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Considerations For Using Charge Amplifiers With High Temperature Piezoelectric Accelerometers

Technical Paper 339

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High temperature piezoelectric accelerometers have proven over the years to be highly reliable, accurate sensors for demanding applications such as jet engine testing and automotive engine development. While "voltage-mode" IEPE type accelerometers have come to dominate the general purpose testing market, "charge-mode" piezoelectric accelerometers and their accompanying charge amplifiers still reign in applications where temperature exposure exceeds 300°F.

High temperature accelerometers are found in both so-called "single-ended" (coaxial) output form, and "balanced differential" (two pin) output. Differential output types have found particular acceptance in applications in high EMI (electro-magnetic interference) environments, such as on power generation gas turbines.

Regardless of the output type, for applications where temperature exposure is greater than 500°F, particular attention needs to be paid to the specified performance of the accelerometer at upper temperature limits and the selection of an appropriate charge amplifier compatible with that performance. A "general-purpose" charge amplifier likely won't perform to expectations while matched with an accelerometer in an application at these temperature levels. A closer examination of both the accelerometer and charge amplifier's specifications reveals why.

Accelerometer and Charge Amplifier Matching

An often overlooked specification of high temperature accelerometers is the piezoelectric resistance specification at the extreme upper temperature limit. While the resistance value can be typically in the GΩ range (~10^9 Ω) at room temperature, at a maximum rated temperature (say, at ~1200°F), this value may drop to almost 10 kΩ. [See Figure 1] Through careful design, material selection and manufacturing techniques, resistance will return to initial values once the accelerometer temperature cools, thereby reducing the concern of inducing damage to the accelerometer. Table 1 lists a representative sample of Endevco accelerometer model numbers and their lowest specified piezoelectric resistance at maximum rated temperature.

Accelerometer model	Single-ended or Differential	Minimum resistance at max. temp
2273AM1	SE	10 MΩ at 700°F
2276	SE	100 kΩ at 900°F
2280	SE	100 kΩ at 900°F
6222S	Diff	50 MΩ at 500°F
6233C	Diff	100 kΩ at 900°F
6237M70	SE	10 kΩ at 1200°F
6243M1	SE	10 kΩ at 1200°F
6243M3	Diff	10 kΩ at 1200°F

Table 1 [Source: Ref 1]

However not just any charge amplifier will work with an accelerometer that performs this way. Charge amplifiers should specify a minimum source resistance that can be connected to its input in order for the charge amplifier to meet its entire set of specifications. Many general-purpose charge amplifiers specify a required source resistance of 10 MΩ or higher, meaning that the accelerometer's resistance must be at least 10 MΩ for the charge amplifier to perform to expectations. So an extreme temperature accelerometer, where its resistance drops to 10 kΩ at high temperature, would work in unexpected and unknown ways with such a charge amplifier. Table 2 lists some common Endevco charge amplifier model numbers and their minimum required source resistance.

Signal Conditioner Model	Application Type	Single-ended or Differential	Minimum source resistance
2721B	High Temp	SE	1 kΩ
2771C	General	SE	100 kΩ
2771CM2	High Temp	SE	10 kΩ
2775B	General	SE	10 MΩ
2777A	High Temp	Diff	50 kΩ
6634C	General	SE or Diff	10 MΩ

Table 2 [Source: Ref 1]

