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Shock Data Filtering Consequences

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ABSTRACT

The plateau of the Pseudo Velocity Shock Spectrum (PVSS) plotted on Four Coordinate Paper (4CP) shows the severe frequency range of the shock. Peak modal stress is proportional to PV [1, 2, 3, 4]; hence filtering effects can be quantified according to changes in the plateau. Maximum acceleration usually defines the high frequency extent of the plateau and low pass filtering reduces the peak acceleration levels of shock data. Thus low pass filtering hides the high frequency content of the shock in the shock analysis. This is demonstrated in both the time history as well as the PVSS. Both Butterworth and Bessel filters are compared to try and see if the linear phase attribute of the Bessel filter causes any changes in the PVSS.

INTRODUCTION

I am helping in a major change of shock analysis technology that is moving from emphasis on the acceleration shock spectrum, the SRS, to rely on the pseudo velocity shock spectrum plotted on four coordinate paper, the PVSS on 4CP. The change has many advantages, but mainly it specifically shows the damage capacity of the shock. It allows a better way to quantify the effects of filtering on shock data. This report presents a brief examination of some of the effects.

I have not done an exhaustive study of the mechanical shock filtering literature. Two documents seem to summarize results from many authors: Piersol's 1992 Sound and Vibration article [5], and the IEST Recommended Practice Handbook [6]. Some filtering recommendations for pyroshock (high frequency shock) from both of these documents are: (a) Low pass filtering should not be used with cutoff frequencies of less than 20 kHz, without a thorough analysis indicating why. The low pass cutoff should always be 1.5 times the highest frequency for later data analysis. [5, 6] (b) For high pass filters to remove "electrical offsets or drift in the transducer instrumentation", the cutoff frequency should be less than 20 Hz or 0.1% of the highest frequency of subsequent data analysis computations." Cutoff frequencies higher than this might remove as temporary zero shift indicating invalid data. My experience is that 75-100 Hz high pass will easily hide an invalid data zero shift, and make the data look gorgeous. Dave Smallwood shows examples of this in [12]. A general rule for low pass filters repeated many times is that the cutoff frequency must be at least 1.5 times the highest analysis frequency. That is, that the shock spectrum of a filtered shock is only accurate to two-thirds of the filter cutoff frequency. The testing I'm reporting here is that it can be below a half of the cutoff frequency.

Matlab became buyable in 1988 or so, and it makes manipulating and handling and plotting digital data quite easy. All of the calculations and plots for this document were made with Matlab Release 12 [7]. About 1988 it became easy for people to filter digital data on their PC's, but before that time, it took a serious programmer or electronic technician or one skilled in electronics to test filtering of shock data. I have books on writing filter routines in C and FORTRAN which are dated 1991 and 1993, so people were still writing C programs then. They refer to "designing" filters, which seems nuts; I use filters and assume Bessel and Butterworth did the designing years ago. Filtering was trusted to instrument makers who were trying to sell a product. Now, because we know the PVSS-4CP plateau is the severe shock region, we can look at filtering effects from a much more sensible point of view and this changes things. We can evaluate filtering by what it does to the plateau. The point being that papers on filtering dated before 1987 or so weren't done with Matlab and were much more difficult to do. In the early to mid 1970's time frame I was testing no-name low pass digital filters on shock data. The filters were FORTRAN programs, programmed by Dan Carlton [8] from WES; I remember him instructing me to run them forward and backward to remove any phase shift, so I did. I didn't want any phase shift; would you? That's terrible. (Matlab's "filtfilt" function does the forward backward filtering.) However I tested the results by calculating the PVSS with the files filtered both ways and could detect no difference.

Now with Matlab it has become very easy to filter data, high pass and low pass, with Butterworth, Bessel, Chebyshev, Elliptical, of any order you desire, forward or fore and back. It's time for more testing of these filters on shock data. I'll start that ball rolling with this paper, and I invite your comments, corrections, or better ideas.

