FILTERING CONSIDERATIONS WHEN TELEMETERING SHOCK AND VIBRATION DATA

Patrick L. Walter, Ph. D.
Endevco
San Juan Capistrano, CA &
Texas Christian University
Fort Worth, TX

ABSTRACT

The accurate measurement of shock and vibration data via flight telemetry is necessary to validate structural models, indicate off-nominal system performance, and/or generate environmental qualification criteria for airborne systems. Digital telemetry systems require anti-aliasing filters designed into them. If not properly selected and located, these filters can distort recorded time histories and modify their spectral content. This paper provides filter design guidance to optimize the quality of recorded flight structural dynamics data. It is based on the anticipated end use of the data. Examples of filtered shock data are included.

KEY WORDS

Accelerometer, Airborne Telemetry, Filter, Shock and Vibration, Test Specifications

INTRODUCTION

The *sampling theorem* in communications tells us that the sampling frequency f_s must be no less that twice the highest signal spectral frequency f_m, i.e., $f_s \geq 2f_m$. When measuring shock and vibration data via airborne telemetry, successful implementation of this theorem can be a challenge. The accelerometers that measure shock and vibration typically have associated high-frequency resonances (Figure 1). If these resonances are unintentionally excited, they occur at frequencies much higher than the highest required data frequency of interest (f_m).[3]

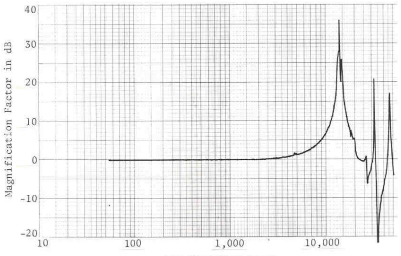

Figure 1: Accelerometer Frequency Response Displaying High Frequency Resonances

BODY

There are many reasons to measure airborne shock and vibration data. These include (1): defining the actual use environment of flight hardware to enable the generation of shock and vibration qualification test specifications for it, and (2): acquiring acceleration response data for correlation to structural dynamics models of this hardware. Due to limitations in available airborne telemetry system data bandwidth, signals from accelerometers are typically afforded the minimum frequency bandwidth required to either (1): be compatible with the capabilities of the ground qualification test equipment, which ultimately will be used to replicate the flight environment, or (2): enable correlation to these structural dynamic models. Thus, most shock or vibration data transmitted over airborne telemetry channels have 2-10 kHz frequency content. The opportunity to determine whether-or-not the resonance of an accelerometer has been excited at 10’s or 100’s of kHz is never afforded. Data limitations occur attributable to the low-pass filters selected to satisfy the sampling theorem. Since mechanical shock analysis is wave shape dependent, these low-pass filters must preserve both the amplitude-frequency and phase-frequency integrity of the measured signals.

Figure 2 shows that this is often difficult to accomplish. Both the amplitude and the phase

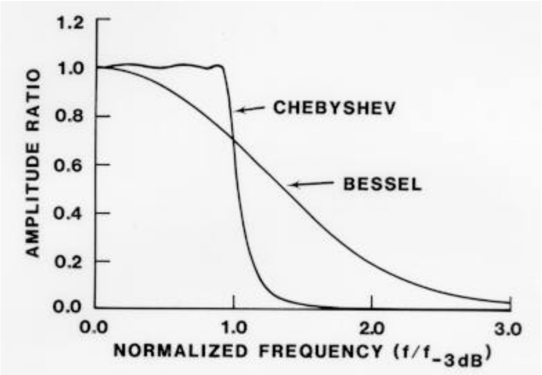

Figure 2a: Amplitude-Frequency Response for Two Filter Types

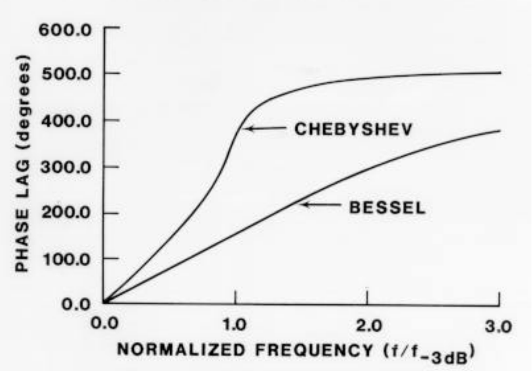

Figure 2b: Phase-Frequency Response for Two Filter Types

Figure 2: Frequency Response Characteristics of Two 6-Pole Filter Types

characteristics are shown for two filter types. The six-pole Chebyshev is the best approximation of an ideal “boxcar” filter based on its amplitude response, but its phase response is more nonlinear than that of the six-pole Bessel. Thus a compromise always exists in filter selection.

