TN-24

# Selecting Accelerometers for and Assessing Data From Mechanical Shock Measurements

Written By

Patrick L. Walter, Ph. D.

# Selecting Accelerometers for and Assessing Data from Mechanical Shock Measurements

**Patrick L. Walter, Ph. D.**

**Measurement Specialist/PCB Piezotronics, Inc.**
**Depew, NY 14043**

**Engineering Faculty/Texas Christian University**
**Fort Worth, TX 76129**

After first clarifying what mechanical shock is and why we measure it, basic requirements are provided for all measurement systems that process transient signals. High- and low-frequency dynamic models for the measuring accelerometer are presented and justified. These models are then used to investigate accelerometer responses to mechanical shock. The results enable "rules of thumb" to be developed for shock data assessment and proper accelerometer selection. Other helpful considerations for measuring mechanical shock are also provided.

**Mechanical Shock:** The definition of mechanical shock is, "a nonperiodic excitation of a mechanical system, that is characterized by suddenness and severity, and usually causes significant relative displacements in the system."[1] The definition of suddenness and severity is dependent upon the system encountering the shock. For example, if the human body is considered a mechanical system, a shock pulse of duration of 0.2 seconds into the feet of a vertical human, due to impact resulting from a leap or a jump, would be sudden. This is because vertical humans typically have a resonant frequency of about 4 Hz. The amplitude of the shock would further characterize its severity. By contrast, for most engineering components, this same shock would be neither sudden nor severe.

The effects of mechanical shock are so important that the International Organization for Standardization (ISO) has a standing committee, TC 108, dealing with shock and vibration; a Shock and Vibration Handbook[1] has been published and routinely updated by *The McGraw-Hill Companies* since 1961; and the U.S. Department of Defense has sponsored a focused symposium on this subject at least annually since 1947.[2] Figure 1 provides several examples of components or systems experiencing mechanical shock.

Package Drop | Projectile Firing | Train/Truck Crash

**FIGURE 1:** *Examples of Mechanical Shock*

Mechanical shock can be specified in either the time, and/or frequency domains, or by its associated shock-response spectrum.[3] Figure 2 is an example of a shock pulse specified in the time domain. This pulse is used as an input to test sleds, to enable qualification of head and neck constraint systems for National Association for Stock Car Auto Racing (NASCAR) crashes.[4] Its duration of approximately 63 msec. produces 68 g's at 43.5 mph.

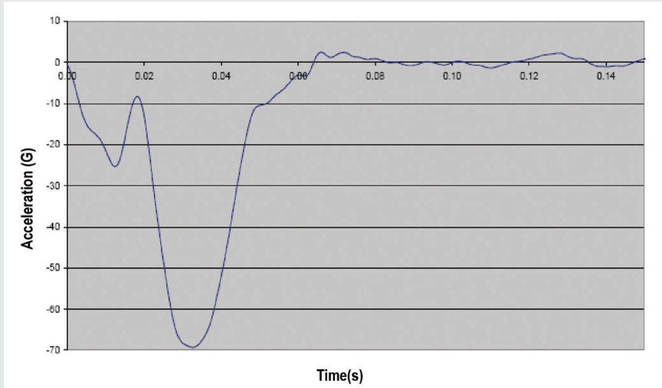


**FIGURE 2:** *Shock Time History Used in* NASCAR *Testing*

Figure 3 on the following page shows an example of a mechanical shock described by its amplitude in the frequency domain. This representation is particularly useful in linear analysis, when system transfer function is of interest (e.g., mechanical impedance, mobility and transmissibility). It provides knowledge of input-excitation frequencies to the mechanical system being characterized.

Figure 4 is an example of a shock-response spectrum. The shock response spectrum (SRS) is one method to enable the shock input to a system or component to be described, in terms of its damage potential. It is very useful in generating test specifications.

