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Signal Conditioning Piezoelectric Sensors

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ABSTRACT

Piezoelectric elements are used to construct transducers for a vast number of different applications. Piezoelectric materials generate an electrical charge in response to mechanical movement, or vice versa, produce mechanical movement in response to electrical input.

This report discusses the basic concepts of piezoelectric transducers used as sensors and two circuits commonly used for signal conditioning their output.

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1 Introduction

The word piezo comes from the Greek word piezein, meaning to press or squeeze. Piezoelectricity refers to the generation of electricity or of electric polarity in dielectric crystals when subjected to mechanical stress and conversely, the generation of stress in such crystals in response to an applied voltage. In 1880, the Curie brothers found that quartz changed its dimensions when subjected to an electrical field and generated electrical charge when pressure was applied. Since that time, researchers have found piezoelectric properties in hundreds of ceramic and plastic materials.

Many piezoelectric materials also show electrical effects due to temperature changes and radiation. This report is limited to piezoelectricity. More detailed information on particular sensors can be found by contacting the manufacturer.

2 Theory and Modeling

The basic theory behind piezoelectricity is based on the electrical dipole. At the molecular level, the structure of a piezoelectric material is typically an ionic bonded crystal. At rest, the dipoles formed by the positive and negative ions cancel each other due to the symmetry of the crystal structure, and an electric field is not observed. When stressed, the crystal deforms, symmetry is lost, and a net dipole moment is created. This dipole moment forms an electric field across the crystal.

In this manner, the materials generate an electrical charge that is proportional to the pressure applied. If a reciprocating force is applied, an ac voltage is seen across the terminals of the device. Piezoelectric sensors are not suited for static or dc applications because the electrical charge produced decays with time due to the internal impedance of the sensor and the input impedance of the signal conditioning circuits. However, they are well suited for dynamic or ac applications.

A piezoelectric sensor is modeled as a charge source with a shunt capacitor and resistor, or as a voltage source with a series capacitor and resistor. These models are shown in Figure 1 along with a typical schematic symbol. The charge produced depends on the piezoelectric constant of the device. The capacitance is determined by the area, the width, and the dielectric constant of the material. As previously mentioned, the resistance accounts for the dissipation of static charge.

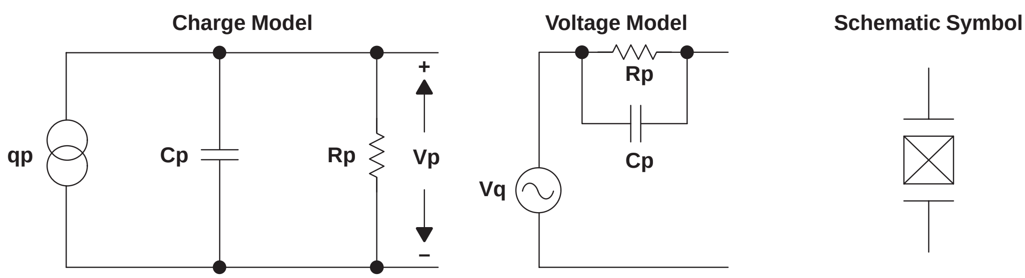

Figure 1. Sensor Models

3 Signal Conditioning

Normal output voltages from piezoelectric sensors can vary from microvolts to hundreds of volts, and signal conditioning circuitry requirements vary substantially. Key items to consider when designing the amplifier are:

- Frequency of operation
- Signal amplitude
- Input impedance
- Mode of operation

The following discussion assumes that the sensor output needs a moderate amount of amplification, and that the desired signal levels are in the 3-V to 5-V range for full scale.

Typically, the high impedance of the sensor requires an amplifier with high-input impedance. JFET or CMOS input op amps, like the TLV2771, are natural choices.

Two circuits are used for signal conditioning. Figure 2 shows a voltage mode amplifier circuit, and Figure 3 shows a charge mode amplifier circuit. Voltage mode amplification is used when the amplifier is very close to the sensor. Charge mode amplification is used when the amplifier is remote to the sensor.

