



Tutorial on signal processing impacts of ICP® Accelerometer Limit Violations

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ABSTRACT

Accelerometers with embedded Integrated Circuit Piezoelectric (ICP) circuitry are complex electro-mechanical systems. Vibrating internal masses induce fluctuating electric charges in surrounding piezoelectric crystals. The ICP circuitry converts the charges to voltages and amplifies them before passing them on to your data acquisition system (DAQ). The sensors have remarkably wide ranges of linear response (a constant voltage/acceleration ratio) but do have usable limits. Amplitude limits, both low and high, depend on the electronic components – the circuitry as well as the constant current power supply. Frequency limits depend on the ICP circuitry (lower) and the fundamental internal resonance of the sensor (upper). Violating these limits causes undesirable behavior in your signal processing. We'll examine all these issues and show you how to use your accelerometer specification sheets to ensure you are staying within allowable limits.

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, any sensor has limits and violating those allowable limits can lead to attenuated, amplified, and even clipped signals. This paper explains:

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

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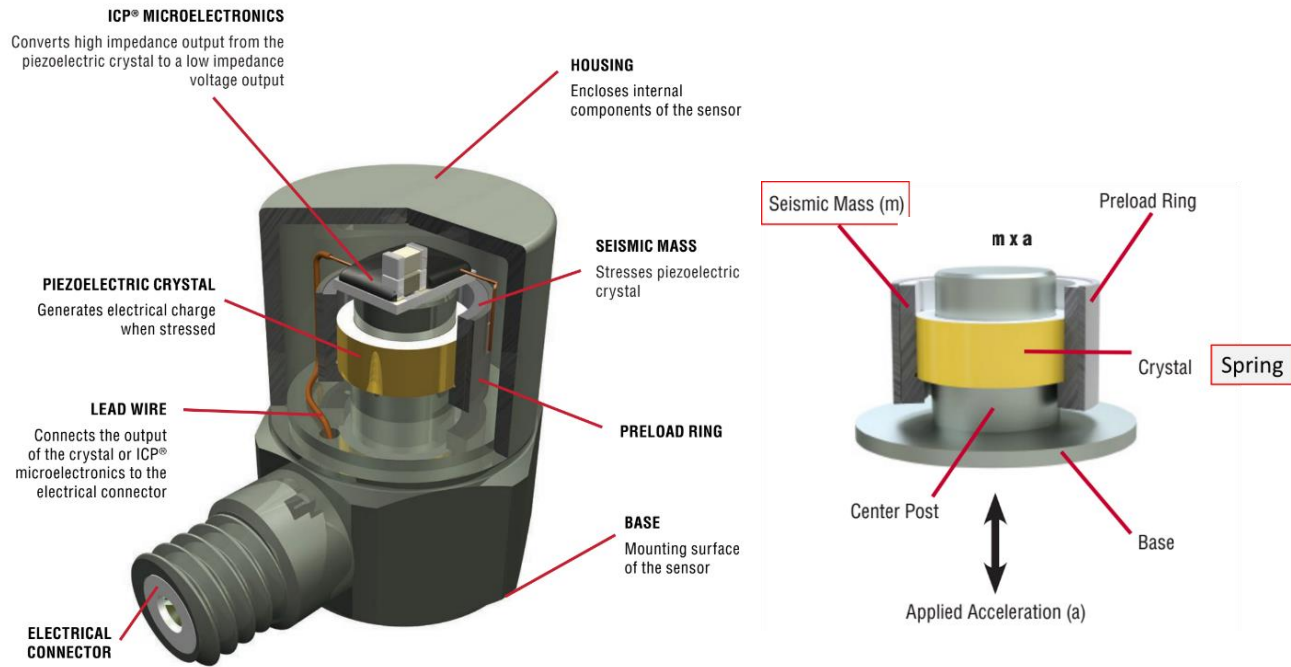


Figure 1: Typical PCB ICP Accelerometer.

2. HOW AN ICP ACCELEROMETER WORKS

A typical PCB ICP-powered accelerometer is shown in the left side of Figure 1 along with the internal seismic mass and crystal on the right. The crystal is compressed between the mass and the center post and is effectively a simple annular spring supporting the mass – a spring-mass oscillator. As 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 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.

Embedding ICP circuitry within the sensor converts the small fluctuating charge into a large fluctuating voltage which loses very little amplitude along the cable and is rarely corrupted by background EM noise. Figure 2 shows how the ICP circuitry works:

- (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 capacitor is easy to understand but let's explore the functions of the resistor and amplifier a little more. The charge generated by the crystal decays quickly over time - so quickly that a low-frequency disturbance from the DUT may not be represented properly. Figure 3 shows how an ideal step signal would be measured by a mass-crystal-capacitor system. The initial impulse would be captured well, 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 DTC so that low-frequency signals can be accurately measured (more on this later).

