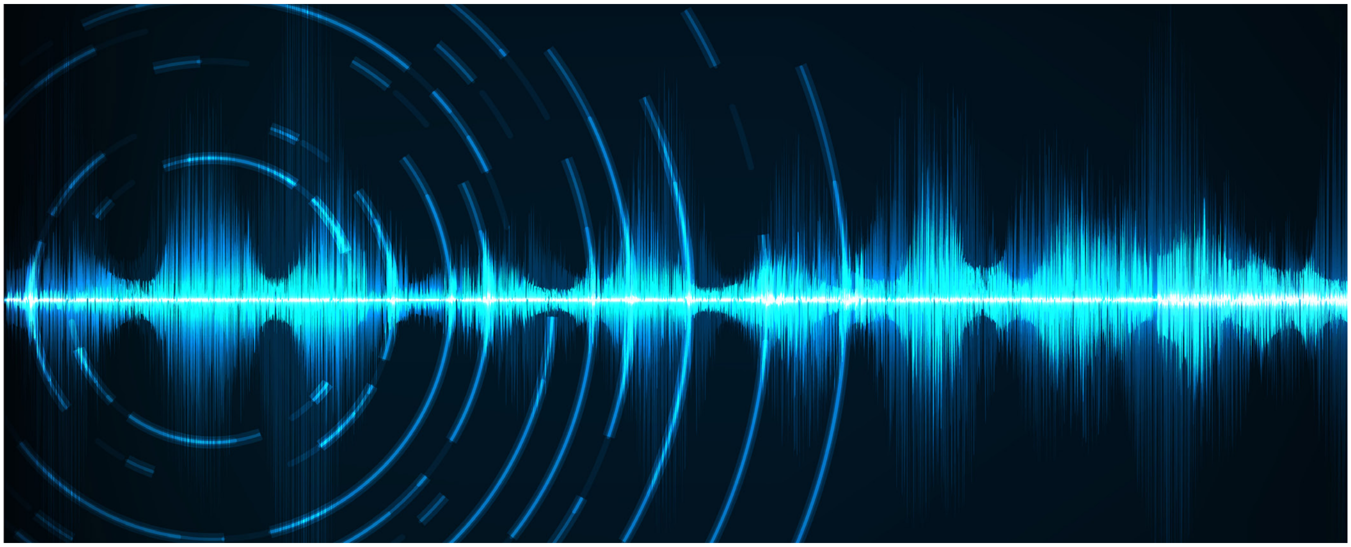

Signal Processing Impacts of ICP® Accelerometer Limit Violations

Written By

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S.A. Hambric
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1 Introduction

Accelerometers with embedded Integrated Circuit Piezoelectric (ICP) circuitry, such as the one shown in Figure 1, are complex electro-mechanical systems. The mechanical and electrical components are designed to provide wide ranges of linear response (voltage induced by a given acceleration) over amplitude and time (frequency). However, every sensor has limits, and exceeding those permissible limits can lead to attenuated, amplified, and even clipped signals. Sometimes, signals are unmeasurable due to 'noise floors.'

This white paper will explain:

1. Piezoelectric sensor operating principles
2. How ICP-powered accelerometers measure fluctuating vibrations
3. The lower and upper limits of linear response and what causes them, both in amplitude and frequency
4. The effects of violating those limits on response frequency spectra using signal processing theory and examples

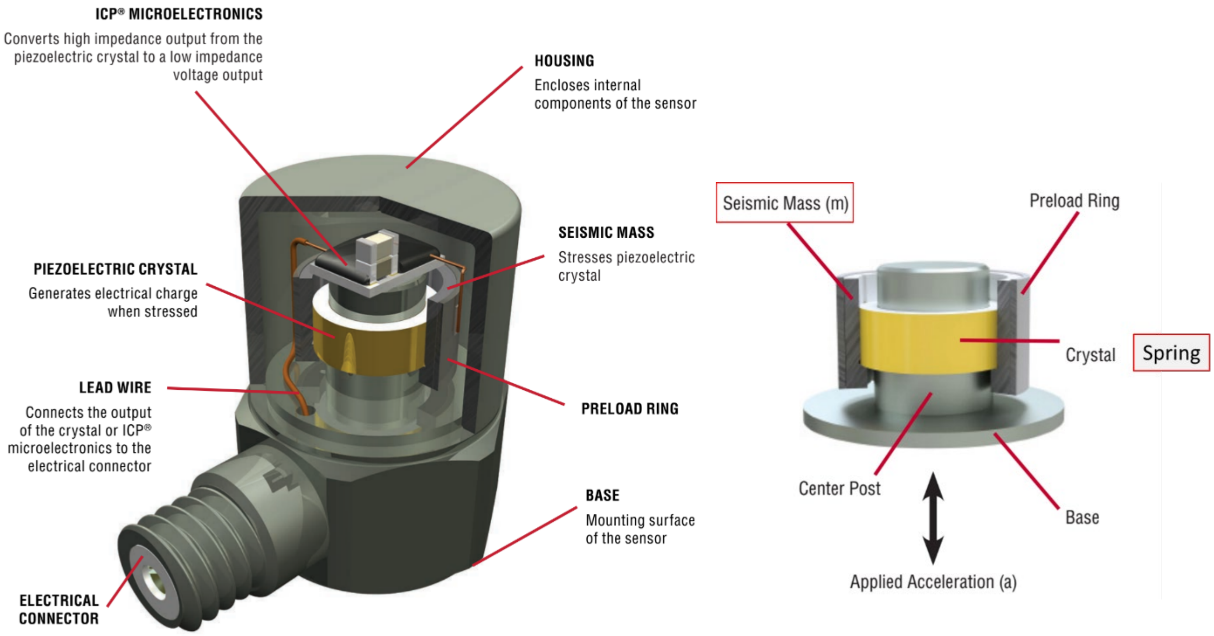


Figure 1. Typical PCB ICP Accelerometer.

