# EDITORIAL

## Pyroshock Standards

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Two major pyroshock standards have been revised and are in the process of review with changes that will implement substantial improvements for pyroshock testing and measurements. The two standards are: MIL-STD-810G Method 517 and NASA-STD-7003 *Pyroshock Test Criteria.* Although most pyroshock test and measurement issues were solved in the 1980s, contaminated data (aliased, slew rate limited, etc.) continue to be prevalent in pyroshock technology. These revisions are intended to emphasize that although pyroshock is a low-net-velocity environment, it is a high-frequency, high-g environment that must be measured correctly to prevent mission failure due to electronic component failure and the creation of contaminated specifications.

**Latest Revisions.** MIL-STD-810G was approved in 2009, and Change 1 of Version G has been underway since then. MIL-STD-810 is a consensus document with participants from Department of Defense organizations and various consultants, including myself as subject matter expert for pyroshock. Only minor changes to Method 517 were made for Version G. Pyroshock definitions were changed to be consistent with other major documents, and other minor changes were made for consistency. However, in MIL-STD-810G, Method 517, Change 1, substantial changes are proposed to emphasize the uniqueness of the pyroshock environment. All data plots have been revised to show near-field pyroshock data measured with a laser Doppler vibrometer and an accelerometer and with a data acquisition system that has a 1-MHz bandwidth and sigma-delta A/D converter. Both acceleration-based and pseudo-velocity shock response spectra (SRS) are presented for these data. The pseudo-velocity SRS emphasizes the pyroshock high velocities at high frequencies that cause electronic component failures. Other proposed changes address major problem areas in pyroshock testing.

**Problem Areas.** The first major problem area is the choice of accelerometers and their calibration. In a report dated 1971, Ralph Plumlee of Sandia National Laboratories (available from National Technical Information Services) presented the results of his piezoelectric material study. It takes very little mechanical energy (velocity change) to reorient the charge distribution of piezoelectric materials that creates an offset (zero shift) in a piezoelectric accelerometer. This discovery resulted in development of high-g piezoresistive accelerometers, and this type of accelerometer is recommended.

Concurrently, isolated piezoelectric accelerometers were developed that have nonlinear amplification below 10 kHz (a typical upper limit for pyroshock specifications), and this characteristic is noted. The use of a piezoelectric accelerometer is prohibited unless the accelerometer is specifically designed for oscillatory shock (most are not). Finally, both a vibration calibration to show linearity with frequency and a shock calibration to show linearity with amplitude are proposed as requirements.

The second major problem area is implementing analog, antialiasing filters. The essential requirement for pyroshock measurements is the analog filter roll-off to prevent high-frequency or "out-of-band" energy aliasing. I found in the IEST Reference Document 012, *Handbook of Dynamic Data Acquisition and Analysis*, a stated antialiasing filter roll-off of 60 dB/octave that is credited to Allan Piersol (deceased). I have had many conversations with Harry Himelblau (Jet Propulsion Laboratory, retired), Dennis Nelson (Sandia National Laboratories, retired), Robert Randall (see Antialiasing), as well as receiving many written comments on this subject. Randall published a discussion of the 120 dB/octave antialiasing filter roll-off in Harris' *Shock and Vibration Handbook*.[1] He has kindly contributed an addendum here with his aliasing analysis. My conclusion is that Piersol stated the 60 dB/octave antialiasing filter roll-off as a compromise between Randall's analysis and current analog filter technology. There are commercial filters that meet this roll-off criterion, but as Randall (and many others) shows, the sigma-delta data acquisition system technology exceeds this criterion of 120 dB/octave.

Sample rates of greater than 10 times the desired bandwidth are proposed for fidelity of amplitude and as another aliasing protection; and a noise gage (inert accelerometer) is proposed as a requirement for data quality assessment. Additionally, I have written an annex to Method 517 that addresses the interpretation of the integral of the accelerometer measurement; the velocity time history. The velocity time history is the best measurement of data quality and seems to have been abandoned by many since the 1980s. The Method 517 Annex discusses common erroneous velocity time histories and their interpretation. MIL-STD-810G, Change 1, is scheduled for publication in 2012.

