5.7 Piezoelectric Sensors

Consider a piezoelectric crystal in the form of a disk with two electrodes plated on the two opposite faces. Since the crystal is a dielectric medium, this device is essentially a capacitor. Accordingly, a piezoelectric sensor may be represented as a charge source $q_s$ with a capacitance $C_s$ in parallel, as shown in Figure 5.29. This is the Norton equivalent circuit. There is an internal resistance as well in the piezoelectric element (between the electrodes), which can be represented in series with the charge source. But it will have no effect on the charge source (because it is in series with the charge source) and is omitted (or considered as internal to the charge source) in Figure 5.29.

The other effects ignored in Figure 5.29 are the finite resistance of the piezoelectric element (which is very high) in parallel with the charge source (to account for charge leakage across the plates of the capacitance $C_s$) and cable capacitance in parallel with the charge source.

Another equivalent circuit (Thevenin equivalent representation) can be given as well, where the capacitor is in series with an equivalent voltage source. This is completely equivalent to the Norton circuit given in Figure 5.29.

$$q_s = \int i_s \, dt$$

*is taken to be a through variable*

**Figure 5.29** Equivalent circuit (Norton) representation of a piezoelectric sensor.
From Equation 5.41, the output impedance of a piezoelectric sensor can be very high, particularly at low frequencies. For example, a quartz crystal may present an impedance of many megs at 100 Hz, increasing hyperbolically with decreasing frequencies. This is one reason why piezoelectric sensors have a limitation on the useful lower frequency, when the charge leakage cannot be neglected. As we will see, a charge amplifier can resolve this problem.

5.7 Piezoelectric Sensors

The impedance of the capacitor is given by

\[ Z_s = \frac{1}{j\omega C_s} \]  

(5.41)

Figure 5.29 Equivalent circuit (Norton) representation of a piezoelectric sensor.
piezoelectric transducers are inherently high output-impedance devices, which generate small voltages (in the order of 1 mV). For this reason, special impedance-transforming amplifiers (e.g., charge amplifiers) have to be employed to condition the output signal and to reduce loading error.

Figure 5.30 Piezoelectric sensor and charge amplifier combination.
Piezoelectric transducers are inherently high output-impedance devices, which generate small voltages (in the order of 1 mV). For this reason, special impedance-transforming amplifiers (e.g., charge amplifiers) have to be employed to condition the output signal and to reduce loading error.

\[ C_s \text{ impedance } \rightarrow \infty \text{ as } \omega \rightarrow 0! \]

Figure 5.30 Piezoelectric sensor and charge amplifier combination.
piezoelectric transducers are inherently high output-impedance devices, which generate small voltages (in the order of 1 mV). For this reason, special impedance-transforming amplifiers (e.g., charge amplifiers) have to be employed to condition the output signal and to reduce loading error.

\[ q_s + C_f \dot{v}_o + \frac{v_o}{R_f} = 0 \]

\[ \Rightarrow \frac{V_o(s)}{Q_s(s)} = -\frac{R_f s}{R_f C_f s + 1} \]

So, provided the frequency content of \( q_s \) is at frequencies higher than \( 1/(R_f C_f) \),

\[ v_o(t) = -\frac{1}{C_f} q_s(t) \]
5.7.3 Piezoelectric Accelerometers

A schematic diagram for a compression-type piezoelectric accelerometer is shown in Figure 5.32. The crystal and the inertia element (mass) are restrained by a spring of very high stiffness. Consequently, the fundamental natural frequency of the device becomes high (typically 20 kHz), and the useful frequency range or operating range (typically up to 5 kHz) is set by factors such as the limitations of the signal-conditioning system, the mounting methods, the charge leakage in the piezoelectric element, the time constant of the charge-generating dynamics, and the SNR. A typical frequency response curve of a piezoelectric accelerometer is shown in Figure 5.33.

The piezoelectric element is not a perfect dielectric, hence a “leakage resistance” allows a small current to flow from one electrode to the other. This current causes the frequency response of a compression-type piezoelectric accelerometer to be undesirable at low frequencies.

Frequencies where accelerometer gain is constant, i.e., where \( v_o \) is proportional to acceleration.

Figure 5.32
A compression-type piezoelectric accelerometer.

Figure 5.33
A typical frequency response curve for a piezoelectric accelerometer.
Figure 5.34
Schematic diagram of a piezoelectric velocity transducer.
Example application for piezo actuators (From Prof. Fuller’s research)
bimorph actuator

piezo actuation

wing

flexure joints

\( V_s \)
insect-scale manufacturing
Autonomous Insect Robotics Laboratory
Prof. Sawyer B. Fuller