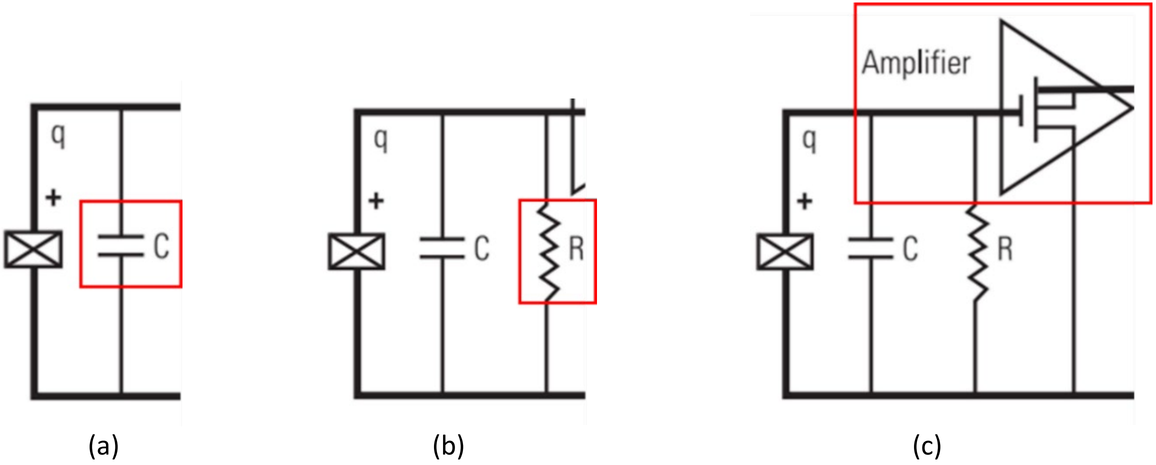
2 How an ICP Accelerometer Works

A typical PCB ICP-powered accelerometer is shown in Figure 1 along with the internal seismic mass and crystal. The crystal is sandwiched between the mass and the center post and is effectively a simple annular spring supporting the mass – a spring-mass oscillator. As the the oscillator is driven by an input acceleration from the Device Under Test (DUT) it induces fluctuating strains in the surrounding crystal (usually quartz or piezoceramic). The crystal responds by generating a fluctuating electrical charge q. This charge can be passed through a cable to a Data Acquisition System (DAQ) but is generally very low amplitude and easily attenuated by losses within the cable and corrupted by electromagnetic (EM) noise in the area around the DUT and along the cable path to the DAQ.

Including ICP circuitry converts the small, fluctuating charge into a large, fluctuating voltage, which experiences very little amplitude loss along the cable and is seldom affected by background EM noise. Figure 2 shows how the ICP circuitry operates:

a) A capacitor in parallel with the crystal converts the fluctuating charge into a fluctuating voltage,
b) a resistor ensures the voltage fluctuations are not attenuated too quickly, and
c) an amplifier boosts the voltage signal.

The function of the capacitor is relatively straightforward, but let's delve deeper into the roles of the resistor and amplifier.



(a) (b) (c)

Figure 2. ICP Components. (a) Capacitor converts fluctuating charge to fluctuating voltage. (b) Resistor increases discharge time. (c) Amplifier boosts voltage levels before sending to data acquisition system.

The charge generated by the crystal decays rapidly over time, so much so that a low-frequency disturbance from the DUT may not be adequately represented. Figure 3 illustrates how an ideal step signal would be measured by a mass-crystal-capacitor system. The initial impulse is captured effectively, but the subsequent charge and voltage level decays according to the system Discharge Time Constant (DTC), which is the time required for a signal to decay to 37% of its original level. Adding a resistor increases the system's DTC, allowing for accurate measurement of low-frequency signals (more on this later).

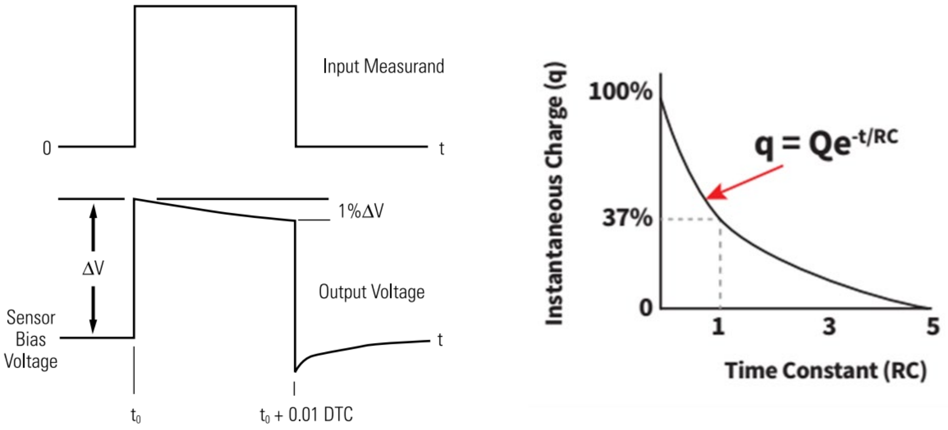


Figure 3. Decay of an electric signal from a crystal/capacitor circuit. DTC = RC.

The choice of amplifier type is contingent upon the crystal used. Both amplifier options are Field Effect Transistors (FET). Piezoceramic-based sensors work well with Junction FET (JFET) charge amplifiers, while quartz sensors work better with Metal Oxide Semiconductor FET (MOSFET) voltage amplifiers. We won't differentiate the amplifier types further except to state that both are used to establish the amplification factor and, consequently, the final sensitivity of a sensor (V/g).

To measure signals the accelerometer must be powered, as demonstrated in Figure 4. ICP sensors are powered by simple constant current DC systems, usually rated between 18-30 VDC with the sensor drawing between 2 and 20 mA. The fluctuating voltage must remain within the bounds of the supply voltage, as we'll discuss shortly.

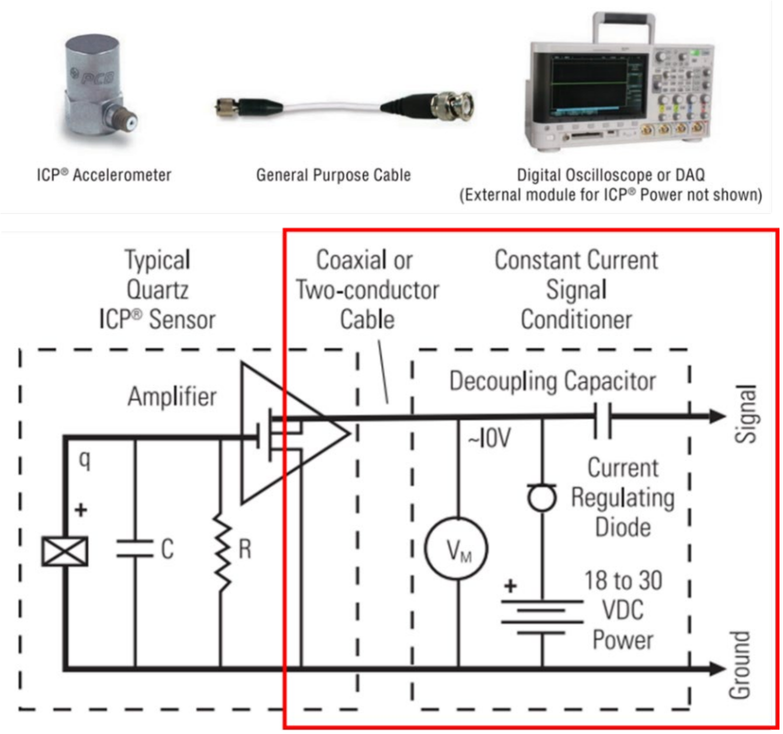


Figure 4. Constant current DC power supply.