*Obviously, accurate measurement of mechanical shock is a subject of great importance to designers.*

**Measurement System Requirements:** There are a number of general measurement requirements that must be dealt with in measuring any transient signal that has an important time-history. The more significant of these requirements are listed below:

1. The frequency response of a measuring system must have flat amplitude-response and linear phase-shift over its response range of interest.[5]

2. The data sampling rate must be at least twice the highest data frequency of interest.
    a. Properly selected data filters must constrain data signal content, so that data doesn't exceed this highest frequency.
    b. If significant high frequency content is present in the signal, and its time history is of interest, data sampling should occur at 10 times this highest frequency.
3. The data must be validated to have an adequate signal-to-noise ratio.[6,7,8]

It is assumed that the test engineer has satisfied the aforementioned requirements, so that this paper may focus on accelerometer selection.

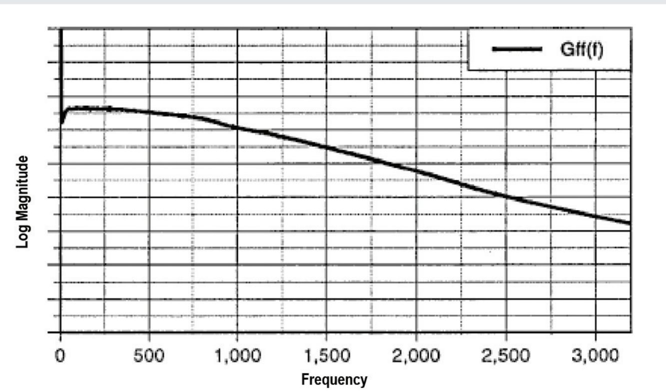


**FIGURE 3:** *Frequency Spectrum of a Shock Used to Excite a Structure*

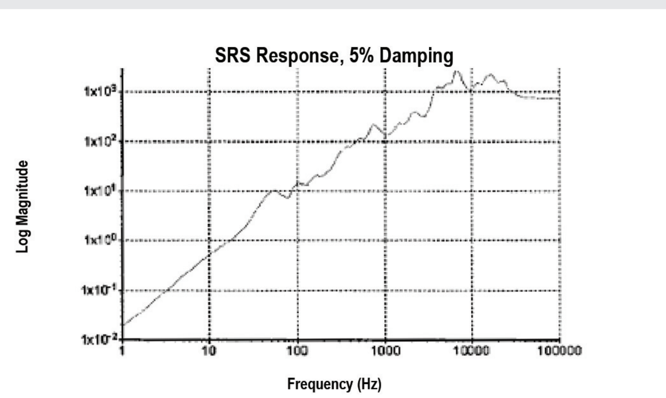


**FIGURE 4:** *Shock Response Spectrum of Acceleration Pulses Due to Gun Fire*

**Accelerometer Mechanical and Electrical Models:** Two types of accelerometer sensing technologies used for mechanical shock measurements are piezoelectric and piezoresistive. Piezoelectric accelerometers contain elements that are subjected to strain under acceleration-induced loads. This strain displaces electrical charges within the elements and charges accumulate on opposing electroded surfaces. A majority of modern piezoelectric accelerometers have integral signal-conditioning electronics (ICP® or IEPE), although such "on-board" signal conditioning is not mandated. When measuring mechanical shock, ICP® signal conditioning enhances the measurement system's signal-to-noise ratio.

Today, the term "piezoresistive" implies that an accelerometer's sensing flexure is manufactured from silicon, as a microelectro mechanical system (MEMS). MEMS shock accelerometers typically provide an electrical output due to resistance changes produced by acceleration-induced strain of doped semiconductor elements in a seismic flexure. These doped semiconductor elements are electrically configured into a Wheatstone bridge. Both of these preceding technologies will be discussed further in a subsequent section of this paper.

