Selecting Accelerometers for Mechanical Shock Measurements

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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-frequency and low-frequency dynamic models for a 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.

The definition of mechanical shock is: *a non-periodic 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 depends on the system encountering the shock. For example, if the human body is considered as a mechanical system, a shock pulse of 0.2 sec 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 McGraw Hill since 1961; and the 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.

Mechanical shock can be specified in 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 the 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 at 43.5 mph.

Figure 3 shows an example of a mechanical shock described by its amplitude in the frequency domain. This representation is particularly useful in linear analysis when the transfer function of a system is of interest (mechanical impedance, mobility, and transmissibility). It provides knowledge of the 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, the accurate measurement of mechanical shock is a subject*

> **The effects of mechanical shock are considered so important that there are international standards, handbooks and symposiums just on this subject alone.**

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 requirements are:

- The frequency response of the measuring system must have flat amplitude response and linear phase shift over its response range of interest.[5]
- The data sampling rate must be at least twice the highest data frequency of interest. Properly selected data filters must constrain data signal content so that the data don't exceed this highest frequency. 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.
- The data must be validated to have an adequate signal/noise ratio.[6,7,8]

We assume that the test engineer has satisfied these requirements so we can now focus on accelerometer selection.

Accelerometer Considerations

The 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 the charges accumulate on opposing electrode surfaces. The 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 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 the preceding technologies will be discussed further in a subsequent section of this article.

Accelerometers themselves are mechanical structures. They have
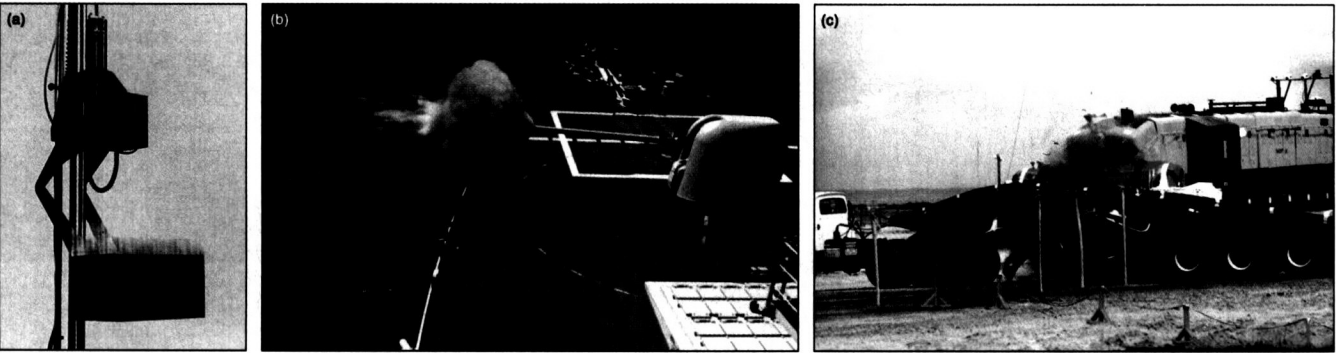

Figure 1. Examples of mechanical shock: a) Package drop; b) Projectile firing; c) Train/truck crash.
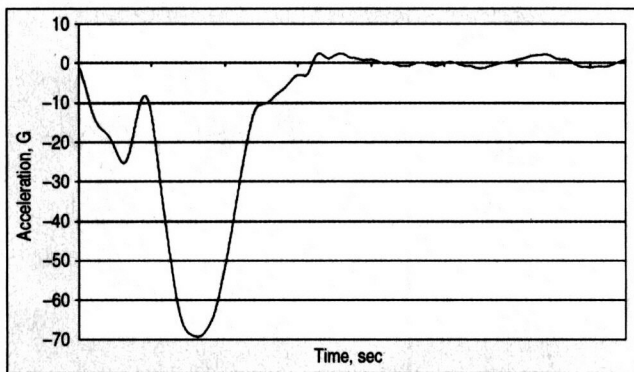
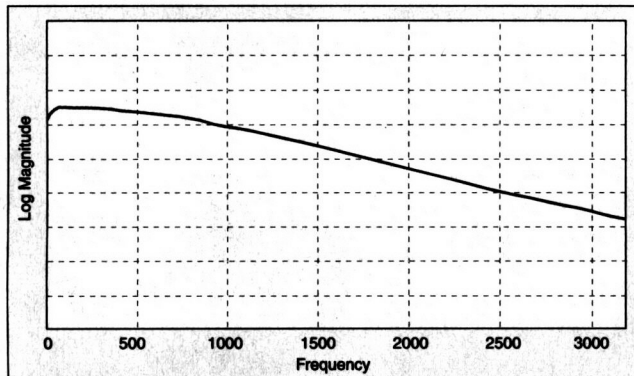Figure 2. Shock time history used in NASCAR testing.