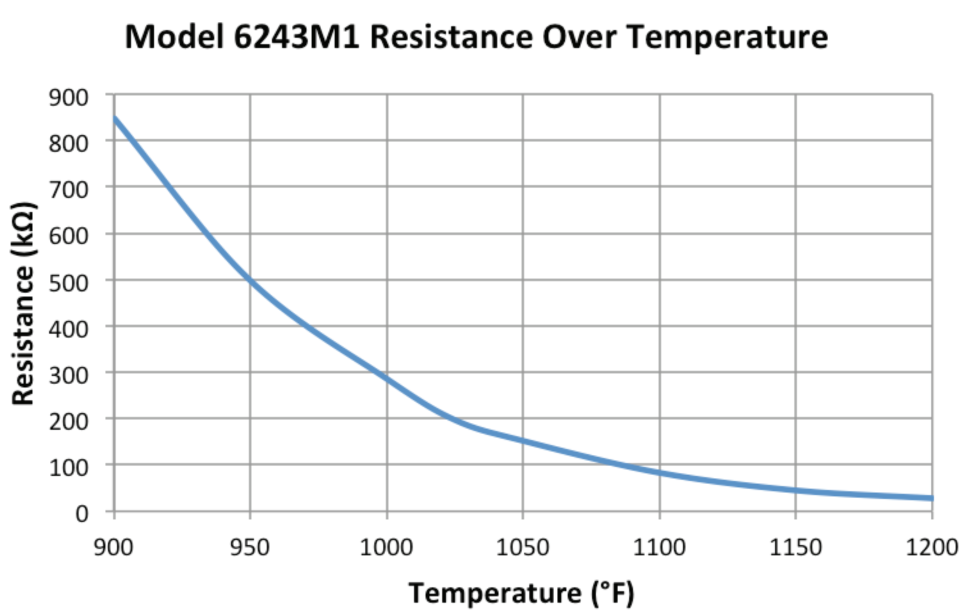

Figure 1

Several questions arise at this point:

- Why does the accelerometer's resistance drop?
- How does a charge amplifier work?
- Why do some charge amplifiers fail to work properly with low source resistances?

Let's tackle each of these separately.

Accelerometer Resistance

Piezoelectric accelerometers use piezoelectric crystalline material as its sensing element, whether that material is a "single" crystal (quartz and tourmaline, for example) or a "polycrystalline" ceramic (PZT or many others). These materials are insulators (more scientifically known as a dielectric). Piezoelectricity appears only in insulating solids. [Ref 2: page 1]

Consider a slab of solid "arbitrary" material. While there are many things we might consider to describe the properties of this slab, for our purposes, we will only consider a select few electrical properties. This slab, for instance, could be a conductor (of an electric current) or an insulator (or even a semi-conductor). These are not scientifically precise words, and are in fact quite relative. Copper metal, for example, is quite a good conductor, while other metals are less so. Plastic is an insulator, but glass, for instance, is a better insulator. To be more precise, scientists have defined a material property called resistivity, known by the symbol ρ, and quantified with the unit Ω-m (not Ω/m). Resistivity is a quantitative indication of how much a material resists the conduction of current flow. [Conductivity is sometimes applied here and is the reciprocal of resistivity. But resistivity better fits our purposes here.] Copper metal has a very low resistivity, while glass has a very high resistivity. See Table 3 for a list of the resistivity of various materials.

But why are metals good conductors and why are insulators bad conductors? Good conductors (low resistivity) have an atomic structure such that there are a large number of free (outer) electrons available to conduct an electric current. Insulators (high resistivity) have an atomic structure where the electrons are tightly bound, leaving very few free electrons to conduct a current. For the purposes of our discussion here, it's important to note that resistivity of all materials is temperature dependent. [Ref 3: page 508]

Material	Resistivity (Ω-m) (at room temperature)
Silver	1.6×10^{-8}
Copper	1.7×10^{-8}
Aluminum	2.8×10^{-8}
Iron	10×10^{-8}
Carbon	3500×10^{-8}
Silicon	6.4×10^{2}
Glass	1×10^{11}
Fused quartz	7.5×10^{17}

Table 3

So what happens to the resistivity of a metal as it is exposed to increasing temperature? Even with no electric field present in the metal, there is still electron movement within the atomic lattice of the material. This is because, assuming the temperature is above absolute zero, the electrons are thermally excited. But the movement is random and there is no net flow of current. With an electric potential (a voltage source) applied across the conductor, an electric field will establish in the metal and the electrons will begin to drift in one direction, thus creating a current flow. But the electrons are still thermally excited and moving about, colliding with one another. As the temperature is increased, the level of thermal excitement increases, increasing the number of electron collisions and impeding current flow. So the resistance of a conductor increases with increasing temperature, a positive temperature coefficient (PTC).

What happens in an insulator at temperature is much different. While the electrons are thermally excited, because the material is an insulator, there are not many free electrons available to facilitate current flow, even with an electric field present. But, as the temperature increases, thermal excitement increases, freeing more electrons and facilitating further current flow. So the resistance of an insulator decreases with increasing temperature, a negative temperature coefficient (NTC).