**New NASA Standard.** In the early 1990s the NASA Office of Chief Engineer implemented a program to develop NASA-wide standards to provide uniform engineering and technical requirements for processes, procedures, practices, and methods employed for selection, application, design, and test criteria for spaceflight hardware. In addition, the program developed NASA handbooks to encourage the use of best practices and to support consistent treatment of engineering issues across the agency. NASA is now making some selected standards "endorsed" for all NASA flight hardware projects, and the NASA handbooks are being updated to reflect advances in the technology. (The selected standards were originally to become "mandatory" standards, but the designation has recently been changed to endorsed standards.) The Jet Propulsion Laboratory (JPL) is the lead center for one of the standards and three handbooks relating to dynamics environments criteria and testing. These documents are currently undergoing development or revision. NASA-STD-7003 *Pyroshock Test Criteria,* May 18, 1999, has been revised as directed by NASA headquarters to make it an endorsed standard and to update it for advances in the discipline since its initial release.

The contents of NASA-STD-7003 include subjects such as: (a) definition and description of the pyroshock environment; (b) definition of the maximum-expected flight environment (MEFE); (c) test margins, methods, and facilities; (d) state-of-the-art data acquisition and analysis methods; (e) prediction methods for pyrotechnic shock; and (f) preferred methods for determining MEFE. Numerous changes have been made for 7003A to incorporate pyroshock technology advances, improve the clarity of the information, update technical references, make definitions compatible with IEST and MIL-STD-810G pyroshock standards, and most importantly, to conform to the NASA template for endorsed standards. The current 7003A draft includes 18 endorsed or "shall" statements, some with multiple parts. Those statements represent minimum requirements endorsed for NASA flight projects.

Dennis Kern (JPL) and I developed NASA-STD-7003A and performed the rewrite effort.[2] Currently, the draft standard has undergone two NASA peer reviews with pyroshock experts with most of the NASA facilities taking part. A consensus draft of the revised standard was submitted for agency review in July 2010. The review was completed in December 2010 and resulted in 107 comments or recommended changes. Resolution of the comments and changes to the consensus draft NASA-STD-7003A should be completed by the 26th Aerospace

Testing Seminar (2011), with the revised standard ready for agency release.

**Antialiasing (***contributed by Robert Bond Randall***).** Aliasing results when a signal before sampling contains frequency components above half the sampling frequency $f_s$ the so-called Nyquist frequency. To avoid it, a low-pass filter should be applied before sampling that attenuates frequency components above the Nyquist frequency so that they are below the desired dynamic range when aliased (folded) back into the measurement range. Because of the finite slope of analog low-pass filters, the valid measurement range is somewhat less than the theoretical maximum of half the sampling frequency. (The first filter before initial sampling must be analog, although digital filters can be used before resampling to lower sampling frequencies.)

Correct antialiasing filtering is illustrated in Figure 1. The figure also illustrates the problems that arise when the sampling frequency is changed from this value while retaining the same low-pass filter, but first let's discuss justification for the specification of "correct" low-pass filtering.

To avoid aliasing, it is virtually always necessary to use an antialiasing filter with a very steep roll-off. For FFT analyzers, it has become fairly standard to use filters with a roll-off of 120 dB/octave that allow approximately 80% of the calculated spectrum to be used. Therefore, with a 1K (1024 point) transform, it is common to want to have a valid spectrum of 400 lines. Spectrum line number 512 is at the Nyquist frequency, and higher frequencies fold back toward the measurement range. Line number 624 folds back into the top of the desired measurement range (line number 400), and is only 64% of an octave above it, and so is attenuated by 77 dB, taking it below the typical dynamic range of approximately 80 dB.