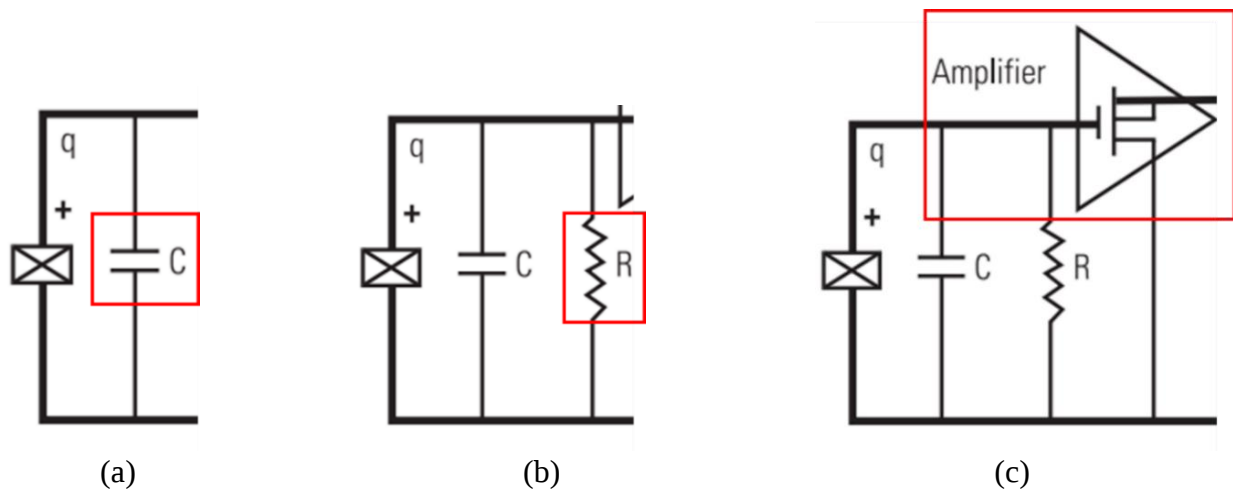


Figure 2: ICP Components: (a) Capacitor converts fluctuating charge to fluctuating voltage, (b) Resistor increases discharge time, (c) amplifier boosts voltage levels before sending to data acquisition system.

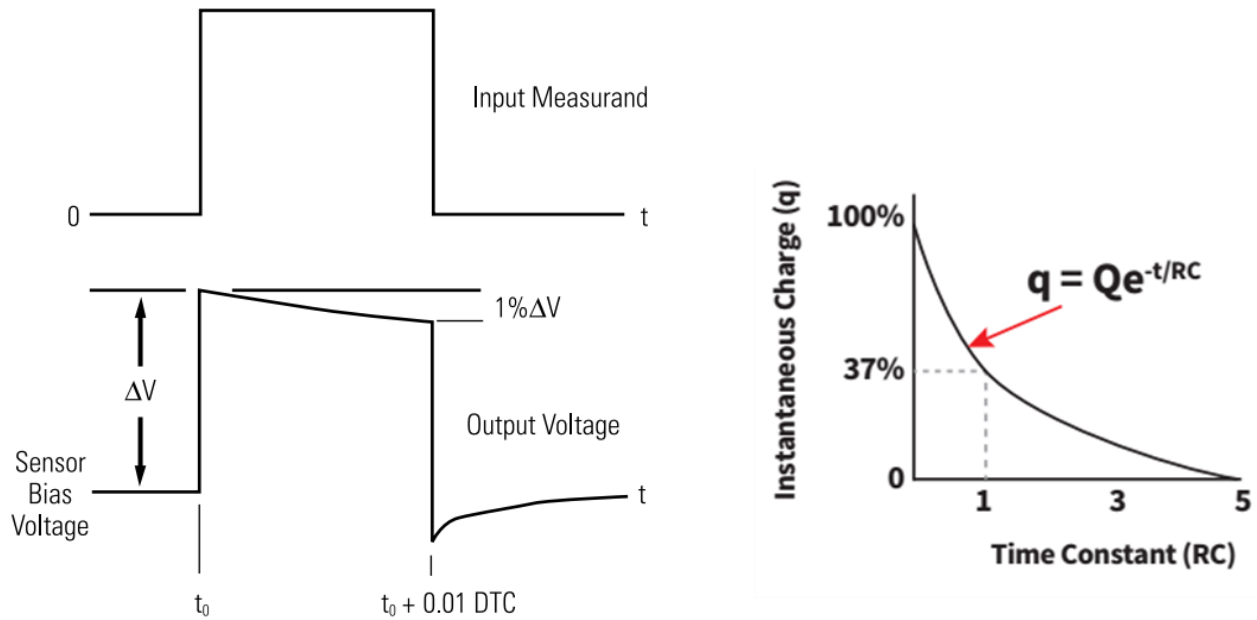


Figure 3: Decay of an electric signal from a crystal/Capacitor circuit. $\text{DTC} = RC$.

The amplifier type is chosen based on the crystal, usually Field Effect Transistors (FET). Piezoceramic-based sensors work well with Junction FET (JFET) charge amplifiers. 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 set the amplification factor and therefore the final sensitivity of a sensor (Volts/g).

To measure signals the accelerometer must be powered, as shown 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 – more on this soon.

