b (where the leakage resistance of the piezoelectric material has been approximated with an open circuit), we can derive the transfer function of the system in this case:

$$i(t) = K_q \frac{dx(t)}{dt} = i_C(t) + i_R(t) \tag{4.16}$$

$$i_R(t) = \frac{V(t)}{R_{in}} \tag{4.17}$$

$$i_C(t) = C \frac{dV_C(t)}{dt} \tag{4.18}$$

$$V_C(t) = V(t) \frac{R_{in} + R_{ser}}{R_{in}} \tag{4.19}$$

By replacing (4.19) into (4.18) and then by replacing (4.18) and (4.17) in (4.16), we have

$$K_q \frac{dx(t)}{dt} = C \frac{R_{in} + R_{ser}}{R_{in}} \frac{dV(t)}{dt} + \frac{V(t)}{R_{in}} \tag{4.20}$$

By Laplace transforming (4.20)

$$sK_q x(s) = \frac{V(s)}{R_{in}} (sC(R_{in} + R_{ser}) + 1) \tag{4.21}$$

$$G(s) = \frac{V(s)}{x(s)} = \frac{sK_q R_{in}}{1 + sC(R_{in} + R_{ser})} = \frac{K_q}{C} \frac{R_{in}}{R_{in+}R_{ser}} \frac{sC(R_{in} + R_{ser})}{1 + sC(R_{in} + R_{ser})} = K'' \frac{s\tau''}{1 + s\tau''} \tag{4.22}$$

The transfer function in (4.22) is of the same type as before (high-pass); it has time constant $\tau'' = C(R_{in} + R_{ser})$ greater than in the original configuration (Figure 4.7, where $\tau = CR_{in}$ when $R_{in} \ll R_s$), thanks to the addition of R_{ser}, and sensitivity $K'' = \frac{K_q}{C} \frac{R_{in}}{R_{in}\ R_{ser}}$ less than in the original configuration (Figure 4.7), because of the factor $\frac{R_{in}}{R_{in+}R_{ser}}$ less than 1.

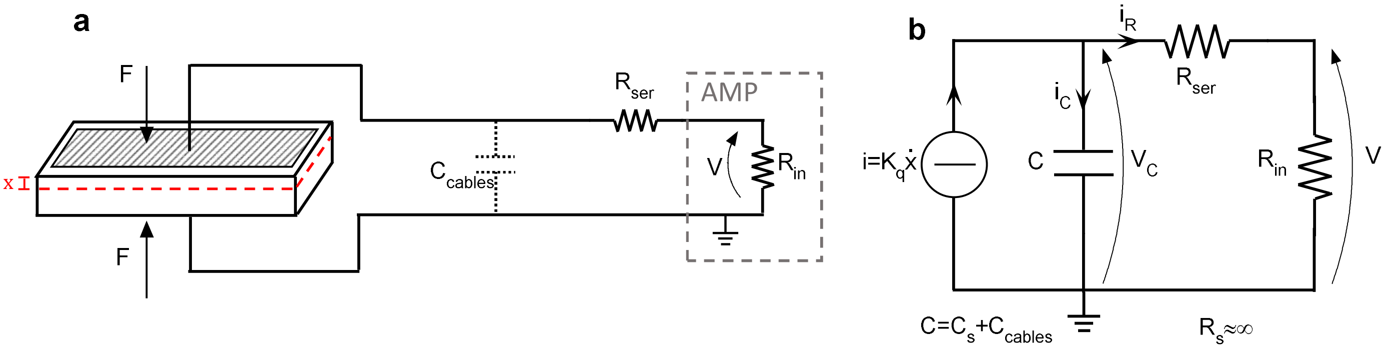

Figure 4.11 *Panel a*: The piezoelectric sensor is connected to an amplifier having input resistance R_{in} (for brevity, only the input resistance is represented rather than the overall amplifier as in Figure 4.7). A resistance R_{ser} is connected in series to increase the time constant of the system. *Panel b*: Electrical equivalent circuit. The equivalent circuit of the piezoelectric sensor includes the current generator in parallel with the capacitance C_s. For simplicity, the resistance R_s has been approximated by an open circuit, in consideration of its high value. The capacitances in parallel are combined together.