Accelerometers themselves are mechanical structures. They have multiple mechanical resonances[9] associated with their seismic flexure, external housing, connector and more. If accelerometer structures are properly designed and mounted, their response at high frequencies becomes limited by the lowest mechanical resonance of their seismic flexure. Because of this limiting effect, accelerometer frequency response can be specified as if it has a single resonant frequency. Figure 5 pictorially shows a mechanical flexure in a piezoresistive accelerometer. Figure 6 on the following page shows a piezoelectric accelerometer cut away. In Figure 6, the annular piezoelectric crystal acts as a shear spring with its concentric outer mass shown. Thus a simple, spring-mass dynamic model for an accelerometer is typically provided as shown in Figure 7.

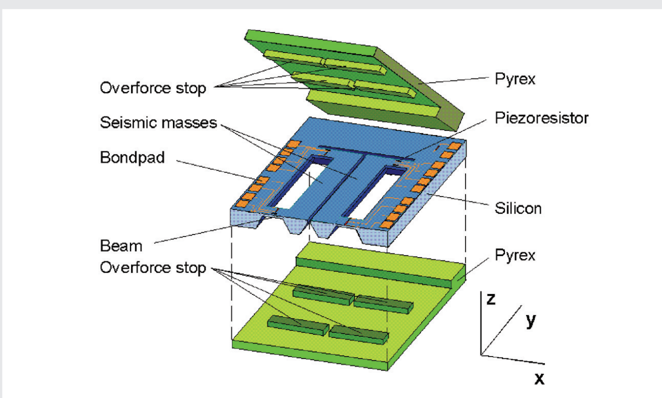


**FIGURE 5:** *Mechanical Flexure for a MEMS Accelerometer*

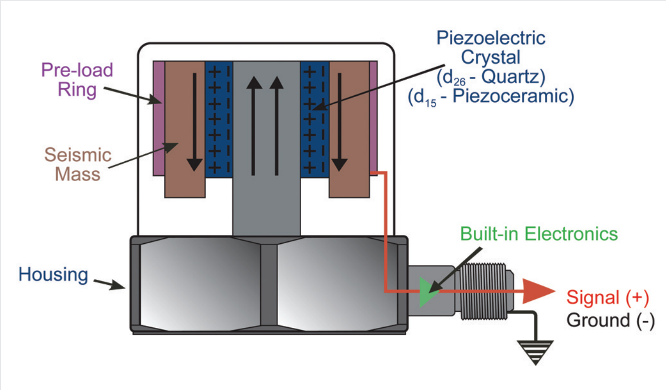


**FIGURE 6:** *Cut Away of a Shear-Mode Piezoelectric Accelerometer*

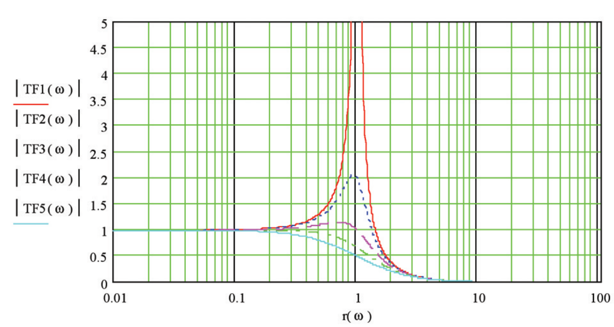


***Figure 7:*** *Simple Spring-Mass Accelerometer Model*

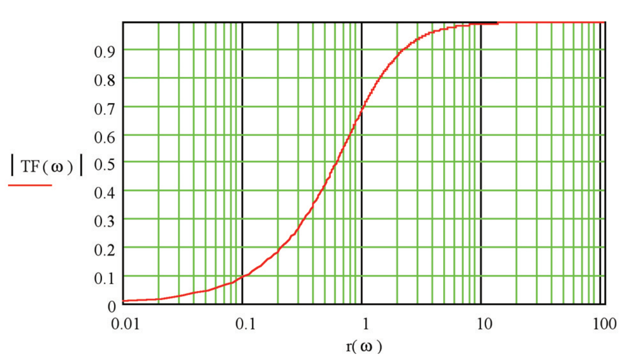


**FIGURE 8:** *Low-Frequency Response of Piezoelectric Accelerometer*

The various curves in Figure 7 represent different values of damping. These curves are normalized to the natural frequency $\omega_n$: $(r(\omega) = \omega/\omega_n)$. For low damping values, the natural and resonant frequencies may be considered synonymous. For a shock accelerometer to have a high natural frequency ($\omega_n = (k/m)^{1/2}$), and, as a byproduct, a broad frequency response, its flexure must be mechanically stiff (high k). Stiff flexures cannot be readily damped; therefore, shock accelerometers typically possess only internal damping of the material from which they are constructed (typical value of 0.03 critical damping is the highest curve of Figure 7).

Piezoresistive accelerometers have frequency response down to 0 Hz. Piezoelectric accelerometers do not have response to 0 Hz. At low frequencies, piezoelectric accelerometers electrically resemble a high-pass RC filter. Their -3 dB frequency is controlled by their circuit time constant ($RC = \tau$). Typically, this time constant is controlled within the aforementioned ICP® circuit. [Figure 8 shows this frequency response curve. The plot is normalized to the low frequency -3 dB frequency $(r(\omega) = \omega/\omega_{-3dB})$].

Before beginning to measure any shock motion, a test engineer has to understand accelerometer theory, mounting techniques, cable considerations, and more. Fortunately, this information is readily and effectively available in an IEST document, entitled RP-DTE011.1: *Shock and Vibration Transducer Selection*. In going forward, we will assume a properly mounted and signal-conditioned accelerometer is in use. This enables us to focus on understanding measurement limitations on shock pulses imposed by the high- and low-frequency response constraints of an accelerometer. Conversely, it enables one to establish frequency response requirements for an accelerometer measuring mechanical shock.