This work will be easier to understand for those who are now convinced that the pseudo velocity shock spectrum plotted on four coordinate paper, PVSS on 4CP, is the only way you can evaluate severe shock. We believe that stress is proportional to modal velocity, that high modal velocities are around 100 ips, 2.5 meters/sec (modal velocities at the elastic limit of materials range from 100 for mild steel on up 1000 ips, 25 meters/sec, for ultra strong materials) and that the modal velocity a shock can deliver to equipment is given by the 5% damped PVSS on 4CP,

So we are gong to look at filtering shock data according to what it does to the 5% damped PVSS on 4CP of the shock data. Low pass filtering is a high frequency information erasing operation, and high pass filtering is a low frequency erasing operation. I'll demonstrate and explain the information erased by low pass. Low pass filtering cuts the peak acceleration, which in turn erases the high frequency portion of the plateau, and the plateau shows the frequencies where the shock is strong.

DROP TABLE SIMPLE SHOCKS

I'll start with a simple theoretical (algebraically specified), half sine drop table shock. Then I'll test an explosive shock, and finally move on to a real simple shock. The equation specified simple shock I'll use is a high frequency half sine shock of 2000 g and a 0.0004 sec duration, including the drop and a rebound with a coefficient of restitution of 0.65. Figure 1, shows its time history and integrals.

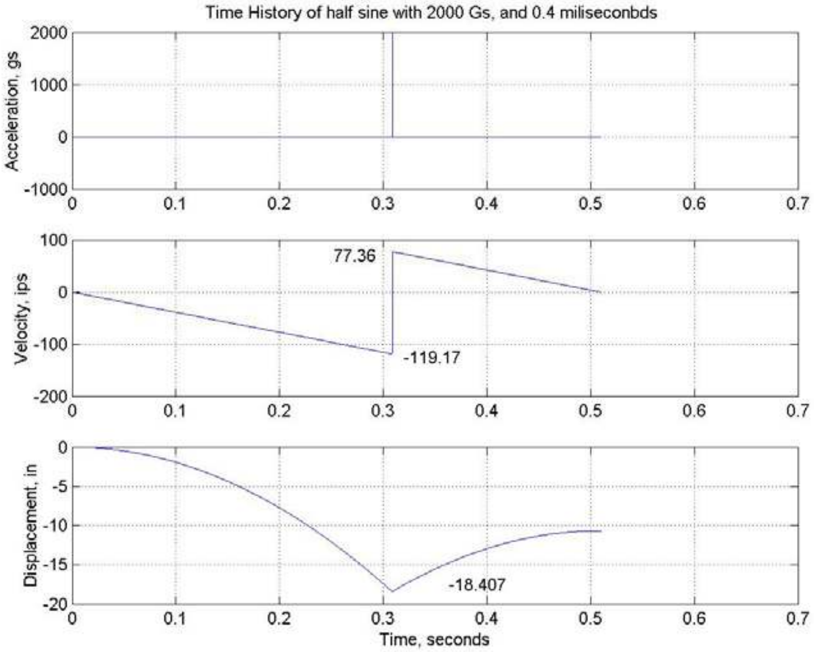


Figure 1. Acceleration, velocity and displacement of the severe high frequency half sine shock

Figure 2 shows its 5% damped PVSS. The plateau comes out to be 185.3 ips. Stopping the analysis at 10,000 Hz barely lets us see that it hits the 200 g asymptote.