3 Usable Linear Ranges

The three main components—oscillating mass, ICP circuitry, and power supply/signal transmission systems—all lead to lower and upper bounds on the usable linear amplitude and frequency ranges of an accelerometer. By “linear” we mean that a constant voltage per unit acceleration level g (sensitivity) is measured across a range of amplitudes (from low to high) and frequencies (also from low to high).

3.1 Amplitude Limits

3.1.1 Upper Limit – Power Supply Voltage Range

It’s important to remember that ICP sensors rely on a constant current source with an 18-30 VDC range for power. The voltage fluctuations from the sensor oscillate above and below a mean, or *bias voltage*. To be accurately measured, these fluctuations need to remain within the bounds of the voltage source. Figure 5 illustrates a sinusoidal voltage signal that exceeds permissible ranges. The original signal oscillates around the bias voltage (10 V in the figure). If the lower limit is breached, the signal is slightly attenuated. However, surpassing the upper limit can ‘clip’ the signal, effectively capping it at the upper voltage limit. To prevent clipping most accelerometers are limited to a +/- 5 V range.

Clipping effects on processed signals are presented in Figure 6. A hypothetical time series comprised of random broad-band noise and a tone at 100 Hz (a) is processed into a power spectral density (PSD). The signal is then clipped at +/- 2 EU (Engineering Units). The effects of clipping effects are more evident in the zoomed-in time history on the right of the figure (b), and lead to broad-band attenuation of the resulting PSD (c). Clipping is not always evident in a PSD since the effect is broad-band. Therefore, it’s best to periodically examine the peaks of your measured time histories to ensure that obvious clipping is not occurring.

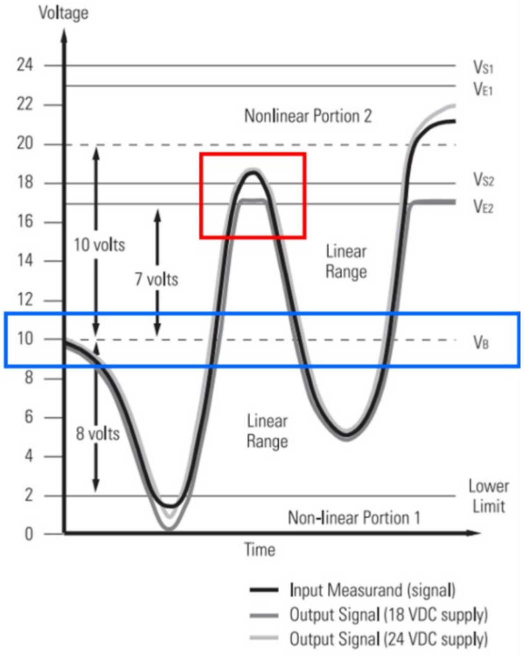
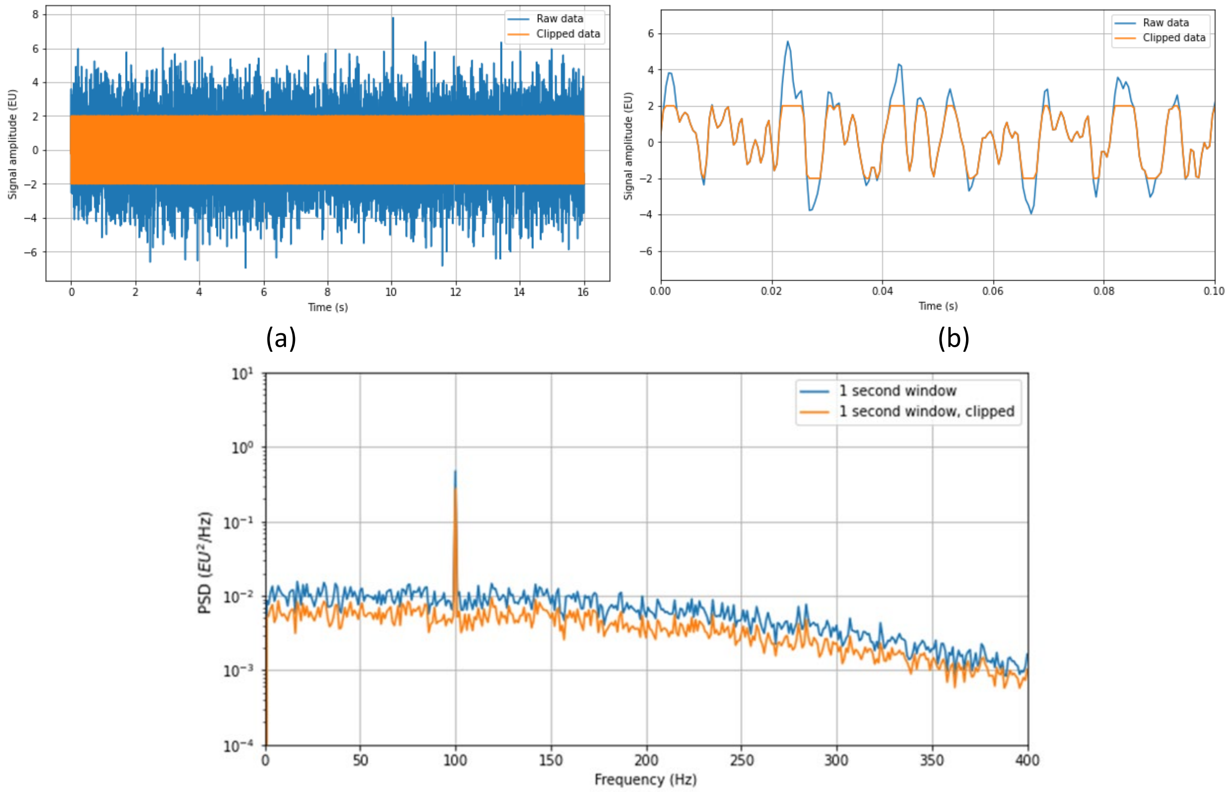


Figure 5. Sinusoidal signal which exceeds allowable voltage range.