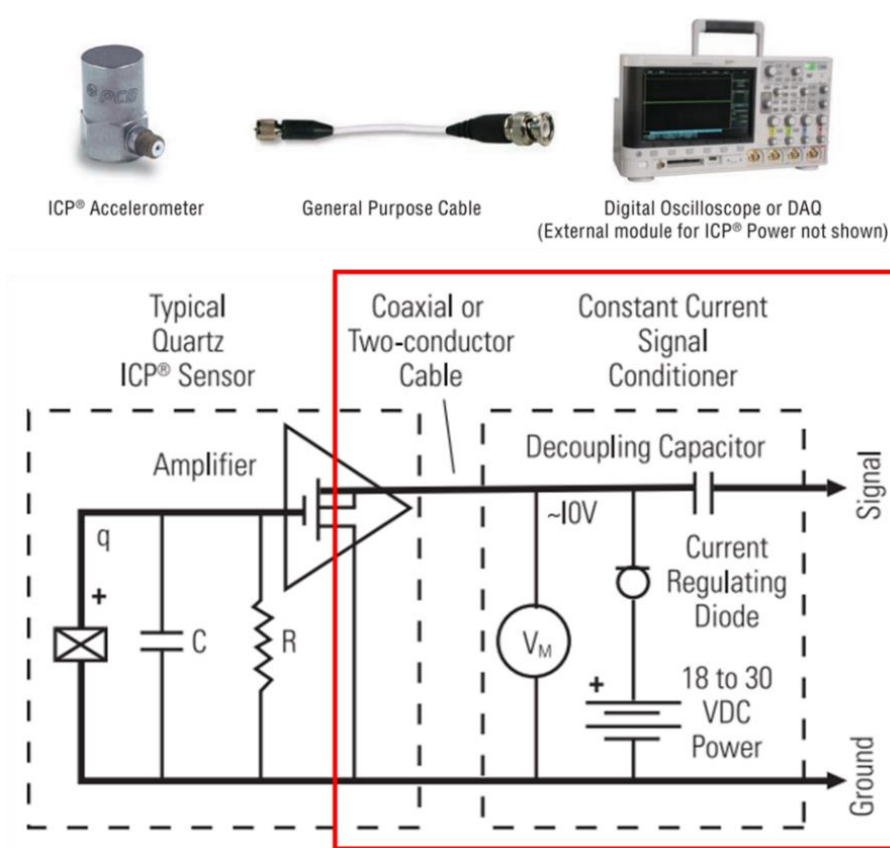


Figure 4. Constant current DC power supply.

3. USABLE LINEAR RANGES

The three main components of a sensor – the 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. By linear we mean that a constant voltage per unit acceleration level g (sensitivity) is measured over a range of amplitudes (low to high) and frequencies (also low to high).

3.1. Amplitude Limits

3.1.1. Upper Limit – Power Supply Voltage Range

Recall that ICP sensors are powered by a constant current source with an 18-30 VDC range. The sensor voltages fluctuate above and below a mean, or *bias voltage*. The fluctuations need to remain within the bounds of the voltage source to be properly measured. A sinusoidal voltage signal that exceeds allowable ranges is shown in Figure 5. The original signal fluctuates about the bias voltage (10 V in the figure). Violating the lower limit attenuates the signal slightly. Violating the upper limit can ‘clip’ the signal, effectively capping it at the upper voltage limit. To avoid clipping most accelerometers are limited to a ± 5 V range.

Clipping effects on processed signals are shown in Figure 6. A notional 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 clipping effects are clearer in the zoomed 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.

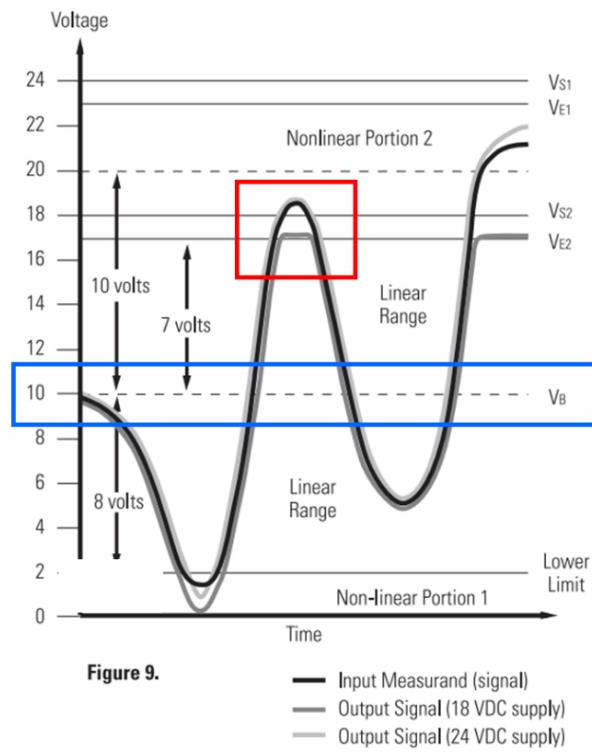


Figure 5. Sinusoidal signal which exceeds allowable voltage range.