**High-Frequency Limitations**: The key to selecting a shock accelerometer, based on its high-frequency performance, is knowledge of its resonant frequency. This resonant frequency $f_n$(in Hz) is related to its equivalent value $\omega_n$ (in radians/second) as: $\omega_n = 2\pi f_n$. Typically, an accelerometer shouldn't be used above one-fifth its resonant frequency. At that point on the graph, device sensitivity, as a function of frequency, is 4% higher than its value near 0 Hz. Since shock pulses are composites of all frequencies, the total error due to this sensitivity increase will always be much smaller than 4%.

Conversely, if the shock pulse is analyzed in the frequency domain, and if considerable frequency content is found above one-fifth of an accelerometer's resonant frequency, increasingly greater errors will exist in the data. (This comes as no surprise, since the accelerometer is operating outside of its flat frequency-response range). Operation within the flat frequency-response range has been previously stated as a requirement for all measurement systems and their components.

Since most shock pulses are first viewed in the time domain, it is important to establish a relationship as to the credibility of the observed shock pulse based upon knowledge of resonant frequency of the accelerometer. The natural period $T_n$ of the accelerometer will be defined as $T_n = 1/f_n$. For example, if an accelerometer has a resonant frequency of 50 kHz, its natural period $T_n = 20\mu$ sec. Natural period $T_n$ is introduced at this time, because "rules of thumb" will next be provided based on this natural period.

Figures 9 A – C are very informative, in that they portray responses of symmetric shock-pulse inputs (of varying durations T) to an accelerometer, as a function of an accelerometer's natural period. What all of these plots show is that at $T/T_n$ equal to 5, the peak error of the measured shock pulse is always less than 10%, and for $T/T_n$ equal to 10, almost perfect reproduction is achieved. Thus, the "rule of thumb" when selecting an accelerometer or assessing already recorded shock data, is:

$$T/T_n > 5$$

Real pulses typically do not have symmetric rise or fall times. The terms rise and fall time $t_r$ as used throughout this paper, refer to the 10 to 90% time from zero to, or from, the pulse peak. By analogy to the preceding rule:

$$t_r/T_n > 2.5$$

When applying these rules, a test engineer can prescribe any additional amount of conservatism thought to be needed, based upon intended use of data.