(a) (b)

(c)

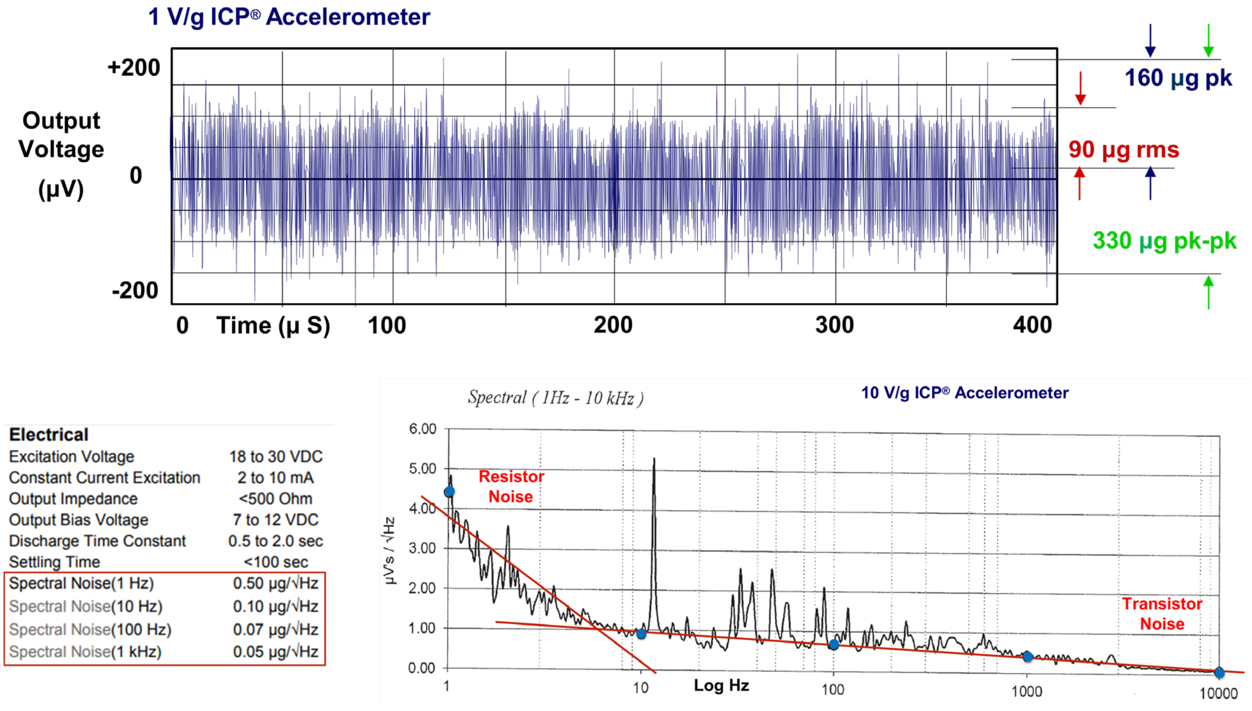
Figure 6. Example of clipping effects. Top: time histories; bottom: resulting PSDs.

3.1.2 Lower Limit – ICP Circuitry Noise

The smallest signal that can be measured by an ICP accelerometer depends on its sensitivity and ICP components. The simplest measure of the low amplitude limit is the *broad-band resolution,* which is measured by powering the sensor, usually mounted on a large stationary mass, in a low-noise environment. Examining the background noise time signal, like the one shown in Figure 7, quickly reveals the lowest measurable values. Vibrations from a DUT must exceed these values to be measurable.

To understand the origin of this limit, it's necessary to process the time history into a power spectrum, as shown in the example at the bottom of Figure 7 (note this is for a different accelerometer). In this 'noise floor spectrum' two distinct frequency ranges are clearly visible. At very low frequencies the background noise is caused by random fluctuations in the resistor, primarily due to thermal effects. The noise is proportional to R/f (resistance/frequency) and becomes more pronounced at lower frequencies. At higher frequencies, the background noise is attributable to the amplifier (FET). The overall broad-band resolution is simply the integration of the spectrum across frequencies, ensuring that low frequencies, where the bulk of the noise occurs, are captured.

Hence, the question of "how low can you go" with a measurement is frequency-dependent. Relying only on the total broad-band resolution as a guide may lead you to believe that some measurable signals cannot be accurately measured. However, if your important signals are significantly higher than the low-frequency background noise caused by the resistor, the actual lowest measurable signals may be much smaller. Since all sensors differ, careful background noise measurements are crucial.



Electrical	
Excitation Voltage	18 to 30 VDC
Constant Current Excitation	2 to 10 mA
Output Impedance	<500 Ohm
Output Bias Voltage	7 to 12 VDC
Discharge Time Constant	0.5 to 2.0 sec
Settling Time	<100 sec
Spectral Noise(1 Hz)	0.50 μg/√Hz
Spectral Noise(10 Hz)	0.10 μg/√Hz
Spectral Noise(100 Hz)	0.07 μg/√Hz
Spectral Noise(1 kHz)	0.05 μg/√Hz

Figure 7. Examples of lower amplitude limits. Top: broad-band resolution from time history analysis of a 1V/g accelerometer; bottom: frequency-dependent noise floor in a 10 V/g accelerometer. (The low frequency electrical tone is not associated with the accelerometer.)

3.2 Frequency Limits

3.2.1 Lower Limit – Discharge Time Constant (DTC)

A common question regarding low-frequency background noise is, “Why not simply reduce the resistance in the RC circuit to reduce the noise?” The answer lies in the fact that the RC circuit does something else that influences our limits—it operates as a high-pass filter with a low cutoff frequency, as demonstrated in Figure 8. Decreasing the resistance (R) shifts the high-pass filter upward in frequency, reducing our usable range. To understand why, let’s examine the voltage transfer function for the simple RC circuit within the ICP system:

$$H(\omega) = \frac{V_{out}}{V_{in}}(\omega) = \frac{R}{R - \frac{i}{\omega C}}$$

The Discharge Time Constant (DTC) is just the product of the resistance and capacitance (RC) so that:

$$H(\omega) = \frac{\omega RC}{\omega RC - i} = \frac{\omega DTC}{\omega DTC - i}$$

The inverse of the DTC is also the ‘cutoff frequency’ of the high-pass filter, also known as the ‘3 dB down’ frequency:

$$\omega_c = 2\pi f_c = \frac{1}{DTC}$$

So:

$$H(\omega) = \frac{\omega/\omega_c}{\omega/\omega_c - i} = \frac{1}{1 - i\omega_c/\omega}$$

Figure 9 shows the amplitude and phase behavior of this basic first-order high-pass filter. Note that frequency on the amplitude plot is shown on a logarithmic scale to highlight the slope of the filter below the cutoff frequency. Along with the amplitude attenuation, the phase of the fluctuating voltage is also distorted by the RC-circuit, gradually increasing as the frequency decreases, to a limit of 90 degrees.