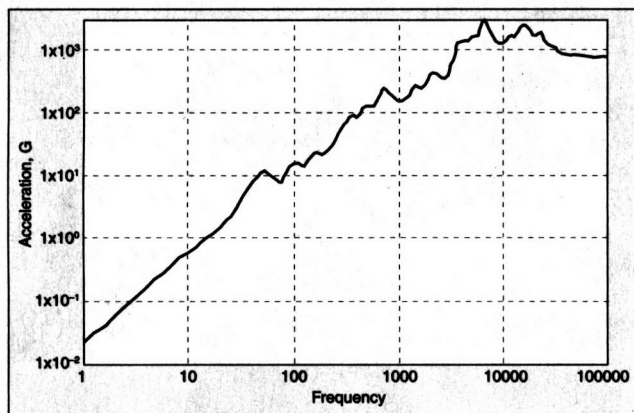Figure 3. Frequency spectrum of shock used to excite structure.

Figure 4. Shock response spectrum of acceleration pulses due to gunfire; SRS response, 5% damping.
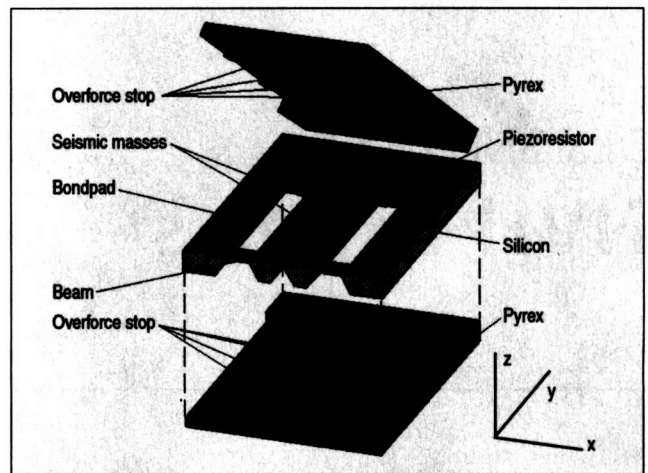

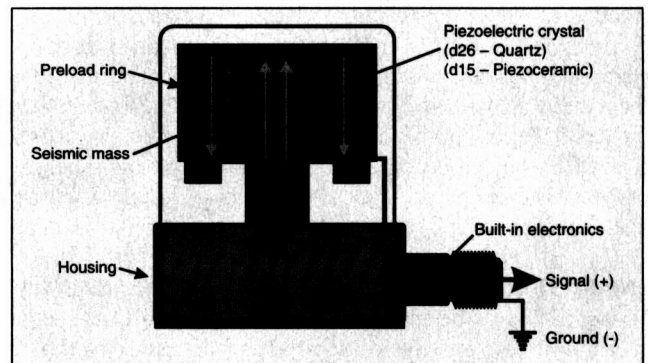Figure 5. Mechanical flexure for MEMS accelerometer.

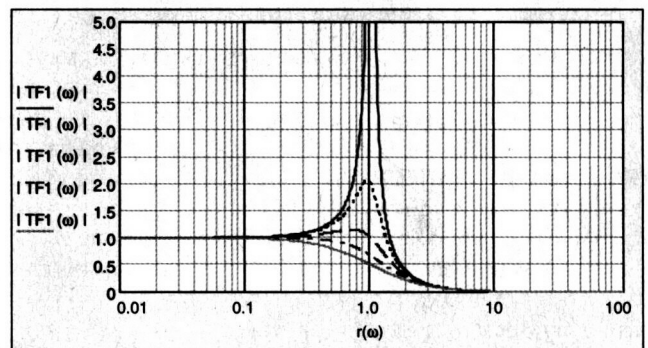Figure 6. Cut-away view of shear-mode piezoelectric accelerometer.