It is this phenomenon, an NTC, which happens in the piezoelectric sensing element of an accelerometer. As stated earlier, a high temperature piezoelectric accelerometer's worst case (lowest value) resistance at maximum rated temperature will be specified on the sensor's datasheet.

So why is this resistance a problem and how does it interact with a charge amplifier? The answer to this question requires an in-depth discussion of how a charge amplifier works.

Accelerometer and Charge Amplifier Circuit Models

First, we must develop a circuit model of the piezoelectric accelerometer itself. A piezoelectric device is essentially a charge generator. So it can be modeled as a voltage source in series with a capacitor C_{PE}. C_{PE} is the capacitance of the piezoelectric sensing element and is specified on the sensor's datasheet (or it can be measured). In addition, the piezoelectric resistance R_{PE} previously discussed is across the voltage source and capacitance. For completeness the capacitance of the cable leading between the sensor and charge amplifier is represented by C_c. The complete circuit model is

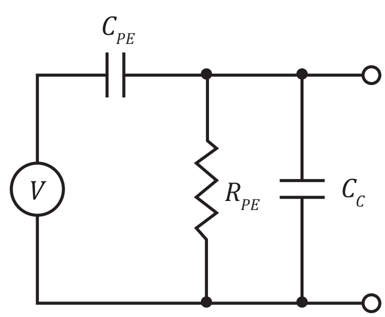

Figure 2

Piezoelectric resistance R_{PE} is ideally a very high value but as discussed previously can drop to as low as 10 kΩ at very high temperatures. This resistance will be problematic to the connecting charge amplifier circuit, as we shall see.

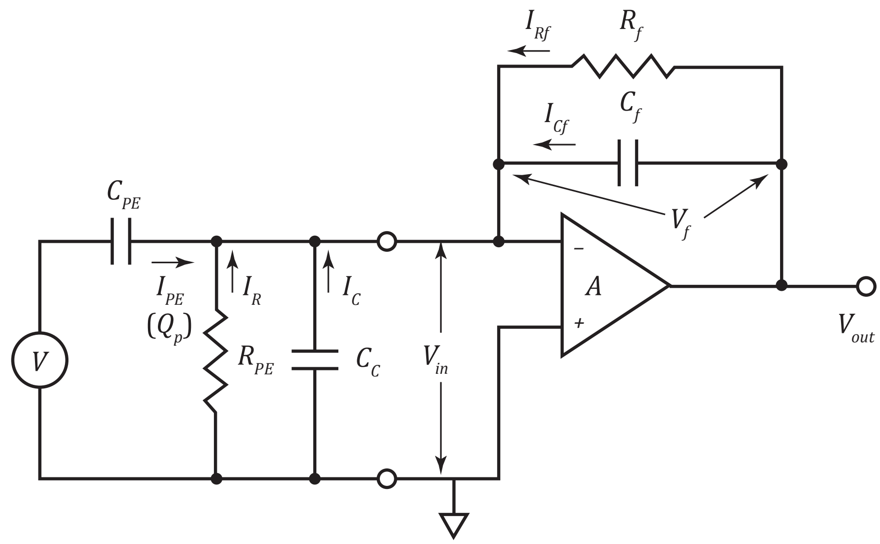

Figure 3

Figure 3 illustrates a basic charge amplifier (actually the charge converter), along with the piezoelectric sensor model connected. It will be insightful to analyze this circuit, discussing assumptions for the analysis along the way. Our goal is to derive an expression for the "gain" of the circuit, in terms of voltage output V_{out} and input charge Q_p.

First, we can make some assumptions about this circuit that makes the analysis easier:

1. "Open-loop" gain (A) of the op-amp is infinitely high.
2. Input resistance of the op-amp is infinitely high, meaning that no current flows in to or out of the op-amp's terminals.
3. There are no "offset" voltages at the terminals of the op-amp. [For a fuller discussion of an "ideal" op-amp's characteristics, see Ref 4: chap 3]

We will revisit these assumptions later, as the degree to which these assumptions are true will have an effect on how an actual charge amplifier performs, as discussed later on.