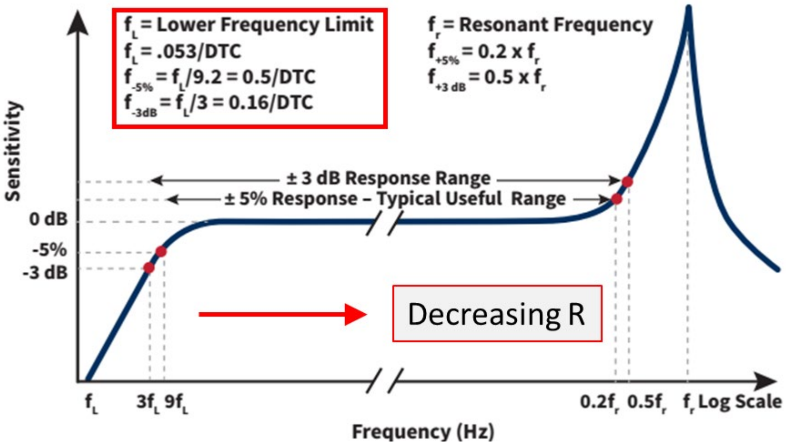


Figure 8. Relationships between RC-circuit, DTC, and lower frequency limits.

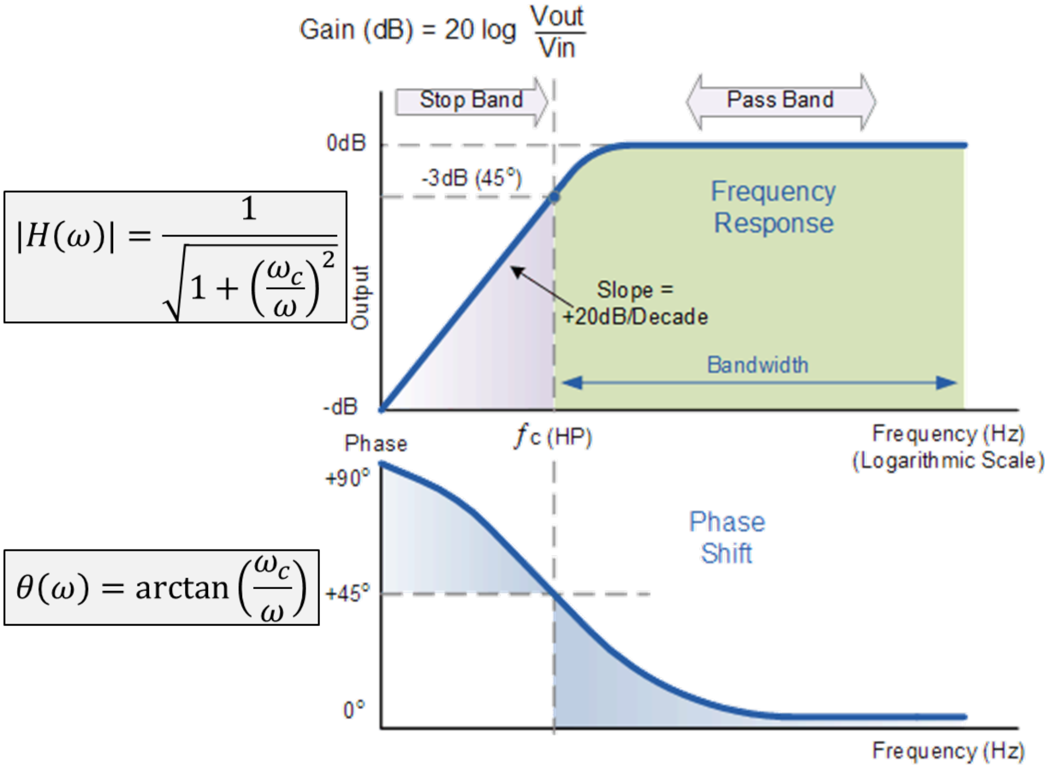


Figure 9. First-order high-pass filter behavior (from *Electronics Tutorials* online).

3.2.2 Upper Limit – Accelerometer Moving Mass Resonance

While the lower frequency limit relies on the electrical properties of the circuitry within an accelerometer, the upper frequency limit depends on its mechanical properties. The oscillating mass, which generates the fluctuating charge (and therefore voltage), is mounted on a pre-loaded crystal with a characteristic stiffness. Therefore, the mass-crystal combination is a simple harmonic oscillator with a characteristic resonance frequency:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{k_{crystal}}{m}}$$

The amplifying effects of the resonance are shown in Figure 8 and are most pronounced at f_r. However, the resonator also amplifies the voltage at frequencies well below f_r. The frequency at which a 3 dB amplification occurs is influenced by the damping within the crystal and mounting system, but a good rule of thumb is approximately half the resonance frequency. The usable upper frequency is usually determined based on 5% or 10% signal amplification, as we'll discuss when exploring specification sheets later.