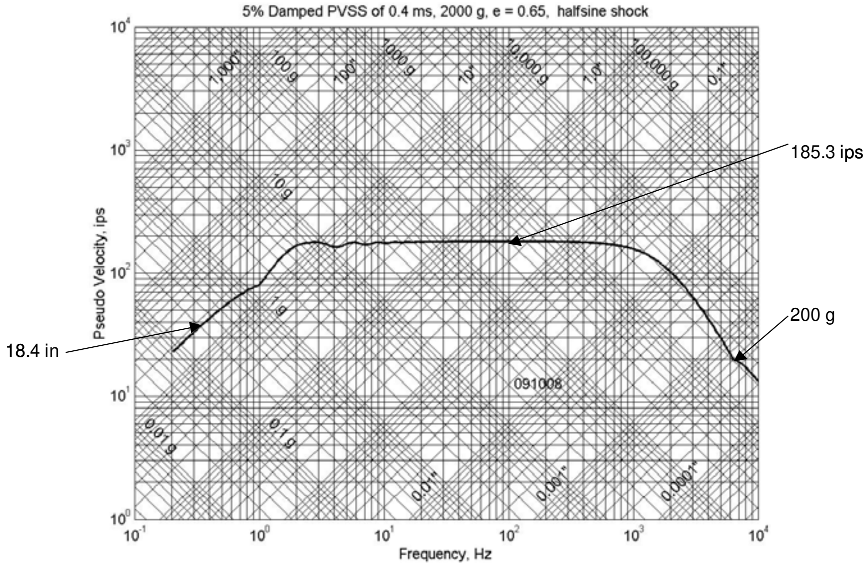


Figure 2. The 5% damped PVSS plotted on four coordinate paper for the high frequency shock of Figure 1. It has a long plateau going from 2 Hz out to about 800 Hz.

I call this is a high frequency shock because it has a high PV content near 200 ips (5 meters/sec) out close to 1000 Hz. Since PV indicates stress, this shock is severe for equipment with modal frequencies from 2 to 1000 Hz. Figure 3 shows the effect of low pass filtering the shock with 2 pole Butterworth filters with cut off frequencies of 1000, 500, and 250 Hz.

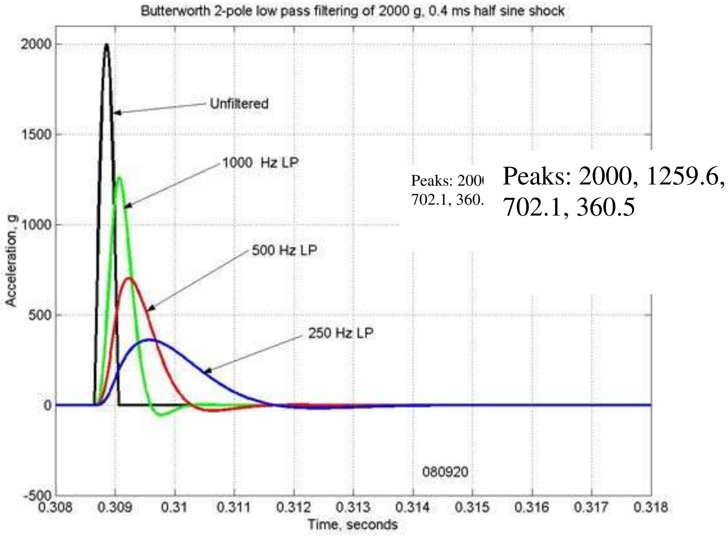


Figure 3. This shows a comparison of filtered time histories to the unfiltered shock. Notice the drastic effect on the peak acceleration. Black is unfiltered, green is 1000 Hz low passed, red 500, and blue 250 Hz low passed. The maxima of the filtered halfsines are 1000: 1259.6, 500: 702.1, 250: 360.5.