Referencing figure 3, the circuit can be analyzed thusly:

The output voltage V_{out} is related to the input voltage V_{in} by:

$$V_{out} = -AV_{in} \quad \text{Eq 1}$$

where A is the op-amp's open-loop gain. Solving for V_{in}, we have:

$$V_{in} = -\frac{V_{out}}{A} \quad \text{Eq 2}$$

We can also state the following for the voltage across the feedback capacitor C_f

$$V_f = V_{out} - V_{in} \qquad \text{Eq 3}$$

Substituting in Eq. 2 for V_{in}, we can rewrite this equation as

$$V_f = \left(1 + \frac{1}{A}\right) V_{out} \qquad \text{Eq 4}$$

Now, by Kirchhoff's law (and noting assumptions 2 and 3 above), we can write,

$$I_{pe} + I_R + I_c + I_{R_f} + I_{C_f} = 0 \qquad \text{Eq 5}$$

Let's now write an equation for each current term in Eq. 5 in the final terms we want our final result to be in, Q_p and V_{out}.

Current through C_{PE} can be written as the following:

$$I_{pe} = \frac{dQ_p}{dt} \qquad \text{Eq 6}$$

since current is the time rate of change of charge.

Current through R_{PE} can be written as (using Eq. 2):

$$I_R = \frac{V_{in}}{R_{PE}} = -\frac{V_{out}}{AR_{PE}} \qquad \text{Eq 7}$$

Current through C_c can be written as (using Eq. 2):

$$I_c = C_c \frac{dV_{in}}{dt} = -\frac{1}{A} C_c \frac{dV_{out}}{dt} \qquad \text{Eq 8}$$

Current through R_f can be written as (using Eq. 4):

$$I_{R_f} = \frac{V_f}{R_f} = \left(1 + \frac{1}{A}\right) \frac{V_{out}}{R_f} \qquad \text{Eq 9}$$

Current through C_f can be written as (using Eq. 4):

$$I_{C_f} = C_f \frac{dV_f}{dt} = \left(1 + \frac{1}{A}\right) C_f \frac{dV_{out}}{dt} \qquad \text{Eq 10}$$

Eq. 5 can now be re-written as:

$$\frac{dQ_p}{dt} - \frac{V_{out}}{AR_{PE}} - \frac{1}{A} C_c \frac{dV_{out}}{dt} + \left(1 + \frac{1}{A}\right) \frac{V_{out}}{R_f} + \left(1 + \frac{1}{A}\right) C_f \frac{dV_{out}}{dt} = 0 \qquad \text{Eq 11}$$

Since we want to solve this equation in terms of V_{out} and Q_p, we can rearrange Eq. 11:

$$\frac{dQ_p}{dt} = \frac{1}{A}\left[\frac{V_{out}}{R_{PE}} + C_c \frac{dV_{out}}{dt}\right] - \left(1 + \frac{1}{A}\right)\left[\frac{V_{out}}{R_f} + C_f \frac{dV_{out}}{dt}\right] \qquad \text{Eq 12}$$

Using advanced solution techniques (beyond the scope of this article [see Ref 5: chap 2]), Eq. 12 can be solved as:

$$j\omega Q_p = \frac{1}{A}\left[\frac{V_{out}}{R_{PE}} + j\omega V_{out} C_c\right] - \left(1 + \frac{1}{A}\right)\left[\frac{V_{out}}{R_f} + j\omega V_{out} C_f\right] \qquad \text{Eq 13}$$

where *j* is the complex number and *w* is angular frequency.

Rearranging and solving for V_{out}/Q_p, we have:

$$\frac{V_{out}}{Q_p} = \frac{1}{\frac{1}{A}\left(\frac{1}{j\omega R_{PE}} + C_c\right) - \left(1 + \frac{1}{A}\right)\left(\frac{1}{j\omega R_f} + C_f\right)} \qquad \text{Eq 14}$$

If we invoke assumption 1 from the list above, that gain *A* is infinitely large, and we assume R_f is infinitely large as well, Eq. 14 simplifies to:

$$\frac{V_{out}}{Q_p} = -\frac{1}{C_f} \qquad \text{Eq 15}$$

If we assume only that R_f is finite, but still assume gain *A* is infinitely large, we can see the effect R_f has on our circuit:

$$\frac{V_{out}}{Q_p} = -\frac{1}{C_f\left(1 + \frac{1}{j\omega R_f C_f}\right)} \qquad \text{Eq 16}$$