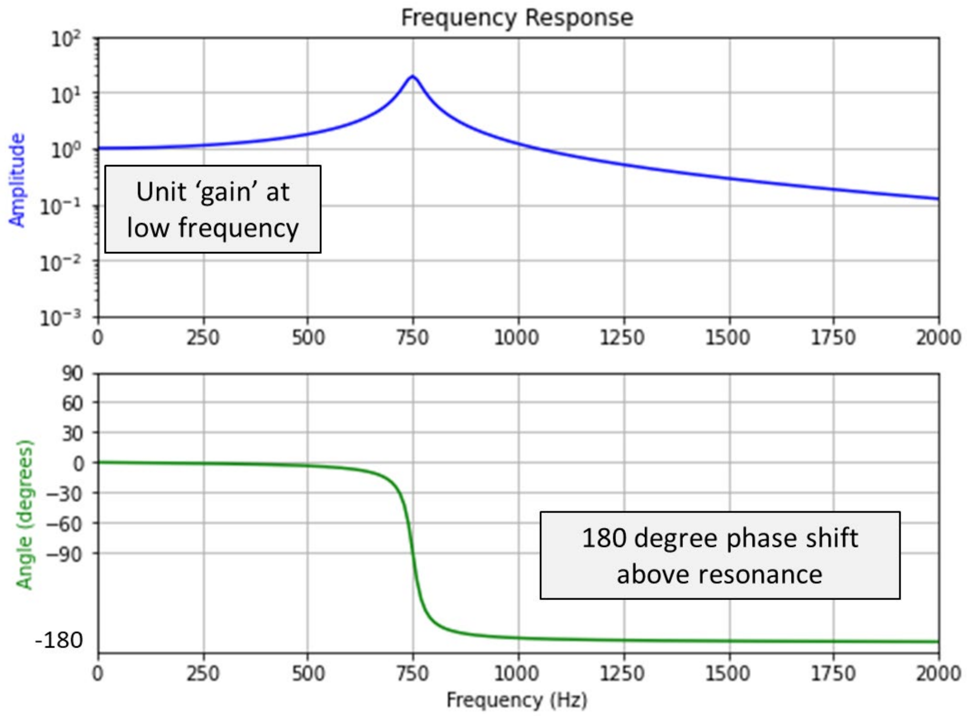
The resonator behaves like a second-order low-pass filter, where:

$$H(\omega) = \frac{1}{1 + \frac{i}{Q}\left(\frac{f}{f_r}\right) - \left(\frac{f}{f_r}\right)^2}$$

Here, Q represents the 'gain factor' of the resonator, which is essentially the inverse of the structural loss factor. Q is rarely reported for accelerometers but typical values range from 50 to 100. Figure 10 shows the filter frequency response in terms of both amplitude and phase. At low frequencies, there is a unit gain (essentially no effect), with amplification occurring at and around the resonance frequency. Above resonance, the signal also experiences a 180-degree shift in phase.

Another hypothetical signal, with broad-band noise and a tone (this time at 500 Hz), is processed with and without a low-pass resonator filter, as shown in Figure 11. Resonant amplification is evident in both the time and frequency plots, and behaves similarly to an accelerometer at its internal resonance frequency.

In practice, the resonance frequency of an accelerometer is also influenced by on how strongly it is mounted to a surface. The stiffest possible connection is achieved with a stud mount. Resonance frequencies of stud mounted accelerometers are quite close to the internal mass resonance frequencies. However, using softer mounting methods, such as adhesive or wax, leads to a more complex mechanical system. In such cases, the accelerometer behaves like a two-oscillator system; the internal mass and spring are connected to the housing mass, which is mounted to the DUT by the 'spring' induced by the adhesive. The lowest resonance frequencies of softly mounted accelerometers are lower than those of stud-mounted ones. Always examine the high frequency range of measured accelerometer signals to ensure resonant amplifications aren't occurring, particularly with adhesive or wax mounting.



Unit ‘gain’ at low frequency

180 degree phase shift above resonance

Figure 10. Second-order low-pass filter behavior.

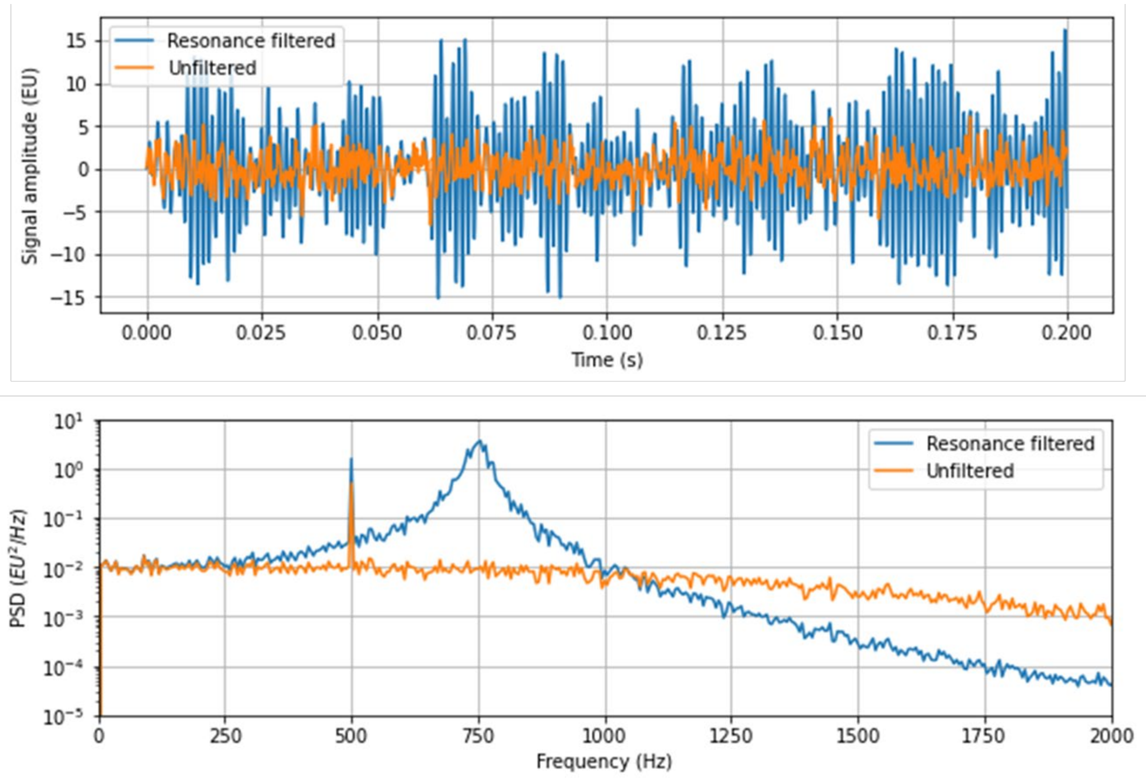


Figure 11. Effects of a high-pass resonator filter on a typical signal.