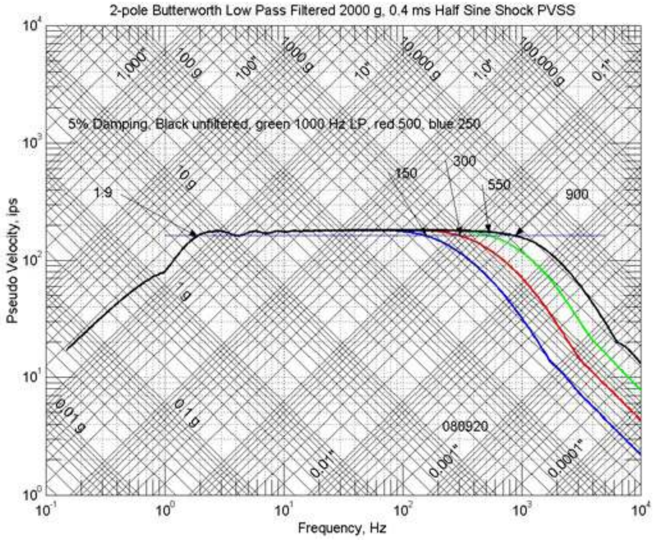


Figure 4. PVSS of the unfiltered, and Butterworth, 2-pole, low pass filtered high frequency simple drop table shocks. Notice thin blue line at 90% of plateau, 162.40 ips. This is where the stress has dropped to 90%. Filtering obscures part of severe plateau.

Figure 4, shows the effect of low pass filtering on the 5% damped PVSS of our high frequency half sine simple shock. On this shock the flat portion or plateau is at a PV of 180.54 ips. Recall that this is proportional to stress. I have drawn a thin blue line at 90% of this value or 162.40 ips. Where this line intersects the PVSS's one might consider the high and low frequency limits of the shock; it's where the stress has dropped to 90% of its peak value. Thus the thin line intersection with the four PVSS plots shows the high frequency limits of the shock. I estimate these intersections to be at 900, 550, 300, 150, and 1.9 Hz. The unfiltered shock has high PV content from 1.9 Hz out to 900 Hz; 1000 Hz low pass cuts plateau upper frequency to 550 Hz, 500 Hz LP cuts it to 350 Hz, and 250 Hz LP cuts it to 150 Hz. The unfiltered data is the shock felt by the equipment. The filtered shock is what we might show in a report acknowledging that the data had been filtered, but probably misleading the reader about the extent of this effect. One would certainly expect a 1000 Hz low pass filter to leave the plateau untouched until after 1000 Hz. It is shown here that a 1000 Hz low pass filter hides high frequency data beyond 550 Hz. The conclusion is that low pass filtering hides the high frequency damage potential of the shock.

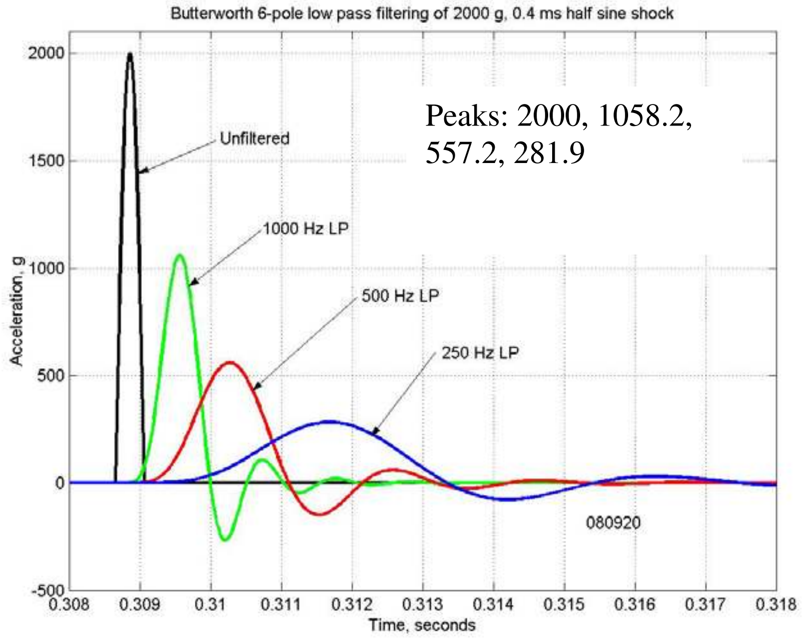


Figure 5 This shows a comparison of the 6-pole Butterworth filtered time histories to the unfiltered shock. Notice the drastic effect on the peak acceleration. Black is unfiltered, green is 1000 Hz low passed, red 500, and blue 250 Hz low passed. Notice also the ringing or decaying waviness of the 6-pole filter. The maxima of the filtered half sines are 1000: 1058.2, 500: 557.2, 250: 281.9