Overall, two points can be derived. i) The piezoelectric sensor connected to a voltage amplifier is a measurement system with a first-order high-pass behavior. Solutions can be adopted to augment the time constant (see the solutions in Figure 4.10 and 4.11 or the solution of using an amplifier with greater input resistance), so to enlarge the passband zone of the frequency response towards lower frequencies. However, the high-pass behavior remains, and these systems are unable to respond to static or low-frequency phenomena. This is an intrinsic limitation of the piezoelectric sensors. ii) In all configurations considered so far (Figures 4.7, 4.10, 4.11, all involving the voltage amplifier connected to the piezoelectric sensor) corresponding to transfer functions (4.8), (4.15) and (4.22), we can note that both the sensitivity and the time constant depend on the overall capacitance, and the latter includes the capacitance of the cables C_{cables}. This is a limitation since C_{cables} is not a design parameter but is a parasitic parameter; using long cables (as it may occur in some practical setups) can result in a reduced sensitivity or a variation in the frequency response.

Connection to a charge amplifier

The wide use of piezoelectric sensors has led to the development of an amplifier type, the *charge amplifier*, that may offer some advantages compared to the voltage amplifier. The charge amplifier connected to the piezoelectric sensor is shown in Figure 4.12a; in Figure 4.12b the piezoelectric sensor has been replaced by its electrical equivalent circuit.

With reference to Figure 4.12b, we can derive the transfer function ($G(s) = \frac{V_u(s)}{x(s)}$) of the system consisting of the piezoelectric sensor attached to the charge amplifier. Note that in this case, we are considering the voltage at the output of the charge amplifier, since the amplifier (having a capacitance in the feedback branch) has a role in determining the dynamics of the system. Note also that the overall capacitance C still includes the parasitic capacitance of the cables C_{cables}.
By considering the Op Amp ideal (and that the Op Amp works in its linear region), the virtual short circuit hypothesis holds ($V^+ = V^-$). Hence, the voltage drop across both the resistance R_s and capacitance C is zero and no current flows through them ($i_C = 0$ and $i_R = 0$). Moreover, since no current flows through the input terminals of the Op Amp, the current i provided by the current generator flows entirely through the parallel $R_f//C_f$ on the feedback branch. This is why it is called 'charge amplifier': the current provided by the generator goes entirely on the feedback branch. In other words, the charge generated by the piezoelectric material is totally transferred on the feedback capacitance C_f, and then it discharges through the resistance R_f. The parallel $R_f//C_f$ is connected virtually to ground (at the inverting input of the Op Amp) on one side, and to the output of the Op Amp on the other side; hence the voltage across this parallel is V_u. Therefore, we can write

$$V_u(s) = -i(s)\frac{R_f}{1 + sR_fC_f} = -K_q s x(s)\frac{R_f}{1 + sR_fC_f} \tag{4.23}$$

$$G(s) = \frac{V_u(s)}{x(s)} = -K_q\frac{sR_f}{1 + sR_fC_f} = -\frac{K_q}{C_f}\frac{sR_fC_f}{1 + sR_fC_f} = K\frac{s\tau}{1 + s\tau} \tag{4.24}$$

where in (4.24) the time constant is $\tau = R_fC_f$ and the sensitivity (high-frequency gain) is $K = -\frac{K_q}{C_f}$. It is important to note that (4.24) has identical form as the transfer function of the piezoelectric sensor attached to a voltage amplifier (compare (4.24) with (4.8), (4.15), (4.22)). Hence, the use of a charge amplifier in place of a voltage amplifier does not modify the type of the frequency response that remains high-pass, and the system still exhibits loss of static and low-frequency response. However, the use of a charge amplifier has the advantage that both the sensitivity K and the time constant τ do not depend on the parasitic capacitance of the cables, but they depend only on design parameters.