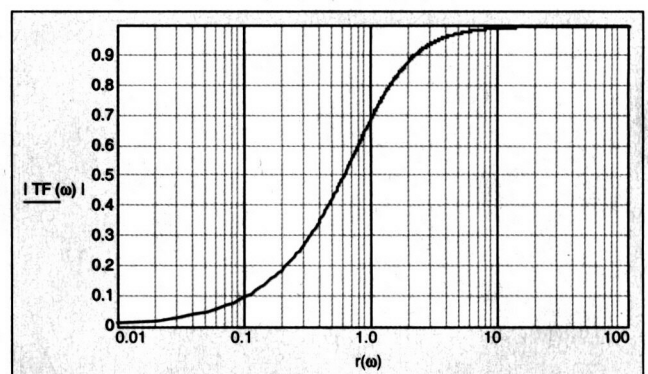Figure 7. Simple spring-mass accelerometer model.

Figure 8. Low-frequency response of piezoelectric accelerometer.

multiple mechanical resonances[9] associated with their seismic flexure, external housing, connector and more. If the 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, the frequency response of an accelerometer can be specified as if it has a single resonant frequency. Figure 5 pictorially shows a mechanical flexure in a piezoresistive accelerometer and Figure 6 shows a cut-away of a piezoelectric accelerometer. 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 in Figure 7.

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

of Figure 7.)

Piezoresistive accelerometers have frequency response to 0 Hz. Piezoelectric accelerometers *do not* have response to 0 Hz. At low frequencies, piezoelectric accelerometers electrically look like a high-pass RC filter. Their −3 dB frequency limit 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, $(r(\omega) = \omega/\omega_{-3\,dB})$.

Before beginning to measure any shock motion, the test engineer must understand accelerometer theory, accelerometer mounting techniques, cable considerations and more. Fortunately, this information is readily and effectively available in an IEST document RP-DTE011.1: *Shock and Vibration Transducer Selection*. In going forward, we will assume the use of a properly mounted and signal-conditioned accelerometer. This enables us to focus on understanding the measurement limitations on shock pulses imposed by the high- and low-frequency response constraints of the 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 ω_n (in radians/second) as: $\omega_n = 2\pi f_n$. Typically, an accelerometer shouldn't be used above 1/5th its resonant frequency. At that point on the graph, the device's 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 1/5th of the 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 on knowledge of the 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 50,000 Hz, its natural period $T_n = 20$ μsec. T_n is introduced at this time because rules of thumb will next be provided based on this natural period.

Figure 9 is very informative in that it portrays the response of symmetric shock-pulse inputs (of varying durations T) to an accelerometer as a function of the accelerometer's natural period. What these plots all 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 article, refer to the 10-90% 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, the test engineer can prescribe any additional amount of conservatism that might be needed based on the intended use of the 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 to 0 Hz.) If a piezoresistive accelerometer is AC coupled to eliminate thermal drift, however, the following considerations also apply to it.

Figure 8 showed 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.
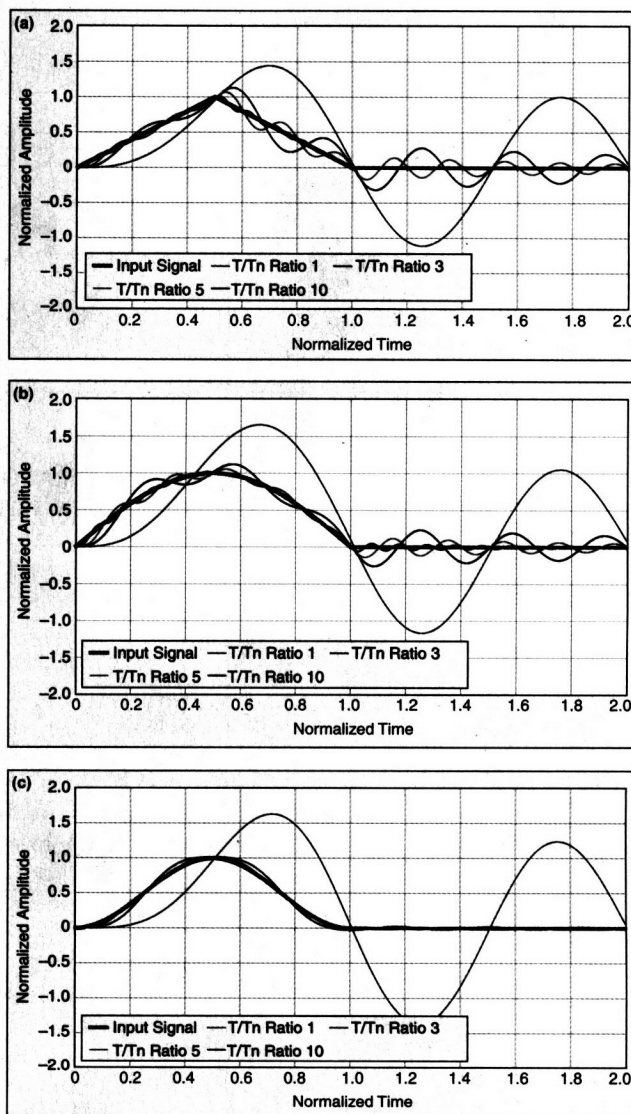
Figure 9. Shock pulse response as a function of accelerometer natural period (damping ratio = 0.03): a) triangular pulse; b) half-sine pulse; c) Haversine pulse.