**Low-Frequency Limitations:** It is necessary to consider low frequencies only when selecting a piezoelectric accelerometer for mechanical shock. (As stated earlier, piezoresistive accelerometers possess a frequency response down to 0 Hz). However, if for example a piezoresistive accelerometer is AC-coupled to eliminate thermal drift, the following considerations also apply.

**Figures 9A–9C: Shock Pulse Responses as a Function of Accelerometer Natural Period**

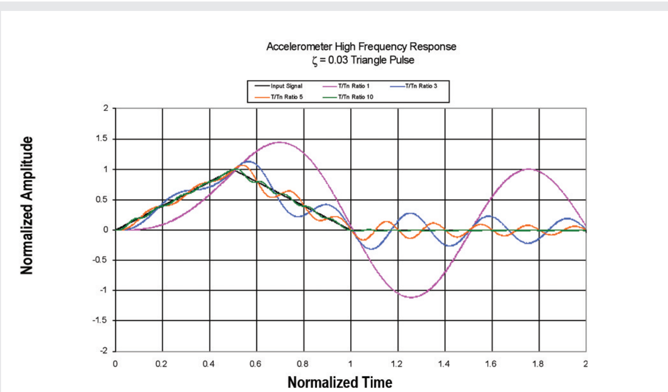


**FIGURE 9A.** *Triangular Pulse*

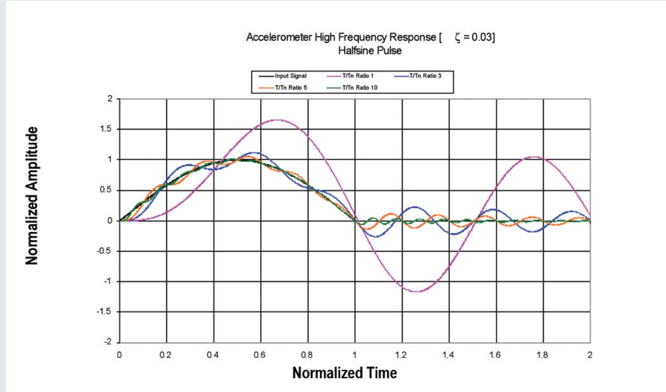


**FIGURE 9B.** *Half-Sine Pulse*

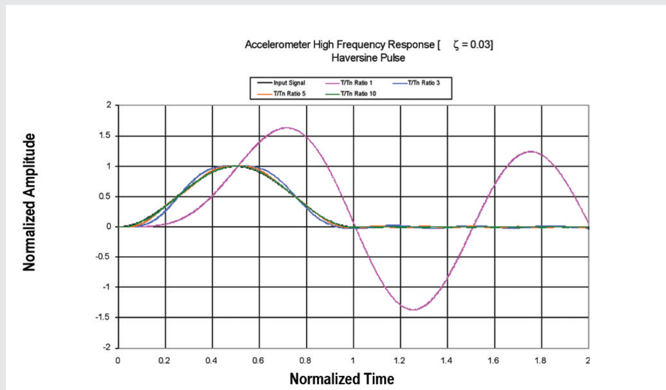


**FIGURE 9C.** *Haversine Pulse*

Figure 8 shows the low-frequency limitation of a piezoelectric accelerometer. The circuit time constant of the accelerometer is related to the low-frequency -3 dB point as: $\tau^{-1} = \omega_{-3dB}$. That is, an increased time constant provides greater low-frequency response. When looking at data in the frequency domain, a simple "rule of thumb" is:

$$f\tau > 0.5$$

This rule guarantees less than 5% attenuation in frequency content above the frequency f (in Hz). For a given time constant, this rule allows a test engineer to select the lowest frequency at which one should begin to use test data, based upon this criterion. Alternatively, it allows one to select an appropriate circuit time constant, in advance of testing.