A Butterworth low-pass filter has an amplitude response characterized as:

$$[1/(1 + \omega^{2n})]^{1/2}$$

where n is the number of filter poles. Its emphasis is on maximally flat amplitude response. A Chebyshev low-pass filter produces an equal-ripple amplitude variation in the passband. Outside the passband the gain also decreases monotonically, but at a faster rate than the Butterworth characteristic. The class of filter that has equal ripple in both the passband and the stop band is the elliptic-function or Cauer filter. Its gain does not decrease monotonically outside the passband, but it offers farther improvement in attenuation than the Chebyshev low pass filter. A Bessel-Thompson filter configuration emphasizes filter phase linearity as opposed to flat amplitude response.

Group delay is defined as the derivative of the phase frequency response $[-(d\phi/d\omega)]$ of a filter. It is of importance when constant time delay is needed in a filter. For a Bessel-Thompson filter, group delay is a constant. The Bessel-Thompson amplitude frequency response, however, is far inferior to that of the other filter configurations discussed. We will focus our attention on those low-pass filters with monotonic decreasing response outside their passband: the Butterworth, Chebyshev, and the Bessel-Thompson (sometimes just referred to as Bessel).[1,2]

The following table, based on calculations by the author,[4] provides filter selection guidelines when recording mechanical shock. Filters considered encompass two, four, six, and eight poles of attenuation. Numeric values presented are the ratio of the upper frequency limit at which the filter should be used to that of its -3 dB frequency. This upper frequency limit is based on the lesser of the two values at which the filter deviates either five percent from a flat amplitude response or five degrees from phase linearity based on its initial phase slope. These criteria should assure waveform reproduction without distortion.

Table 1: Filter Selection Type

Number of Poles	Butterworth	Bessel	0.1 dB Ripple Chebyshev
2	.573	.399	.522*
4	.575*	.399	.489*
6	.541*	.392	.418*
8	.506*	.389	.372*

* upper limit due to phase nonlinearity

An example will show how to use this table. A six-pole Butterworth and a six-pole 0.1 dB Chebyshev filter with a 1,000 Hz, -3 dB frequency would be limited in application to 541 and 418 Hz respectively because of phase nonlinearities. A six-pole Bessel would become limited at 392 Hz due to its deviation from a flat amplitude response. In general, for mechanical shock data, the low-pass Butterworth will always be the preferred filter of the three configurations considered.

It is next desirable to assess where this filtering should occur. Conventional communication theory has this filtering occurring immediately in front of the digital encoder. However, for mechanical shock this filtering should be provided between the measuring accelerometer output and the first-stage gain of the signal conditioning. This location is optimum because it provides three benefits:

- It prevents subsequent signal conditioning components from being driven nonlinear and causing distortion of the time-varying signal. Realistic measurement-system calibration levels can be established once signal distortion is eliminated. Otherwise, analytically unpredictable signal magnitudes are initiated through the measurement system due to discontinuities in loading and/or sudden impulses that excite the resonant frequencies of the transducer.

- It enhances the measurement system signal-to-noise ratio. If initially filtered, all signal amplification can occur in the first available gain stage, and a high first-stage gain maximizes the signal-to-noise ratio of the entire channel.

- It narrows the frequency spectrum occupied by the data transmission. If numerous channels are multiplexed, as in space radio frequency transmission, the data frequency content can be made compatible with available bandwidth. Otherwise, bandwidth limitations of the measurement system may preclude transmission of the entire signal including the accelerometer resonance-based distortion. The overall effect of filtering in this situation is to make more effective use of the information capacity of the measurement system.

One particularly problematic type of mechanical input to airborne structures is pyroshock. Pyroshock is characterized by high-amplitude, high frequency, transient structural responses. Forces causing the transient responses are typically a combination of explosive and/or impact events. Explosive bolts, nuts and pins and V-band separation on rocket systems (sudden release of mechanical energy) are some examples of items that generate these forces in a flight environment. These excitations are particularly troublesome to electrical and electromechanical components (relays, switches, crystals, diodes, etc.). Pyroshock test data (below) will be used to validate the fact that data filtering should occur immediately after the accelerometer.