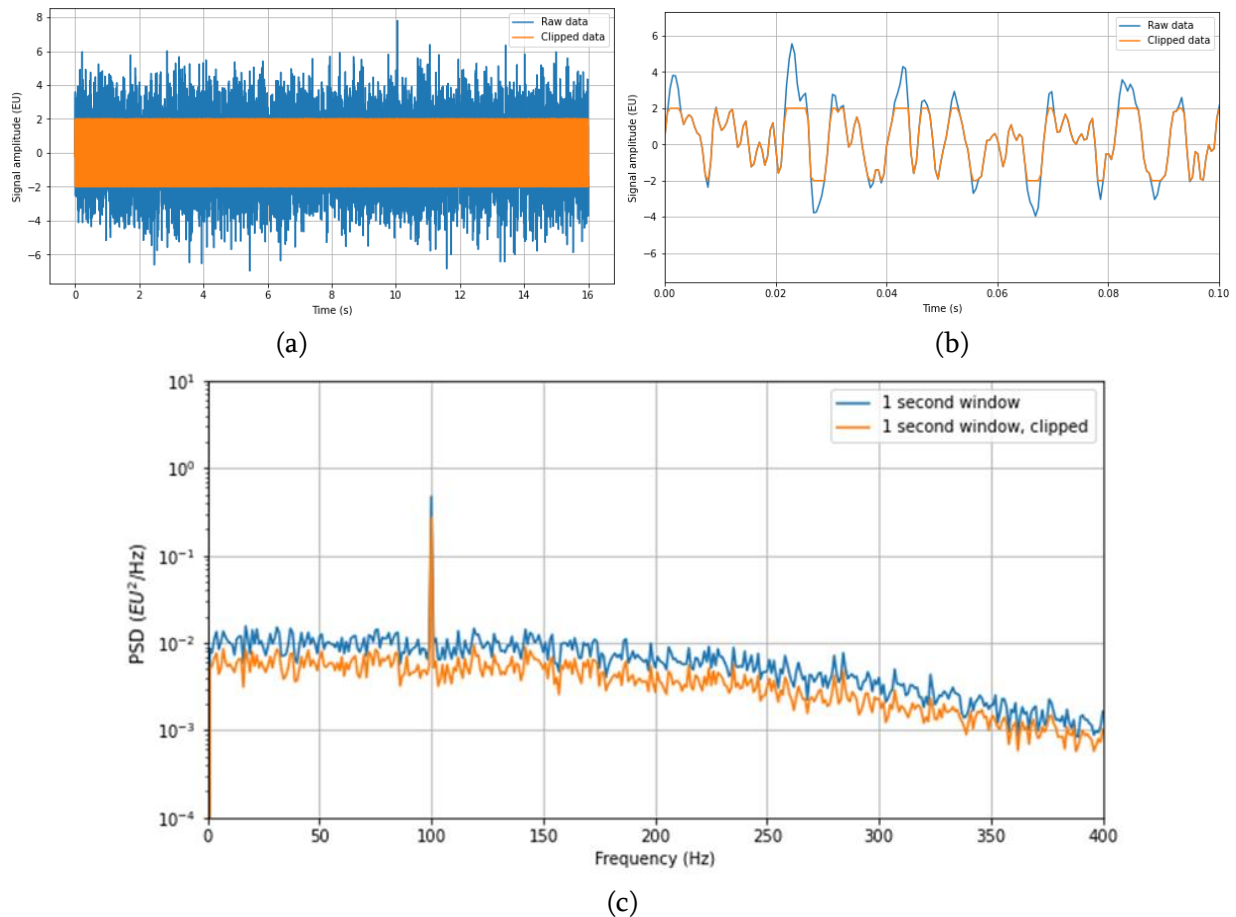


Figure 6. Example of clipping effects: Top – time histories; Bottom – Resulting PSDs.

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. Voltages induced by a vibrating DUT must exceed these values to be measurable.

To better understand this limit we need 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’ there are two distinct frequency ranges. At very low frequencies the background noise is caused by random fluctuations in the resistor, usually due to thermal effects. The noise is proportional to R/f (resistance/frequency) and worsens at lower frequencies. At higher frequencies the background noise is due to the amplifier (FET). The overall broad-band resolution is simply the integration of the spectrum over frequency (being sure to capture signals at low frequencies where the bulk of the noise occurs).

Therefore the question of ‘how low can you go’ with a measurement depends on frequency. Using only the total broad-band resolution as a guide may lead you to believe that some measurable signals cannot be properly measured. However, if your important signals are above the low-frequency resistor-induced background noise, the actual lowest measurable signals may be much smaller. All sensors differ so careful background noise measurements are crucial.