Figure 5 shows a 6-pole Butterworth filtering of the shock. Six poles means the cut off is sharper by 6 dB/octave and per pole. (When searching for filter cutoff rates, I found many references stating that Butterworth filters provide 6 dB/Octave per pole. e.g. [10], a very nice short article.) Thus this filter rolls off at 36 dB/octave. The sharp cutoff causes a ringing which can be seen as undulations in Figure 5. Notice also that the peak g levels are also reduced greatly. Figure 6 shows the PVSS of these 6-pole filtered shocks. I defined a simple shock PVSS characteristic I call the droop zone in [11]. The droop zone is where peak acceleration exceeds the peak acceleration asymptote. In comparing 2 and 6 pole Butterworth filtering effects, the 'droop zone' duration is reduced. Look at the blue PVSS's of Figures 4 and 6. On Figure 4 it ends at 1700 Hz, whereas on Figure 6 it ends at 550 Hz. Notice the blue curve in Figure 6 has an acceleration asymptote of 300 g, and the droop zone, which is between 150 and 600 Hz, rises to about 450 g.

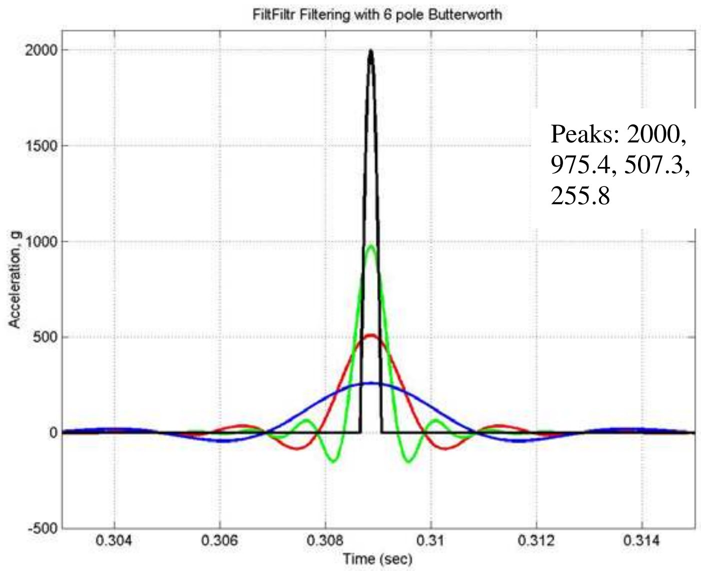


Figure 5a. Forward and backward 6 pole Butterworth filterings of the half sine. Notice now a precursor, and peak value reduction. Filtfilt is a Matlab option; I don't like the precursor.

Figure 5a shows the effect of the forward backward 6-pole Butterworth filtering. SRS, and I assume PVSS analysis may be adversely affected by phase errors in the antialiasing low pass filter. Linear phase, constant time delay filters are theoretically desirable for antialiasing. Bessel filters have this, but they are no good because of their low cutoff rate. Any filter can be made to have a zero phase shift by forward backward filtering. Then without saying if this is a good idea, they jump to "nonlinear phase characteristics of the antialiasing filter can be avoided by simply limiting the analysis to two-thirds of the cut off frequency." [6, p 139]