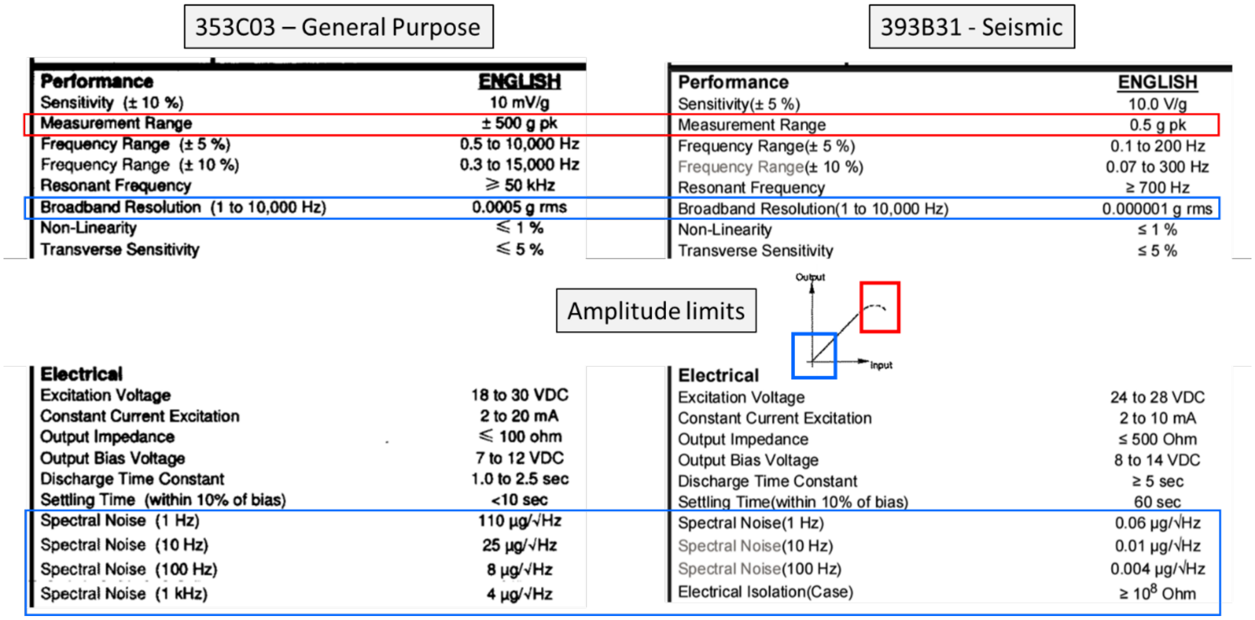
4 Staying Within Usable Ranges – Spec Sheets

The complicated behaviors that determine the usable linear ranges of accelerometers can be hard to keep track of. Fortunately, it's easy to stay within usable linear ranges by reviewing your accelerometer specification sheets. All the terms we've learned about are listed there, as shown in the examples in Figure 12 and Figure 13.

We compare the specifications for PCB 353C03 (general purpose) and 393B31 (seismic, high sensitivity) accelerometers. First, note the large difference in sensitivity – 10 mV/g versus 10 V/g (a factor of 100). This is due to the different amplifier parameters within the ICP circuitry, as well as the amount of moving mass within the accelerometers (more mass in the seismic accelerometer induces more fluctuating charge from the crystal).

Figure 12 highlights the parameters that determine the lower and upper limits of the amplitude range. Measurement range is just the +/- 5 V allowable range due to the power supply divided by the sensitivity (V/g). The seismic accelerometer can only measure a peak acceleration up to 0.5 g, whereas the general-purpose accelerometer can measure up to 500 g's. However, the lower amplitude limit of the seismic accelerometer is much smaller than that of the general-purpose accelerometer—1 μg rms versus 500 μg rms—allowing it to measure much smaller vibrations. The spec sheets also usually provide spectral lower limits (noise floors) at specific frequencies. Unsurprisingly, the seismic accelerometer has much lower noise floors than the general-purpose model.

The parameters that affect frequency limits are highlighted in Figure 13. The Discharge Time Constant (DTC) determines the lower frequency limit of the RC circuit. The higher the resistance, the lower the limit (remember, though, that a high resistance also elevates the low frequency noise floor). The seismic sensor has a significantly longer DTC, allowing it to measure low frequency behavior. The resonance frequency governs the upper boundary of the frequency range, typically around 20% of resonance for a 5% amplification limit. The heavier seismic sensor exhibits a much lower internal resonance frequency.



353C03 – General Purpose

Performance	ENGLISH
Sensitivity (± 10 %)	10 mV/g
Measurement Range	± 500 g pk
Frequency Range (± 5 %)	0.5 to 10,000 Hz
Frequency Range (± 10 %)	0.3 to 15,000 Hz
Resonant Frequency	⩾ 50 kHz
Broadband Resolution (1 to 10,000 Hz)	0.0005 g rms
Non-Linearity	⩽ 1 %
Transverse Sensitivity	⩽ 5 %

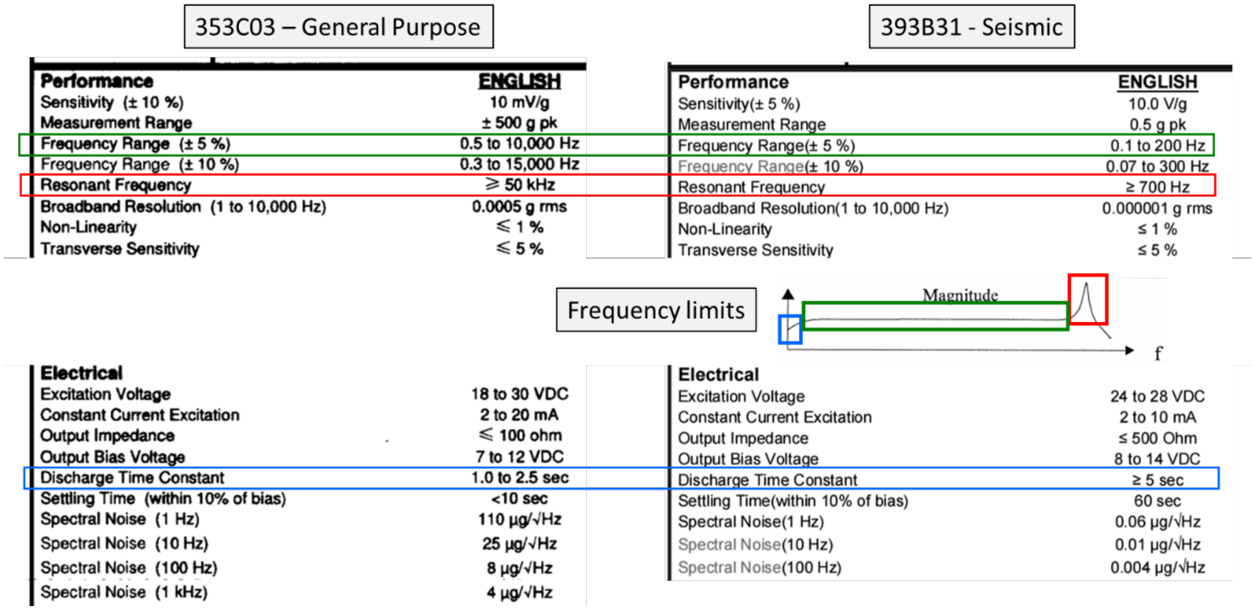
Electrical	
Excitation Voltage	18 to 30 VDC
Constant Current Excitation	2 to 20 mA
Output Impedance	⩽ 100 ohm
Output Bias Voltage	7 to 12 VDC
Discharge Time Constant	1.0 to 2.5 sec
Settling Time (within 10% of bias)	<10 sec
Spectral Noise (1 Hz)	110 µg/√Hz
Spectral Noise (10 Hz)	25 µg/√Hz
Spectral Noise (100 Hz)	8 µg/√Hz
Spectral Noise (1 kHz)	4 µg/√Hz