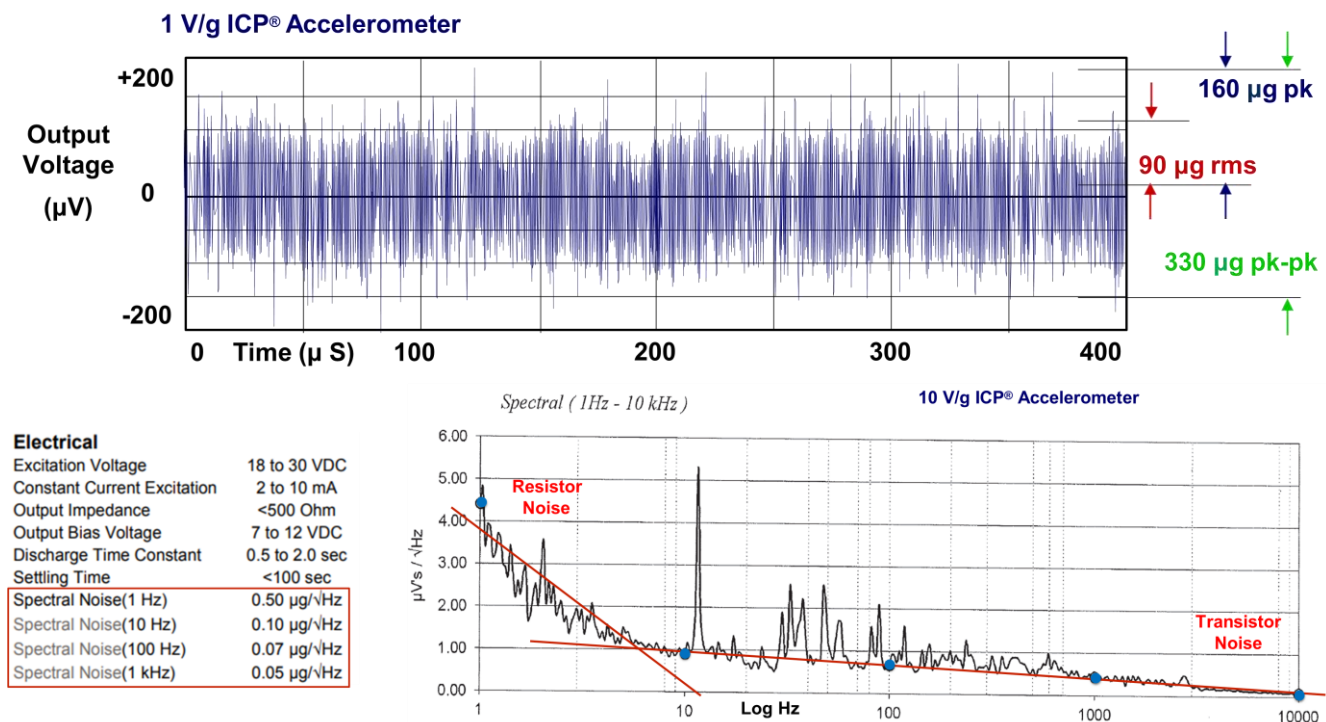


Figure 7. Examples of lower amplitude limits. Top – broad-band resolution from time history analysis of a 1V/g accelerometer; Bottom – Frequency-dependent noise floor in a 10 V/g accelerometer (the low frequency electrical tone is not associated with the accelerometer)

3.2. Frequency Limits

3.2.1. Lower Limit – Discharge Time Constant (DTC)

A common question about low-frequency background noise is why not simply reduce the resistance in the RC circuit to reduce the noise? The answer is that the RC circuit does something else which affects our limits – it acts as a high-pass filter with a low cutoff frequency as shown in Figure 8. Decreasing R shifts the high-pass filter upward in frequency reducing our usable frequency range. To see why let's examine the voltage transfer function $H(\omega)$ for the simple RC circuit within the ICP:

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

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 that:

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

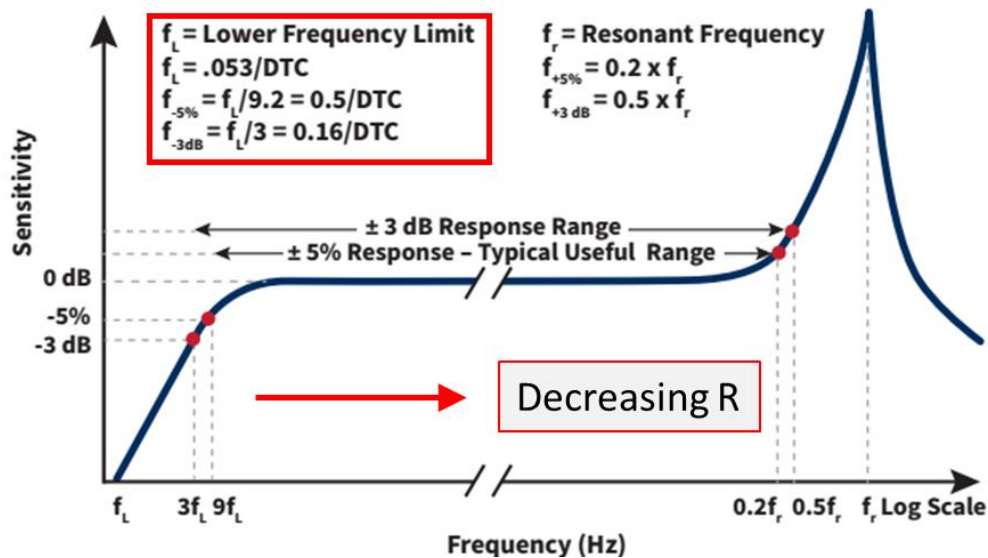


Figure 8. Relationships between RC-circuit, DTC, and lower frequency limits.

Figure 9 shows the amplitude and phase behavior of this simple 1st order high-pass filter. Note that frequency on the amplitude plot is shown on a log scale to better show 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, slowly increasing with decreasing frequency to a limit of 90 degrees.