Again, it is important to establish credibility of an observed shock pulse in the time domain, based on knowledge of the circuit time constant. This relationship will be parameterized as a function of the ratio of the time constant Tau ($\tau$) to the pulse width T. Figures 10A–10C provides these characterizations.

**FIGURES 10A–10C: Shock Pulse Responses as a Function of Circuit Time Constant**

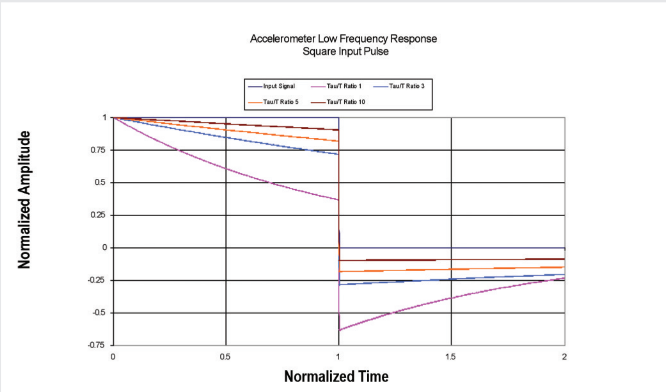


**FIGURE 10A.** *Square Pulse*

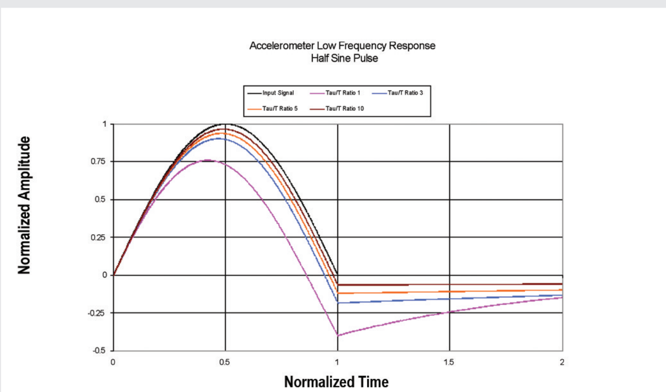


**FIGURE 10B.** *Half-sine Pulse*

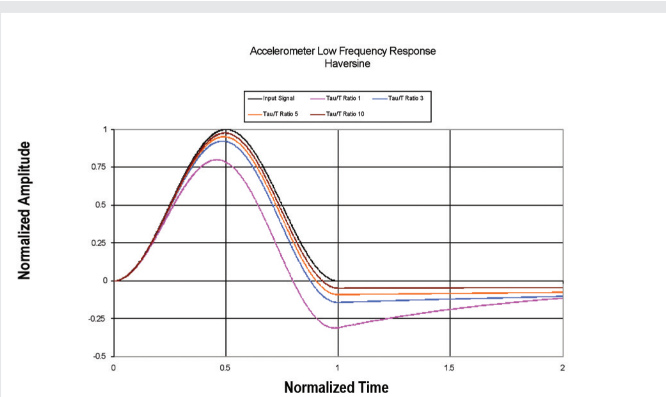


**FIGURE 10C.** *Haversine Pulse*

Figure 10A plots the response in the time domain of an RC circuit to a theoretical square pulse. As the ratio of time constant to pulse duration reaches 10 ($\tau/T = 10$), there remains a 10% droop (error) at the end of the pulse. This would be a worst-case assessment, since most real pulses trail off significantly before pulse termination. In Figures 10B and 10C, the Haversine and Half-sine pulses, illustrate more practical situations. This same ratio of $\tau/T = 10$ would result in a 2.4% error for the peak value determination of a Haversine pulse, and 3.4% error for a Half-sine pulse. While not shown, corresponding error for the peak of a triangular pulse would be 2.6%. Thus, a “rule of thumb” when selecting an accelerometer, or assessing already recorded shock data, is:

$$\tau/T > \mathbf{10}$$

Again, a test engineer can apply as much additional conservatism as an application warrants.