3.1 Voltage Mode Amplifier

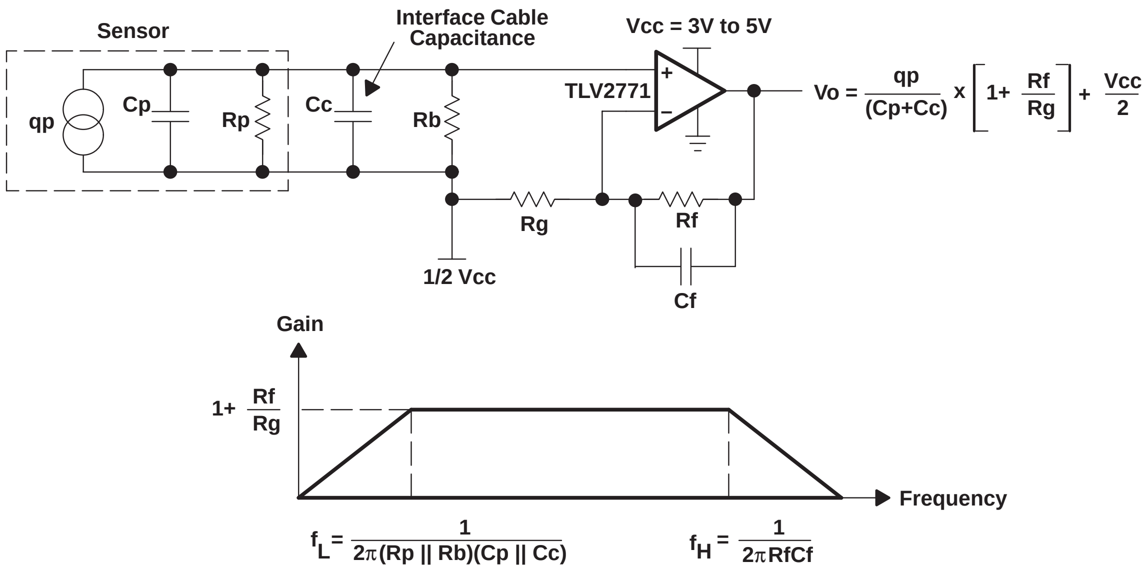

Figure 2. Voltage Mode Amplifier Circuit

In a voltage mode amplifier, the output depends on the amount of capacitance seen by the sensor. The capacitance associated with the interface cable will affect the output voltage. If the cable is moved or replaced, variations in Cc can cause problems.

Resistor Rb provides a dc bias path for the amplifier input stage.

Choice of Rf and Cf sets the upper cutoff frequency.

The lower cutoff frequency is calculated by: $f_L = \frac{1}{2\pi(Rp \parallel Rb)(Cp \parallel Cc)}$.

Resistor Rb should be chosen as high as possible and interface cabling reduced to a minimum. For the TLV2771 op amp, Rb = 10 MΩ will result in a typical offset of 60 µV over the commercial temperature range.

The biasing shown will put the output voltage at 1/2 Vcc with no input. The output will swing above and below this dc level.