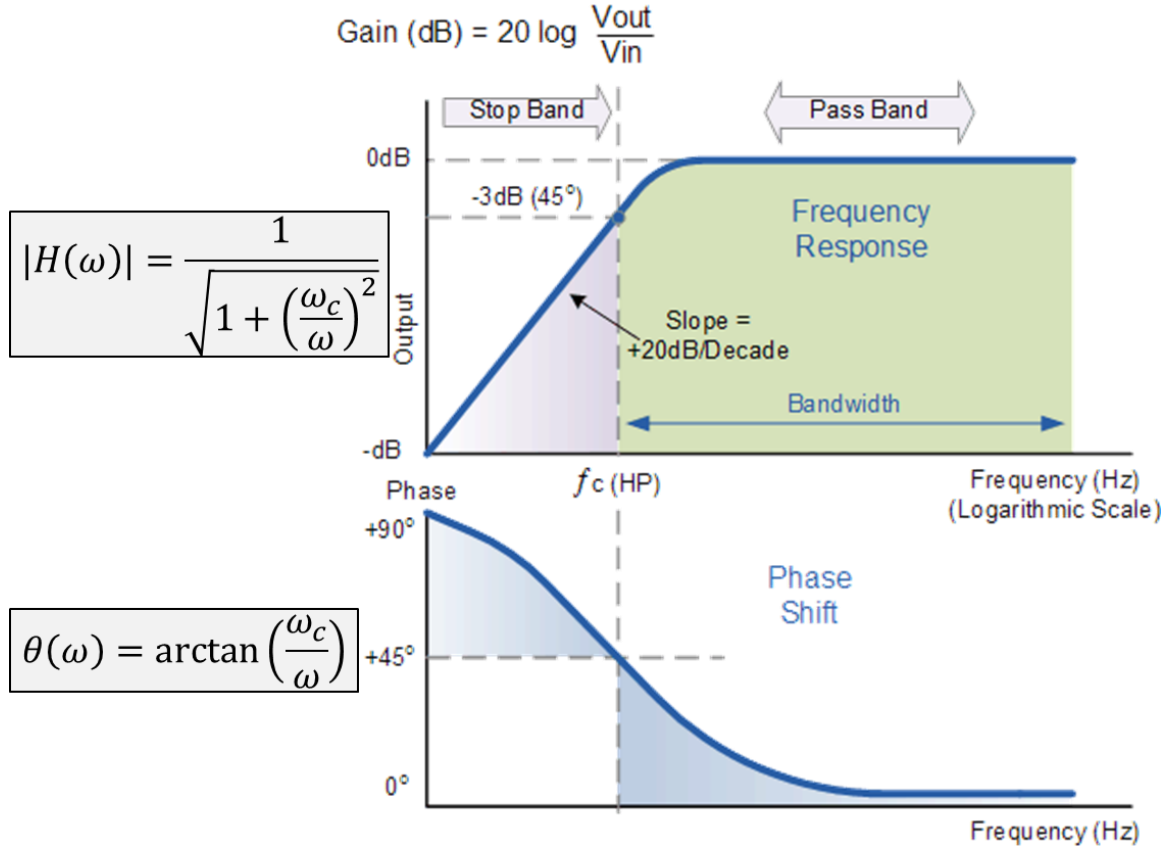


Figure 9. First-order high-pass filter behavior (from *Electronics Tutorials* online).

3.2.2. Upper Limit – Accelerometer Moving Mass Resonance

While the lower frequency limit depends 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 which has a characteristic stiffness. Therefore, the mass-crystal combination is a simple harmonic oscillator which has 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 for 3 dB amplification depends on the damping within the crystal and mounting system, but a good rule of thumb is about half the resonance frequency. The usable upper frequency is usually set based on 5% or 10% signal amplification as we'll see when we discuss specification sheets later.

The resonator behaves like a 2nd order low-pass filter where:

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

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

Another notional 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 clear in both the time and frequency plots and similar to the behavior of an accelerometer at its internal resonance frequency.

In practice the resonance frequency of an accelerometer depends also on how strongly it is mounted to a surface. The stiffest possible connection is with a stud mount. Stud mounted accelerometer resonance frequencies 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 these cases the accelerometer behaves like a two-oscillator system – with the internal mass and spring 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.

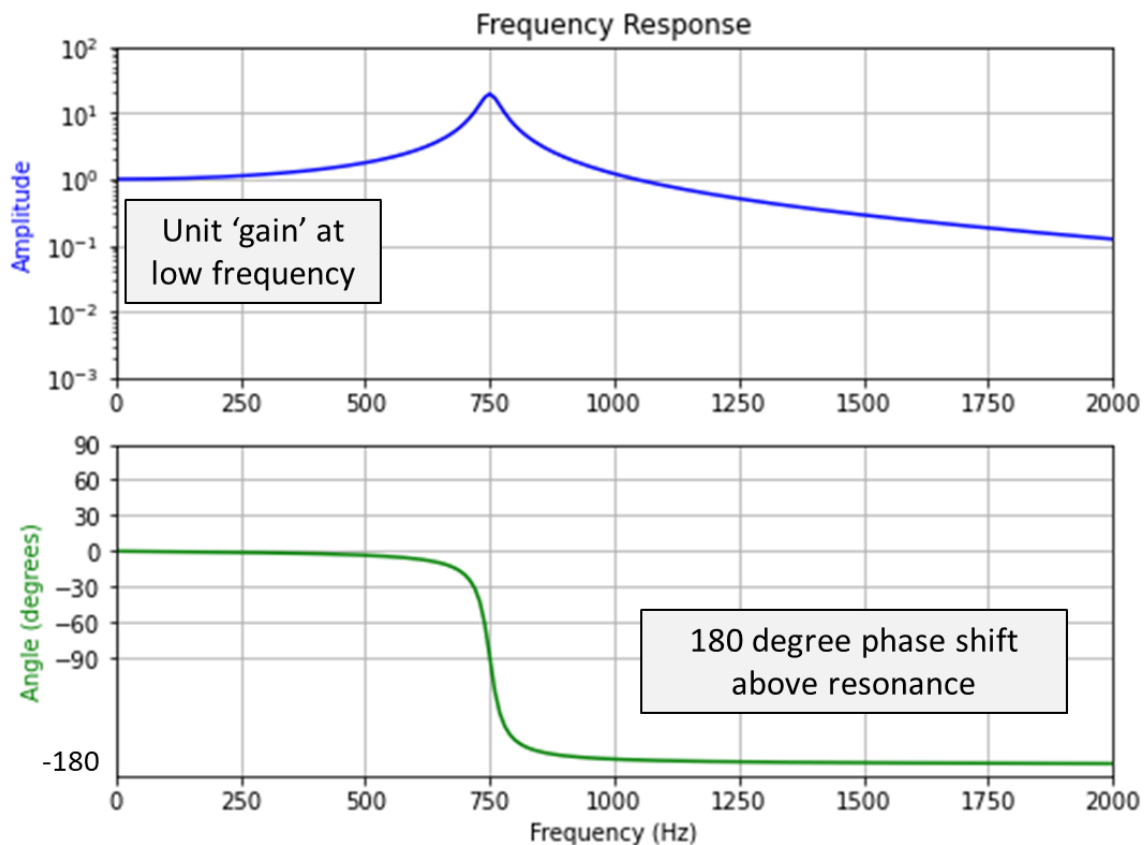


Figure 10. Example of 2nd order low-pass filter behavior.