393B31 - Seismic

Performance	ENGLISH
Sensitivity(± 5 %)	10.0 V/g
Measurement Range	0.5 g pk
Frequency Range(± 5 %)	0.1 to 200 Hz
Frequency Range(± 10 %)	0.07 to 300 Hz
Resonant Frequency	≥ 700 Hz
Broadband Resolution(1 to 10,000 Hz)	0.000001 g rms
Non-Linearity	≤ 1 %
Transverse Sensitivity	≤ 5 %

Electrical	
Excitation Voltage	24 to 28 VDC
Constant Current Excitation	2 to 10 mA
Output Impedance	≤ 500 Ohm
Output Bias Voltage	8 to 14 VDC
Discharge Time Constant	≥ 5 sec
Settling Time(within 10% of bias)	60 sec
Spectral Noise(1 Hz)	0.06 µg/√Hz
Spectral Noise(10 Hz)	0.01 µg/√Hz
Spectral Noise(100 Hz)	0.004 µg/√Hz
Electrical Isolation(Case)	≥ 10^8 Ohm

Figure 12. Spec sheet parameters which determine lower and upper amplitude limits.



353C03 – General Purpose

Performance	ENGLISH
Sensitivity (± 10 %)	10 mV/g
Measurement Range	± 500 g pk
Frequency Range (± 5 %)	0.5 to 10,000 Hz
Frequency Range (± 10 %)	0.3 to 15,000 Hz
Resonant Frequency	⩾ 50 kHz
Broadband Resolution (1 to 10,000 Hz)	0.0005 g rms
Non-Linearity	⩽ 1 %
Transverse Sensitivity	⩽ 5 %

Electrical	
Excitation Voltage	18 to 30 VDC
Constant Current Excitation	2 to 20 mA
Output Impedance	⩽ 100 ohm
Output Bias Voltage	7 to 12 VDC
Discharge Time Constant	1.0 to 2.5 sec
Settling Time (within 10% of bias)	<10 sec
Spectral Noise (1 Hz)	110 µg/√Hz
Spectral Noise (10 Hz)	25 µg/√Hz
Spectral Noise (100 Hz)	8 µg/√Hz
Spectral Noise (1 kHz)	4 µg/√Hz

393B31 - Seismic

Performance	ENGLISH
Sensitivity(± 5 %)	10.0 V/g
Measurement Range	0.5 g pk
Frequency Range(± 5 %)	0.1 to 200 Hz
Frequency Range(± 10 %)	0.07 to 300 Hz
Resonant Frequency	≥ 700 Hz
Broadband Resolution(1 to 10,000 Hz)	0.000001 g rms
Non-Linearity	≤ 1 %
Transverse Sensitivity	≤ 5 %

Electrical	
Excitation Voltage	24 to 28 VDC
Constant Current Excitation	2 to 10 mA
Output Impedance	≤ 500 Ohm
Output Bias Voltage	8 to 14 VDC
Discharge Time Constant	≥ 5 sec
Settling Time(within 10% of bias)	60 sec
Spectral Noise(1 Hz)	0.06 µg/√Hz
Spectral Noise(10 Hz)	0.01 µg/√Hz
Spectral Noise(100 Hz)	0.004 µg/√Hz

Figure 13. Spec sheet parameters which determine upper and lower frequency limits.

5 Summary

Powered ICP accelerometers are complex electromechanical systems comprised of:

1. A spring-mass oscillator to generate fluctuating charge
2. A simple RC circuit to convert charge to voltage and increase the discharge time of the crystal
3. An amplifier to set the sensitivity (number of Volts/g)
4. A constant current power supply using a typical voltage range of 18-30 VDC

These mechanical and electrical parameters effectively set lower and upper ranges on linear accelerometer response in amplitude and time (frequency). The RC circuit establishes the lower limit on both amplitude and frequency. Increasing the resistance results in higher low-frequency background noise and wider broad-band resolution (the smallest signal you can measure). Conversely, reducing the resistance raises the lower frequency limit, limiting how low in frequency you can measure. Therefore, the specified resistance in an accelerometer represents a tradeoff between background noise and the cutoff frequency of the high-pass filtering of the ICP RC circuit. The amplifier and the power supply voltage range determine the upper limits on amplitude, typically allowing for +/- 5 V before 'clipping' can occur. Finally, the oscillating mass and the preloaded crystal determine the resonance frequency and, consequently, the upper frequency limit at which the signals are amplified significantly.

Violating these limits can result in the following signal processing effects:

1. Clipping and signal attenuation (high amplitudes exceeding +/- 5 V)
2. Unmeasurable signals (low amplitudes below the noise floor at low frequencies)
3. Attenuation from the high-pass filter at low frequencies
4. Amplification from the internal resonance at high frequencies

Note that the concepts discussed here are also applicable to other ICP sensors, such as microphones and force cells. While these sensors have slightly different mechanical arrangements and ICP circuitry than accelerometers, they still have usable linear amplitude and frequency ranges. Check your spec sheets for details.

6 Additional PCB References

Most of the figures and explanations in this white paper are sourced from the PCB publications, which can be downloaded from their website. These references include:

- Vibration Fundamentals
- General Signal Conditioning Guide: An Introduction to the Operation of ICP® and Charge Output Sensors and Instrumentation

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