When looking at data in the frequency domain, a simple rule of thumb to use 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 you to select the lowest frequency at which you should begin to use test data based on this criterion. Alternatively, it allows you to select an appropriate circuit time constant in advance of testing.

Again, it is important to establish the credibility of the observed shock pulse in the time domain based on knowledge of the circuit time constant. This metric is a function of the ratio of the time constant tau τ to the pulse width T. Figure 10 provides this characterization.

Figure 10a plots the response in the time domain of an RC circuit to a theoretical square pulse. As the ratio of the time constant to the pulse duration reaches 10 ($\tau/T = 10$), there remains a 10% droop (error) at the end of the pulse. This would be a worse-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 a 3.4% error for a half-sine. While not shown, the 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:
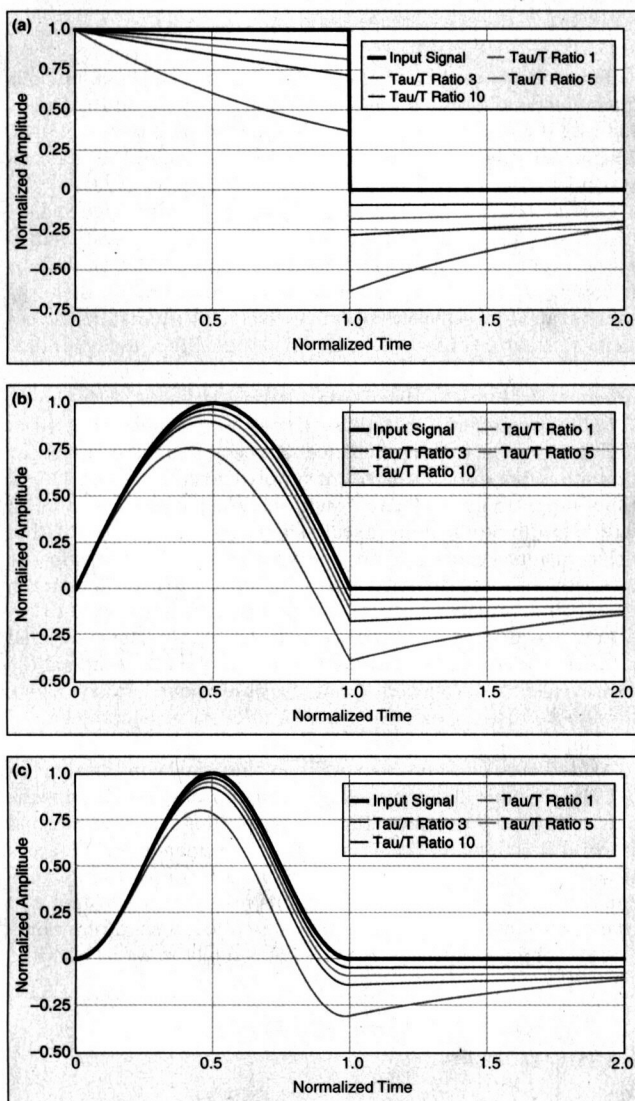
Figure 10. Shock pulse response as a function of circuit time constant: a) square pulse; b) half-sine pulse; c) Haversine pulse.

$$\tau / T > 10$$

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

Other Response Considerations

Considerations in Selecting Piezoelectric versus Piezoresistive Technologies for Shock Measurements. The 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 cause-effect relationship of the zero shift in ceramic materials was established,[10] and this work brought about an increased focus on MEMS accelerometers for shock applications. Theoretically, MEMS accelerometers *do not* zero shift.