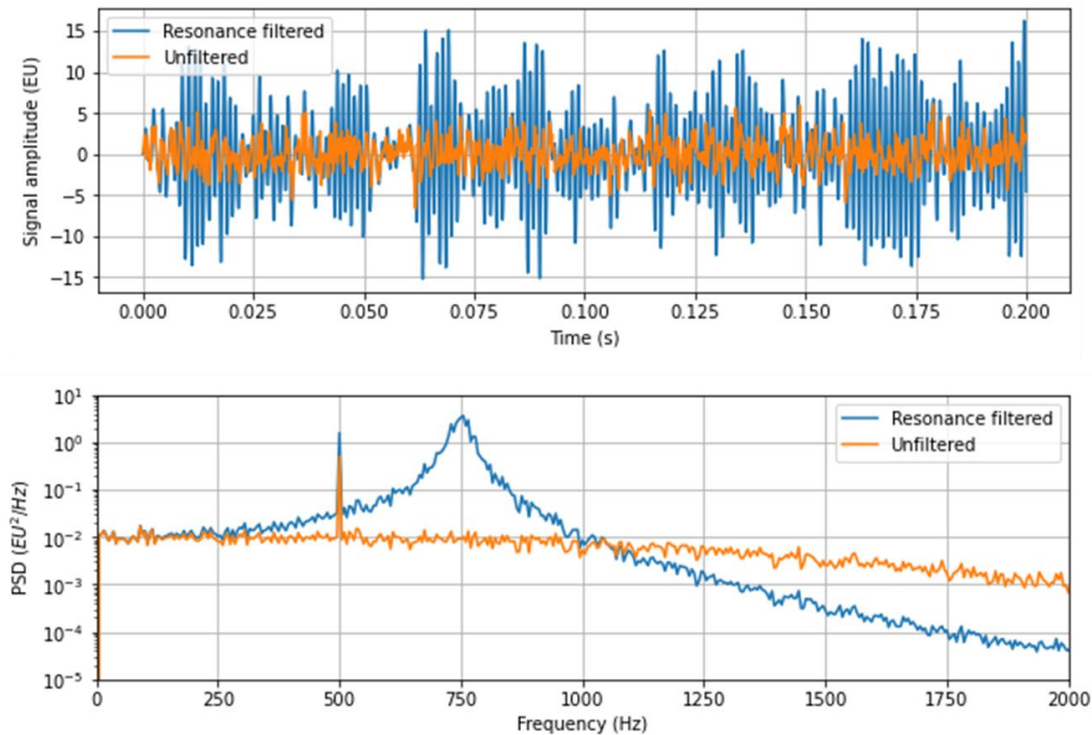


Figure 11. Effects of a high-pass resonator filter on a typical signal.

4. STAYING WITHIN USABLE RANGES – SPEC SHEETS

We've examined some complicated behavior which determines the usable linear ranges of accelerometers and it can be hard to keep track of. Fortunately staying within usable linear ranges is easy when examining 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 vs 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 which dictate the lower and upper limits of the *amplitude range*. The measurement range in g's 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 vs. 500 μ g rms – so tiny vibrations may be measured. The spec sheets also usually provide spectral lower limits (noise floors) at specific frequencies (recall Figure 7). Not surprisingly the seismic accelerometer has much lower noise floors than the general-purpose model.

Parameters which 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 (recall however that a high resistance also raises the low frequency noise floor). The DTC of the seismic sensor is much longer so that very low frequency behavior can be measured. The resonance frequency dictates the upper limit of the frequency range, which is generally about 20% of resonance for a 5% amplification limit. The heavier seismic sensor has a much lower internal resonance frequency.