Where it can be shown that this equation has a frequency response of a high pass filter, with a frequency corner (3 dB) at:

$$f = \frac{1}{2\pi R_f C_f} \qquad \text{Eq 17}$$

From these results, we can conclude that the "gain" of a charge amplifier, in the ideal case, is solely controlled by the feedback capacitor C_f. The cable capacitance C_c plays no part in determining this gain. It further follows from Eq 2 (and assumption 1) that the input voltage to the op-amp V_{in} is zero, meaning that there is no voltage across the sensor, across C_c or across R_{PE}, so there is no current flow through these elements. Note that this conclusion is irrespective of the value of R_{PE}. So, in the ideal case, even a low value piezoelectric resistance, $\boldsymbol{R_{PE}}$, would not negatively affect the performance of a charge amplifier.

Resistance Problem?

So why is a low value piezoelectric resistance a problem? What is being neglected in the above analysis is the DC performance of the circuit. Revisiting the assumption list above, real op-amps do indeed have "leakage" currents (technically called bias currents) that flow through the op-amp terminals. These terminals also have offset voltages on them due to non-ideal op-amp characteristics. These effects must be accounted for, or the charge amplifier circuit will not perform correctly. Indeed, the feedback resistor R_f is present because the op-amp's terminals need a DC path to ground, or the circuit would quickly "saturate" and no AC signal would get through. Saturation of an amplifier means that the amplifier has been forced out of its linear operating range. So the amplifier will output a distorted signal. A distorted signal means data is being corrupted, and for all practical purposes, data is being lost.

Further if R_{PE} becomes small enough, due to the leakage currents and offset voltages at the op-amp terminals, enough current will flow in R_{PE} to also cause the op-amp to saturate. Circuit designers take steps in the design to mitigate these effects. But this is where the performance of a "general-purpose" charge amplifier and one designed for high temperature accelerometers (where one knows R_{PE} will be small at extreme temperature) begin to separate. Using a low R_{PE} accelerometer with a general-purpose charge amplifier, because of its circuit design, will likely result in an undesirable frequency response, especially near low frequencies. Figure 4 illustrates this. Using a general-purpose charge amplifier conservatively rated for a 10 MΩ minimum resistance accelerometer (a common specification), the effects of a source resistance down to 10 kΩ are observed. The amplitude response is up more than 10 dB. This is unacceptable if the user expects to collect useful accurate data in this frequency range. Many sources of outside interference signals occur in this frequency range (for example, pyroelectric effect and triboelectric effect) and will be gained up as governed by this amplitude response curve. Again, this will cause a distorted output and data loss.