**Other Response Considerations in Selecting Piezoelectric vs. Piezoresistive Technologies for Shock Measurements**: A majority of piezoelectric accelerometers use ceramic sensing materials. At sufficiently high frequencies, the resonance of any accelerometer can be excited, but a unique characteristic of ceramic materials is that this excitation can result in a zero-shift of the signal. This remained a mystery until 1971, when the causal relationship of the zero-shift in ceramic materials was established.[10] This work brought increased focus upon MEMS accelerometers for shock applications. Theoretically, MEMS accelerometers <u>do</u> <u>not</u> zero shift.

A limitation in MEMS accelerometers in shock measurement is their tremendous amplification at resonance (e.g., 1000:1), which can lead to breakage in response to high-frequency inputs (e.g., metal-to-metal impact, explosives, etc.) Figure 11 shows an example of a MEMS shock accelerometer which attempts to incorporate a small amount of squeeze film damping to minimize this problem.

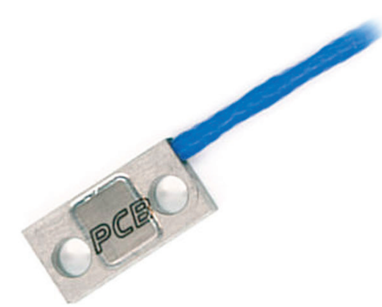


***Figure 11:*** PCB® *Model 3991 MEMS Shock Accelerometer*

*High-Frequency Electronic Limitations*: In order to mitigate the aforementioned zero-shift problems in piezoelectric accelerometers, certain models (e.g., PCB® Model 350) contain mechanical isolation to mitigate high-frequency stimuli. To minimize frequency-response aberrations due to this isolation, accelerometers are electrically prefiltered. Feedback components (resistors and capacitors), internal to an accelerometer and around the signal-conditioning amplifier, enable a 2-pole Butterworth filter to be developed. The high-frequency roll-off of this filter, as opposed to the resonant frequency of an accelerometer, now becomes the measurement system's upper frequency constraint.

In other instances, this same type of frequency limitation may occur outside of the accelerometer. For example, in flight test instrumentation, only 2-3 KHz maximum frequency response per channel is typically allocated. In addition, at shock levels below 2,000 g's, damped accelerometers may be used. The response of properly damped accelerometers appears as the intermediate or "flattest" of curves shown in Figure 7. This curve shows negligible gain and is attenuated approximately -3 dB at the natural frequency of the accelerometer.

The commonality of examples in the preceding two paragraphs is that amplification (i.e., gain) approaching the resonant frequency of an accelerometer no longer limits measurement system response. Instead, the limitation becomes the system's high-frequency attenuation. Due to this attenuation, another "rule of thumb" can be applied.[11] Here again, we base this rule on the shortest duration of the pulse's rise or fall time $t_r$ to or from the pulse peak. By analogy to the preceding observations:

$$t_r f_{-3dB} > 0.45$$

This rule states that the rise or fall time of the shock pulse is guaranteed valid, only if the product of its duration multiplied by the high-frequency -3 dB frequency (in Hz) exceeds 0.45. Again, this rule is helpful for both pretest planning and data assessment.

*Complex Pulses*: As opposed to the simple pulses shown to date, real shock pulses can be quite complex (Figure 12). A question then arises as to how one applies the preceding simple "rules of thumb" to complex pulses. The answer is that we dissect the pulse for its shortest and longest, positive- or negative-going, excursions, as well as its shortest positive or negative rise-time. Since today all data are recorded in digital format, these simple rules can be readily programmed into a software data analysis package.

*Cable Frequency Limitations*: In ICP® circuits, if very long cables are used, cable capacitance can become an upper frequency limitation. For example, 4 mA of supply current driving 100 feet of cable supporting an ICP® circuit with cable capacitance of 30 pF/ft will begin to attenuate full scale signals above 40 KHz[12]. Other drive-current-versus-cable-operating trade-offs can be assessed using reference 12. Frequency attenuation due to cable length can usually be overcome, simply by increasing supply current.