3.2 Charge Mode Amplifier

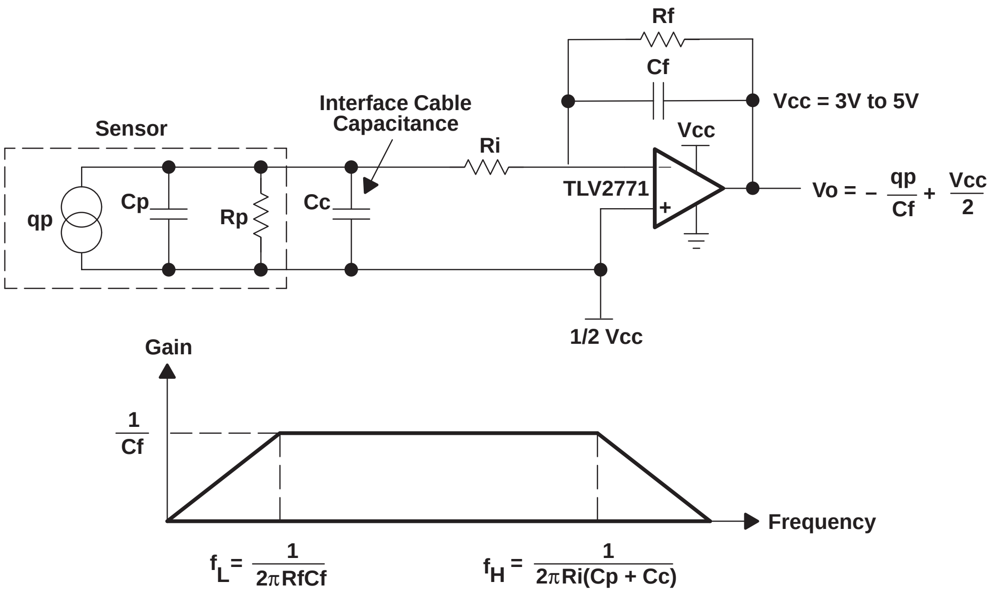

Figure 3. Charge Mode Amplifier Circuit

The charge mode amplifier will balance the charge injected into the negative input by charging feedback capacitor Cf. Resistor Rf bleeds the charge off capacitor Cf at a low rate to prevent the amplifier from drifting into saturation. Resistor Rf also provides a dc bias path for the negative input. The value of Rf and Cf set the low cutoff frequency of the amplifier.

The action of the amplifier maintains 0 V across its input terminals so that the stray capacitance associated with interface cabling does not present a problem. Resistor Ri provides ESD protection. Resistor Ri and capacitors Cp and Cc combine to produce roll off at higher frequency.

The biasing shown will put the output voltage at 1/2 Vcc with no input. The output will swing around this dc level.

3.3 Signal Conditioning Made Easier

Some manufactures have made signal conditioning of their piezoelectric sensors easier by integrating FET buffers into the sensor. Still, proper biasing is important and additional amplification may be desired. Refer to Application Note *3V Accelerometer Featuring TLV2772*, literature number SLVA040 (http://www.ti.com/sc/docs/apps/analog/operational_amplifiers.html) for an example.

Appendix A Circuit Computation With q

Computation of node voltages can always be performed based on current or voltage sources and circuit impedance. Calculating circuit voltages based on a charge source may seem difficult at first, but it is actually simple.

Computing node voltage in a circuit with a charge source and a capacitor is a simple matter when using the definition of capacitance, $C = \frac{q}{v}\left(\text{or } v = \frac{q}{C}\right)$. But what if you have resistors or inductors?

Operational calculus in the form of the Laplace operator, s, is the cornerstone of circuit analysis. Using the impedance form of Ohm's Law, V = I × Z, the technique replaces circuit elements with their s-domain impedance: $C \rightarrow \frac{1}{sC}$, $L \rightarrow sL$, and R remains R. These are based on the relationships: $v = \frac{1}{C}\int i\ dt$, $v = L\frac{di}{dt}$, and $v = iR$. In short form: if the relationship is an integral, divide by s, if it is a differential, multiply by s, and if it is neither, do not do anything.

Since current is the time differential of charge, $i = \frac{dq}{dt}\left(\text{or } \int i\ dt = q\right)$, substituting for i in the standard relationships: $v = \frac{q}{C}$, $v = L\frac{d^2q}{d^2t}$ and $v = R\frac{dq}{dt}$. The new s-domain replacements become: $C \rightarrow \frac{1}{C}$, $L \rightarrow s^2L$, , and $R \rightarrow sR$. In short form, multiply everything by s.

If this is too complicated, perform the circuit analysis as if the charge sources were current sources, multiply the answer by s, and change the i to q. The result is the same. For example, using the charge model for the piezoelectric sensor shown in Figure 1:

Substituting sR_P for R_P and $\frac{1}{C_P}$ for C_p, the sensor output voltage is $v_p = q\left(\frac{sR_P}{1 + sR_PC_P}\right)$.

Or, assuming the charge source is a current source we find $v_p = i\left(\frac{R_P}{1 + sR_PC_P}\right)$. Then multiplying by s and substituting q for i, gives the same result.

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