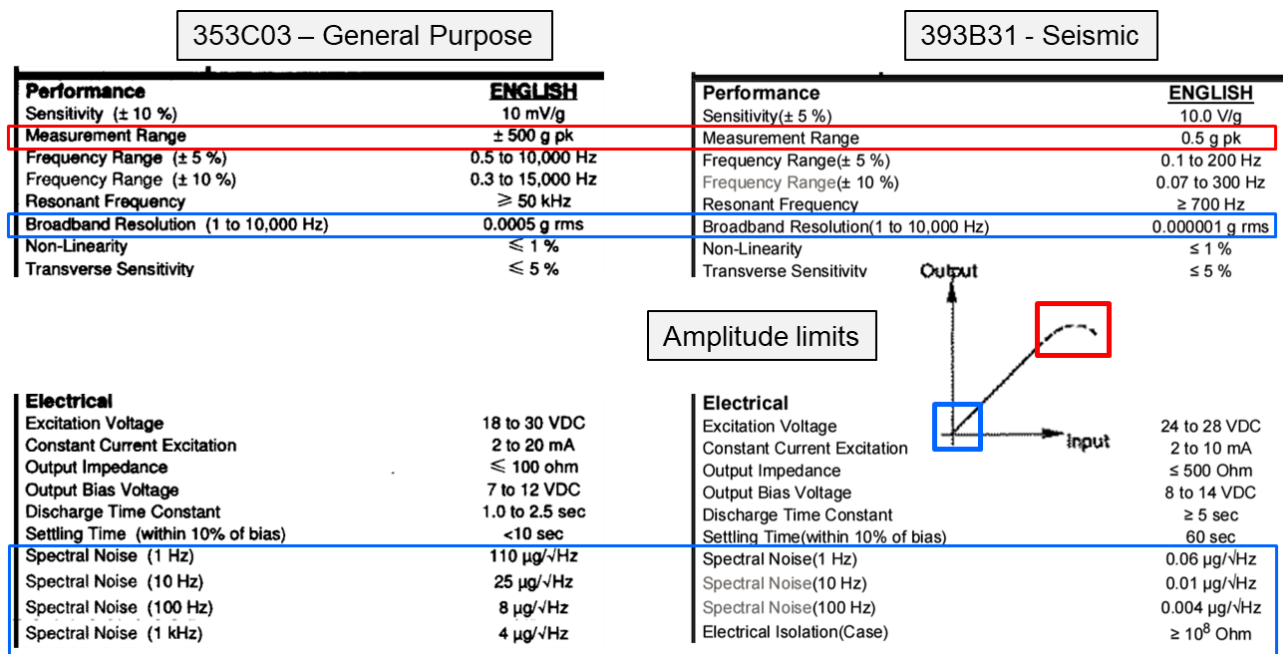


Figure 12. Spec sheet parameters which determine lower and upper amplitude limits.

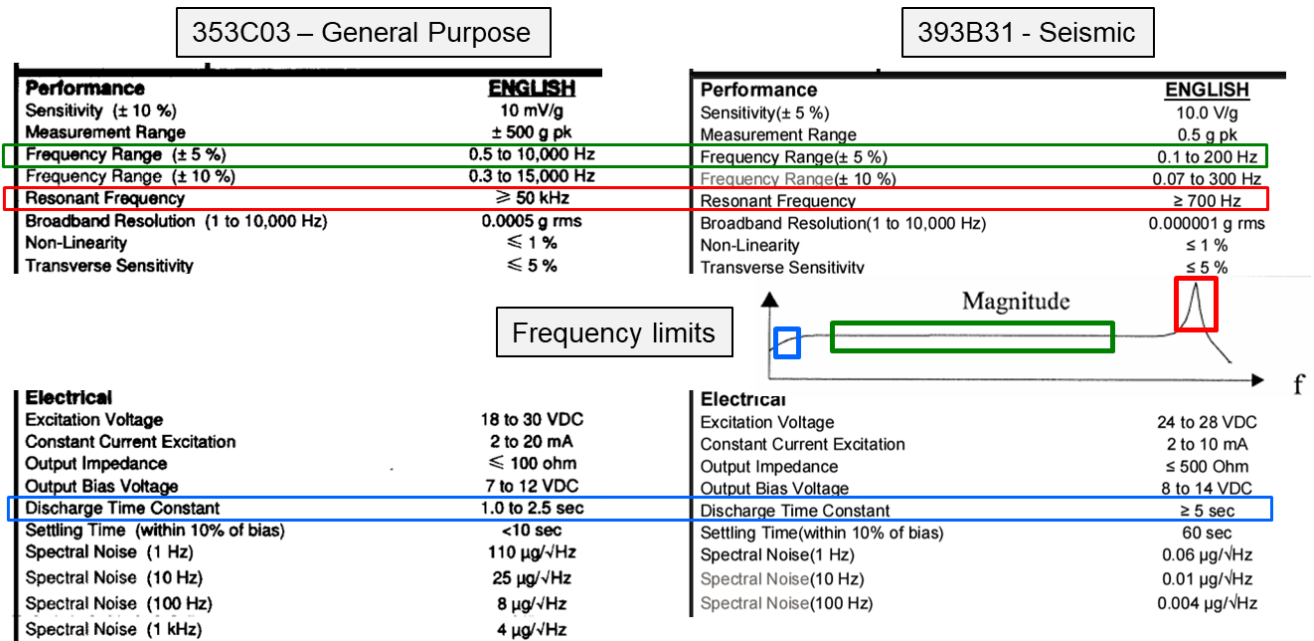


Figure 13. Spec sheet parameters which determine upper and lower frequency limits.

5. CONCLUSIONS

Powered ICP accelerometers are complex electromechanical systems comprised of

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

The mechanical and electrical parameters effectively set lower and upper ranges on linear accelerometer response in amplitude and time (frequency). The RC circuit sets the lower limit on both amplitude and frequency. The higher the resistance, the higher the low-frequency background noise and therefore the broad-band resolution (the smallest signal you can measure). The lower the resistance, the higher the lower frequency limit, limiting how low in frequency you can measure. Therefore, the resistance specified in an accelerometer is 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, with +/- 5 V usually allowable before 'clipping' can occur. Finally, the oscillating mass and the preloaded crystal determine the resonance frequency and therefore the upper frequency limit at which the signals are amplified significantly.

Violating these limits can lead to the following signal processing effects:

- Clipping and signal attenuation (high amplitudes exceeding +/- 5 V)
- Unmeasurable signals (low amplitudes below the noise floor at low frequencies)
- Attenuation from the high-pass filter of the RC circuit at low frequencies
- Amplification from the sensor internal resonance at high frequencies

REFERENCES

Most of the figures in this paper, as well as the explanations, come from the PCB publications (downloadable from www.pcb.com):

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

You can also find many other downloadable tutorials on vibrations and sound at www.hambricacoustics.com