Figures 3 and 4 contain these test data. These are ground tests, where high frequency data content could be recorded. Figure 3 provides one example of an accelerometer responding to pyroshock data. Figure 3a shows the “raw” data, Figure 3b the signal energy spectrum, and Figure 3c the resultant data filtered at 10 kHz. The “small bump” in the frequency content in Figure 3b at 50 kHz is the resonant response of the accelerometer, which has “contaminated” the data in Figure 3a. The filter has removed the effects of this resonance in Figure 3c. The resultant filtered data is 81% of the peak-peak value of the unfiltered data and illustrates the actual response of the structure to which the accelerometer is affixed. Figure 4 shows a second example. In Figure 4a the recording electronics have been overranged with resultant nonlinearities created in the recorded acceleration signal.

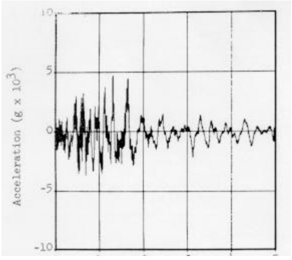

Figure 3a: 0- +/-5,000 g vert.
0-5 msec horizon.

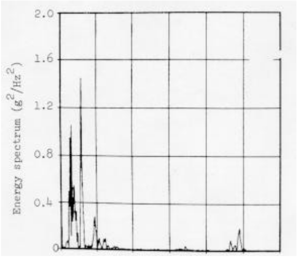

Figure 3b: 0-60,000 Hz

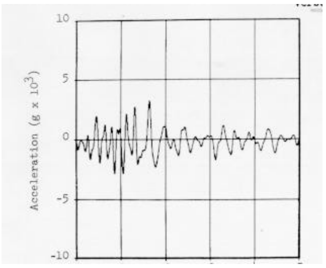

Figure 3c: 0- +/-5,000 g vert.
0-5 msec horizon.

Figure 3: Unfiltered and Filtered Pyroshock data

Figure 4b verifies the presence of these nonlinearities. There is no separation between the accelerometer's resonance and the structural data as in Figure 3b. The nonlinearities in the data resulted in erroneous spectral content. *However, the 10 kHz filter applied in Figure 4c can make the erroneous data appear to be valid.* In a flight application, filtering between the measuring accelerometer and first-stage gain of the signal conditioner (see preceding bullets) would have precluded erroneous data from occurring.

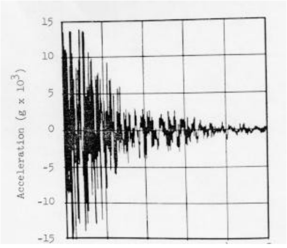

Figure 4a: 0- +/-8,000 g vert.
0-5 msec horizon.

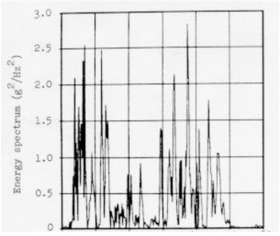

Figure 4b: 0-60,000 Hz

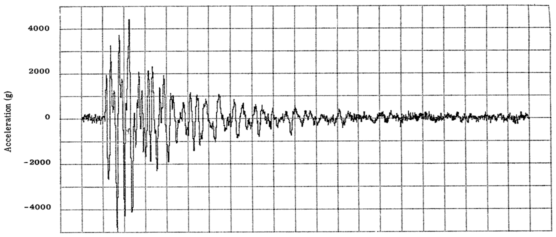

Figure 4c: Filtered Data of Figure 4a

Figure 4: Improper Filter Location Disguises Erroneous Data Signal Content

Having discussed mechanical shock data, the criterion recommended for filter selection for nondeterministic (random vibration) signals is easy to provide. The goal in measuring random vibration in flight applications is almost always to compute a power spectral density for the data. Since phase is not a consideration in power spectral density processing, the filter selected should bear the closest approximation to the ideal “boxcar” filter while passing the low-frequency signal content of interest. Of the three filters discussed, this is typically the Chebyshev.

CONCLUSION

This work has presented guidelines for filter selection and placement when measuring mechanical shock or vibration via airborne telemetry. Filter selection criteria are different for shock than for vibration. Regardless, this filtering should be provided between the measuring accelerometer output and the first-stage gain of the signal conditioning to preclude distortion due to accelerometer resonance excitation.

REFERENCES

1. Waters, Allan, Active Filter Design, McGraw Hill, Inc., NY, 1991.
2. Su, Kendall L., Analog Filters, Chapman & Hall, London, 1996.
3. Walter, P. L., and Nelson, H. D., “Limitations and Corrections in Measuring Structural Dynamics”, Experimental Mechanics, Vol. 12, No. 9, Sept. 1979, 309-316.
4. Walter, Patrick L., “Effect of Measurement System Phase Response on Shock Spectrum Computation”, The Shock and Vibration Bulletin, No. 53, Part 1, The Shock and Vibration Information Center, May 1983, 133-141.