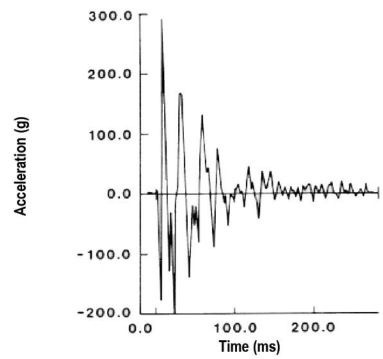


**FIGURE 12:** *Complex Mechanical Shock Pulse*

*Low-Frequency Oscillations*: If an ICP® accelerometer is properly selected, the effect described next should never be a consideration. However, since the effect is sometimes observed in test data where a shock pulse is excessively wide and/or the accelerometer signal-conditioning overranged, it is described for clarity.

Aside from a constant current diode, signal conditioning for ICP® circuits typically includes a coupling capacitor for blocking bias voltage on a signal return. The capacitor is always selected as to avoid impacting an accelerometer's low-frequency performance. However, the capacitor has the effect of creating a second RC time constant in the circuit. The effect of this second time constant is to transform a first-order, high-pass system into a second order one. The signal now returns to zero in anywhere from a few hundred to multiple hundreds of milliseconds with a heavily damped response.

**Conclusions:** This paper has presented simple "rules of thumb" to enable a test engineer to select accelerometers efficiently and accurately for mechanical shock measurements, or to assess data resulting from those measurements. Whereas "rules of thumb" are based upon theory, they result in a number of practical rules that a test engineer, designer, or data analyst can readily apply.

## References:


1. *Shock and Vibration Handbook,* edited by Cyril M. Harris and Allan G. Piersol, The McGraw-Hill Companies, 5th edition, 2002.

2. *50 Years of Shock and Vibration History,* edited by Henry C. Pusey, The Shock and Vibration Information Analysis Center (SAVIAC), 1996.

3. Walter, Patrick L., "The Shock Spectrum: What is It", Technical Note TN-19, http://www.pcb.com/techsupport/docs/vib/, PCB Piezotronics, Inc.

4. SFI Foundation, Inc., Specification SFI 38.1.

5. Walter, Patrick L., "Effect of Measurement System Phase Response on Shock Spectrum Computation", Shock and Vibration Bul., 53, Part 1, 133-141, May 1981.

6. Walter, Patrick L., "Data Validation: A Prerequisite to Performing Data Uncertainty Analysis" PCB Piezotronics Technical Note TN-20, Proceedings International Telemetry Conference, Las Vegas, NV, October 25-27, 2005.

7. Walter, P. L., "Validating the Data Before the Structural Model", Journal of the Society of Experimental Mechanics: *Experimental Techniques,* pp 55-59, November/December 2006.

8. Walter, Patrick L., "Placebo Transducers: A Tool for Data Validation", Technical Note TN-16, http://www.pcb.com/techsupport/docs/vib/, PCB Piezotronics, Inc.

9. Liu, Bin, Transducers for Sound and Vibration – The Finite Element Method Based Design, Ph.D. thesis, Technical university of Denmark, June 2001.

10. Plumlee, Ralph H., "Zero-Shift in Piezoelectric Accelerometers," Sandia National Laboratories Research Report, SC-RR-70-755, March 1971.

11. Walter, Patrick L., "Shock and Blast Measurement – Rise Time Capability of Measurement Systems?" Technical Note TN-11, Sound *and Vibration,* January 2002.

12. Driving Long Cables, http://www.pcb.com/techsupport/tech_cables.php., PCB Piezotronics, Inc.

PCB PIEZOTRONICS
AN AMPHENOL COMPANY

**3425 Walden Avenue, Depew, NY 14043 USA**

pcb.com | info@pcb.com | 800 828 8840 | +1 716 684 0001