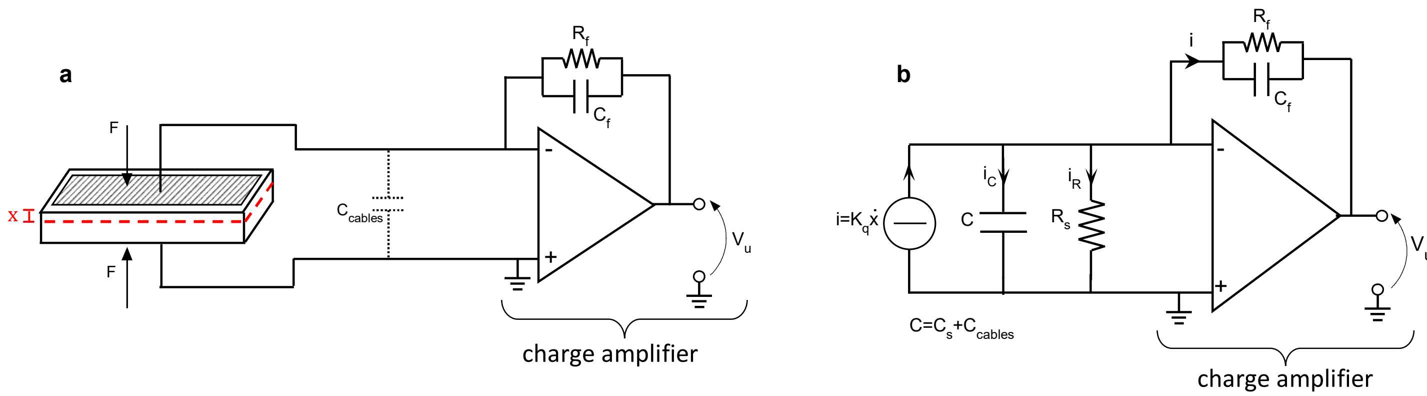

Figure 4.12 *Panel a*: The piezoelectric sensor is connected to a charge amplifier. *Panel b*: The piezoelectric sensor is replaced by its equivalent circuit (i.e., the current generator in parallel to capacitance C_s and resistance R_s). Note that the overall capacitance C still includes the parasitic cable capacitance C_{cables}. However, neither C nor R_s appear in the transfer function thanks to the virtual short circuit hypothesis at the inputs of the Op Amp.

Also in the case of the charge amplifier, a small cutoff frequency, and therefore a high time constant, is desirable to have a wide passband (improving the response at low frequencies). This can be obtained increasing either resistance R_f or capacitance C_f or both. However, an increase in C_f is associated with a decrease in sensitivity K; hence it is more convenient to increase R_f, as in this way τ is increased without a reduction in sensitivity. However, also in this case there is a price to be paid, consisting in the increase in the output noise due to the DC parameters of the Op Amp, in particular due to the bias current I^-. Indeed, the effect of the Op Amp DC parameters at the output of the charge amplifier in Figure 4.12 can be evaluated by considering the circuit in Figure 4.13. The latter is obtained from the circuit in Figure 4.12b where the input has been canceled (by opening the current generator) and the capacitances have been replaced by open circuits (since only DC quantities are considered). We have

$$V_{u\_noise} = V_{os}\left(1 + \frac{R_f}{R_s}\right) + I^- R_f \tag{4.25}$$

where V_{os} is the input offset voltage and I^- the input bias current of the Op Amp. An increase in R_f causes an increase in this noise especially because of the term $I^- R_f$. We deduce that it is possible to use very high values for R_f only usinf an Op Amp with very low bias currents.

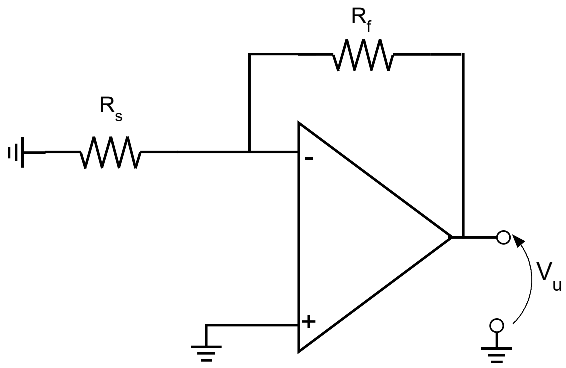

Figure 4.13 Circuit derived from Figure 4.12b to evaluate the effect of the DC parameters at the output of the charge amplifier. The current generator has been canceled (by opening it, to cancel the input signal and consider only the effect of the Op Amp DC parameters) and the capacitances have been replaced by open circuits too, as they have infinite impedance at DC.

In conclusion, the conditioning block of a piezoelectric sensor can be either a voltage amplifier or a charge amplifier. In both cases, the overall system exhibits a high-frequency response (this is an intrinsic limitation of piezoelectric sensors) and for each configuration, solutions can be adopted to increase the time constant of the system extending the passband zone towards lower frequencies. In case of the voltage amplifier, the system is influenced by the parasitic capacitance of the cables, hence stable and small cable capacitance (short cables) should be maintained to reduce the bad impact of this parasitic parameter.