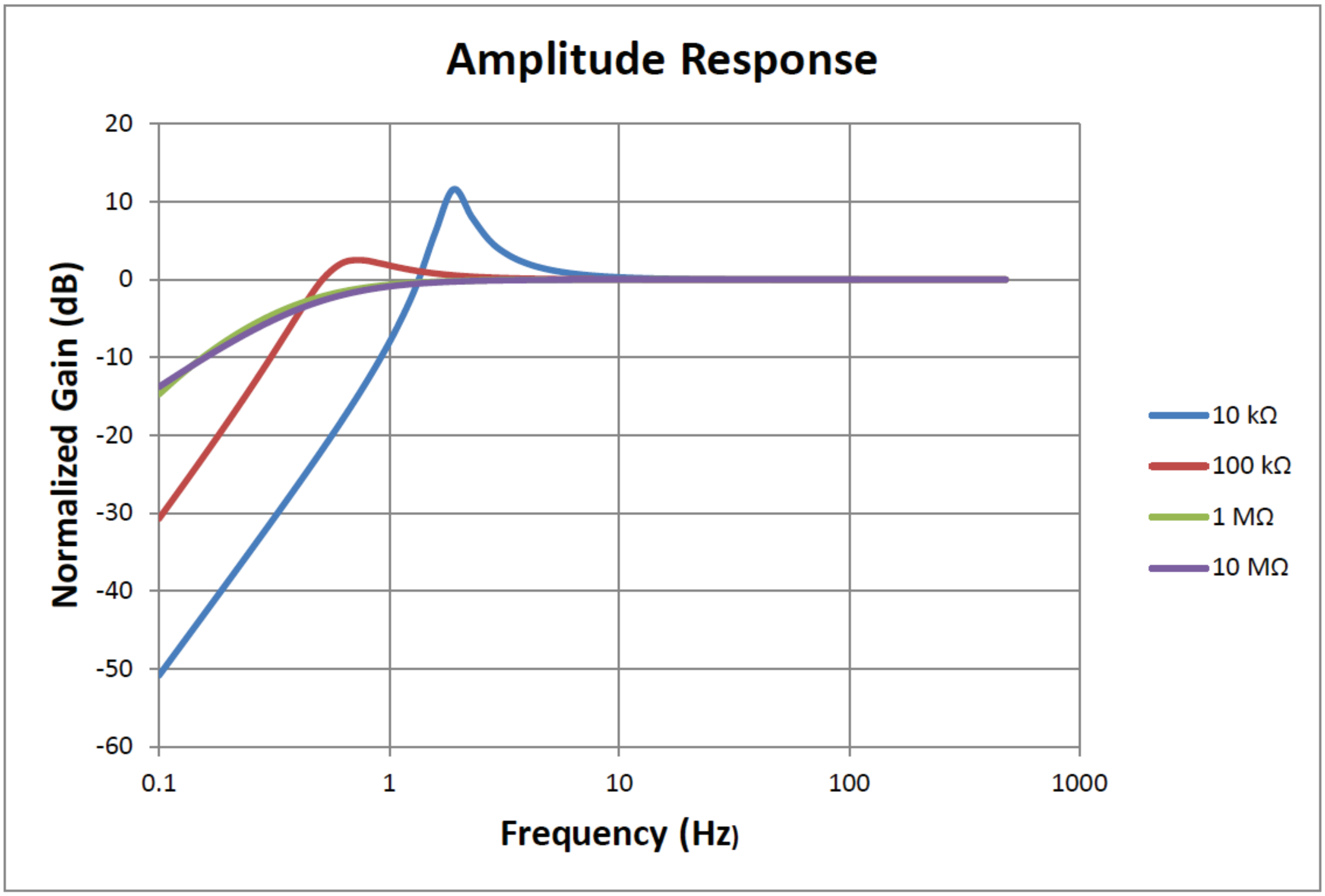

Figure 4: Amplitude Response Curves of a General-Purpose Charge Amplifier Using Different Source Resistances

The key, then, is proper design by the manufacturer that balances the ability of the charge amplifier to handle low R_{PE} resistances while also maintaining a flat amplitude response. This can be done, but requires careful design. But it is incumbent on the user to ensure that a charge amplifier designed for a low piezoelectric resistance accelerometer is being used.

Summary and Conclusion

High temperature accelerometers, both single-ended and differential output, have proven themselves to be accurate and reliable, even under extreme conditions. But attention needs to be paid to the accelerometer's piezoelectric resistance specification at maximum rated temperature extremes and the user needs to make sure a compatible charge amplifier is used.

Due to the physics of the piezoelectric material used in these sensors, the resistance will drop in value dramatically at maximum temperatures. Some models will even drop to as low as 10 kΩ.

An ideal charge amplifier will deal with these low resistances without any problems. But because of nonideal characteristics of the op-amps used, a low piezoelectric resistance will affect the DC performance of the circuit, causing the amplifier to saturate, distorting the signal output and loss of data.

Design attempts on a charge amplifier circuit to correct this problem must be done carefully, or otherwise the resulting amplitude response of the amplifier in combination with a low resistance accelerometer would be unacceptable [see Figure 4]. Use of such an unacceptable amplitude response could again result in distorted signals, again causing loss of data. So the use of "general-purpose"charge amplifiers with low resistance accelerometers must be avoided.

The user has a responsibility here then. To avoid the problems discuss here, the user must review the accelerometer's specifications, determine the worst case piezoelectric resistance at the temperature they plan to operate, and then select a charge amplifier (whether bench top or inline type) that is designed to operate at that resistance. This will avoid potentially erroneous and corrupted data, as well as wasted resources, time and money.

Sources

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