This is of course an approximation, as real filters do not have an exactly linear characteristic in terms of dB/octave, and it applies for one set of typical parameters. It dates back to when A/D (analog to digital) converters only had a valid dynamic range of 75-80 dB and when low-pass filter characteristics were best described in terms of dB/octave.
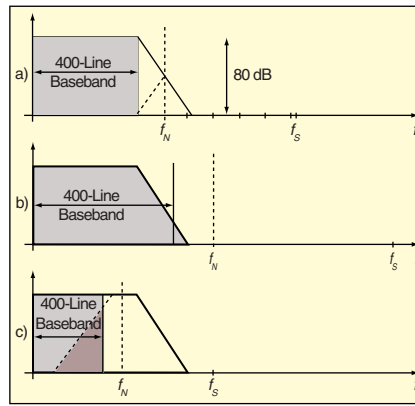


Figure 1. Effects of sampling frequency on spectrum analysis errors assuming an analyzer with 400 line resolution and 80 dB dynamic range, $f_s$ = sampling frequency, $f_N$ = Nyquist folding frequency = $f_s/2$: (a) optimum choice of sampling frequency relative to the low-pass filter cut-off: (b) increased sampling frequency causes upper lines in the spectrum to be influenced by the low-pass filter; (c) decreased sampling frequency causes upper lines in the spectrum to be influenced by aliasing components folded around $f_N$.[1]
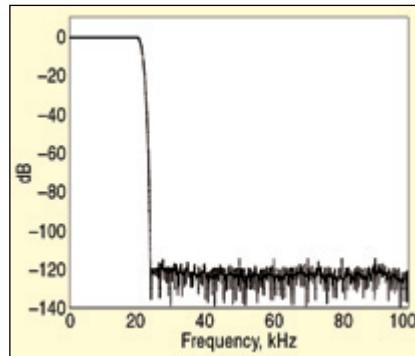


Figure 2. Frequency response of 120 dB/octave low-pass analog filter.

If a filter of 60 dB/octave were used, the same attenuation would be achieved within 1.28 octaves, meaning that the maximum valid frequency range would be close to 300 lines out of 512.

I have recently become aware that a different approach is sometimes used today, typically in connection with sigma-delta A/D converters with a larger valid dynamic range (>100 dB). Here, a "brick-wall" filter is sometimes used, which has a very steep roll-off but then flattens out at a very low level below the increased dynamic range. Such filters may not have much attenuation at the Nyquist frequency but are down 115 dB at 120% of it, meaning that they do not fold back into the measurement range. Such a characteristic for an Analog Devices A/D converter is shown in Figure 2.

I previously used the spectrum level at the Nyquist frequency as a guide to the effectiveness of antialiasing filters (doing FFT analysis in Matlab® because you can only view the valid frequency range on an analyzer), although I was aware that this was not infallible. From Figure 1a, it should be down by roughly half the dynamic range (43 dB minus 3 dB because of the fold-over). But then I was surprised that with the new Brüel & Kjær analyzer there was no drop at all at the Nyquist frequency because of the sigma-delta A/D converters. This applied only in the highest frequency range, with the signal directly from the A/D converter. In all lower frequency ranges, conventional digital filters were used before reducing the sampling frequency, so they had the characteristic I expected. Some of my old colleagues at Brüel & Kjær were not aware of this change until they asked the instrument designers.

These arguments apply to the worst case, where the aliasing components are at full scale, and this would rarely be the case. Unfortunately, no estimate can be made of how much aliasing there is in a signal after it has been sampled, since it is not possible to distinguish real from aliased components. There is always some contamination in the region from the highest valid frequency to the Nyquist frequency. This could be removed by digital post-processing if desired.

1. "Vibration Measurement Equipment and Signal Processing," *Shock & Vibration Handbook*, Third Edition, Chapter 13, page 40, McGraw-Hill, New York, NY, 1988.
2. Material for NASA-STD-7003A is excerpted from a paper by Dennis Kern, Jet Propulsion Laboratory, to be presented at the upcoming 26th Aerospace Testing Seminar, entitled "Status of a NASA Standard and Three NASA Handbooks."

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