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

High-Frequency Electronic Limitations. To mitigate the aforementioned zero-shift problems in piezoelectric accelerometers, certain models (like the PCB Model 350 for example) contain mechanical isolation to mitigate high-frequency stimuli. To minimize frequency-response aberrations due to this isolation, the accelerometers are electrically prefiltered. Feedback components

(resistors and capacitors) internal to the 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 the accelerometer, now becomes the measurement system's upper-frequency constraint.

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

The commonality of the examples of the preceding two paragraphs is that amplification (gain) approaching the resonant frequency of the accelerometer no longer limits the response of the measurement system. 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:
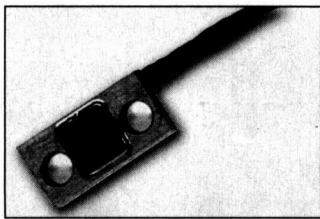
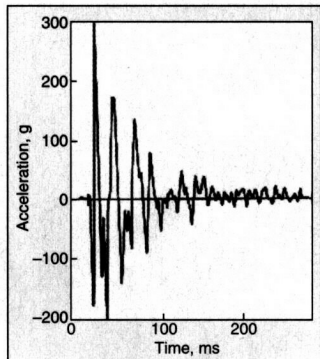Figure 11. PCB Model 3991 MEMS shock accelerometer.

Figure 12. Complex mechanical shock pulse.

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

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 cutoff 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 we apply 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. If very long cables are used in ICP® circuits, the cable capacitance can become an upper frequency limitation. For example, 4 mA of supply current driving 100 ft 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 by simply increasing the supply current.

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

Aside from a constant current diode, the signal conditioning for ICP circuits typically includes a coupling capacitor for blocking the bias voltage on the signal return. The capacitor is always selected to avoid affecting the 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
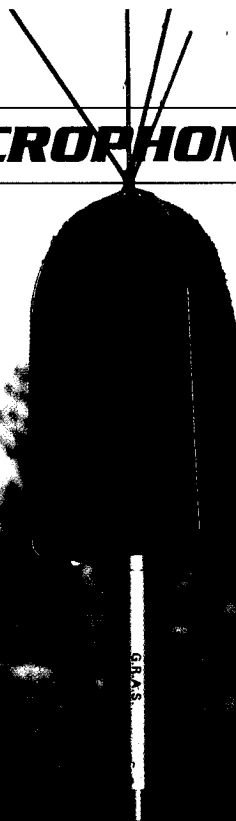
to multiple hundreds of msecs with a heavily damped response. This indicates one or more problems with the data.

Conclusions

The simple "rules of thumb" presented here enable the test engineer to select accelerometers efficiently and accurately for mechanical shock measurements or to assess data resulting from those measurements. While these rules are based on theory, they result in a number of practical rules that can readily be applied.

References

1. *Shock and Vibration Handbook*, Cyril M. Harris and Allan G. Piersol, Eds., McGraw Hill, Fifth Edition, 2002.
2. *Fifty Years of Shock and Vibration History*, Henry C. Pusey, Ed., 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. Specification SFI 38.1, SFI Foundation, Inc., Poway, CA.
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," *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," *Sound and Vibration*, January 2002.
12. Driving Long Cables, http://www.pcb.com/techsupport/tech_cables.php., PCB Piezotronics, Inc. **SV**

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Errata

Please note the corrections to "Predicting Footfall-Induced Vibrations of Floors," by Eric C. Ungar and Jeffrey A. Zapfe, *Sound and Vibration*, November 2004. pp 16-22.

A copying error occurred in Equation (B1c). This equation should read:

$$F_2(t) = 0 \quad \text{for} \quad 0 < t < T - T_P / 2$$

The curve-fit expressions given in Figure 9B do not cover the entire frequency range well due to the limited precision of the coefficients. The following give better curve-fits:

For 125 steps/min: $y = 0.001325x^4 - 0.0783x^3 + 1.7086x^2 - 16.487x + 67.196$

For 100 steps/min: $y = 0.0034x^3 + 0.1579x^2 - 2.2474x + 17.96$

For 75 steps/min: $y = 0.00014x^4 - 0.01025x^3 + 0.262x^2 - 2.9083x + 16.235$