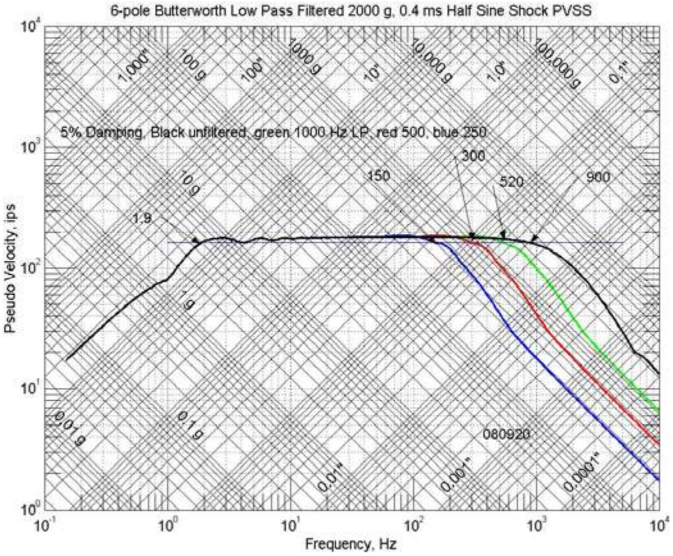


Figure 6. The effect of using a 6 pole Butterworth is essentially the same as using a 2 pole.

Bessel filters are reported to be best for low pass filtering because of their linear phase characteristics I'll examine the two and six pole Bessel's to see how they compare with the two and six pole Butterworth filters. I won't use the forward backward, filtering, because it introduces a precursor. See Figure 5a.

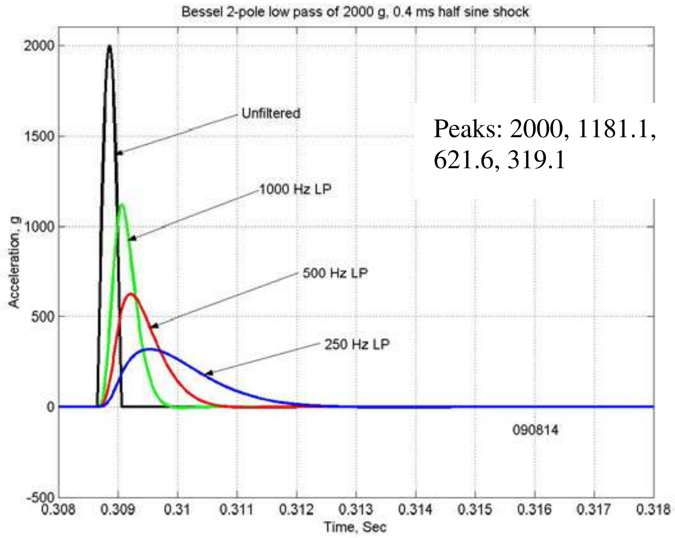


Figure 7 This shows a comparison of filtered time histories to the unfiltered shock. Notice the drastic effect on the peak acceleration. Black is unfiltered, green is 1000 Hz low passed, red 500, and blue 250 Hz low passed. Maxima of the filtered halfsines: 1000: 1181.1, 500: 621.6, 250: 319.1.

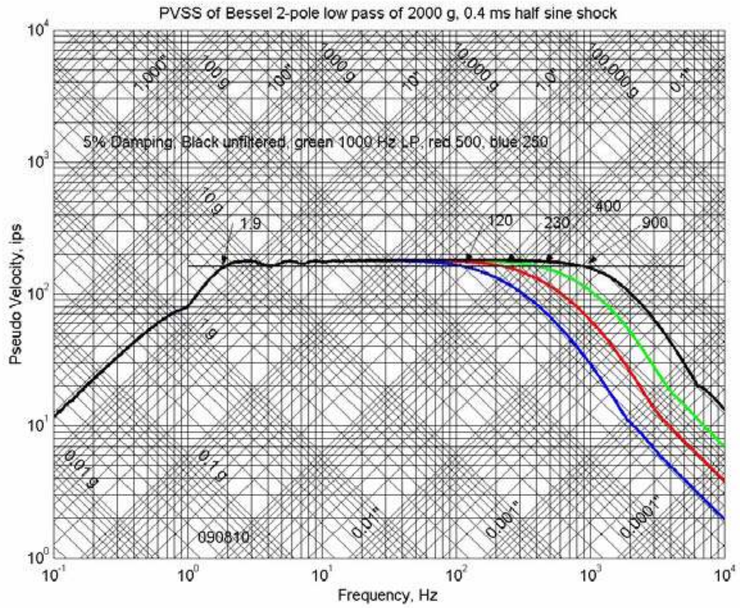
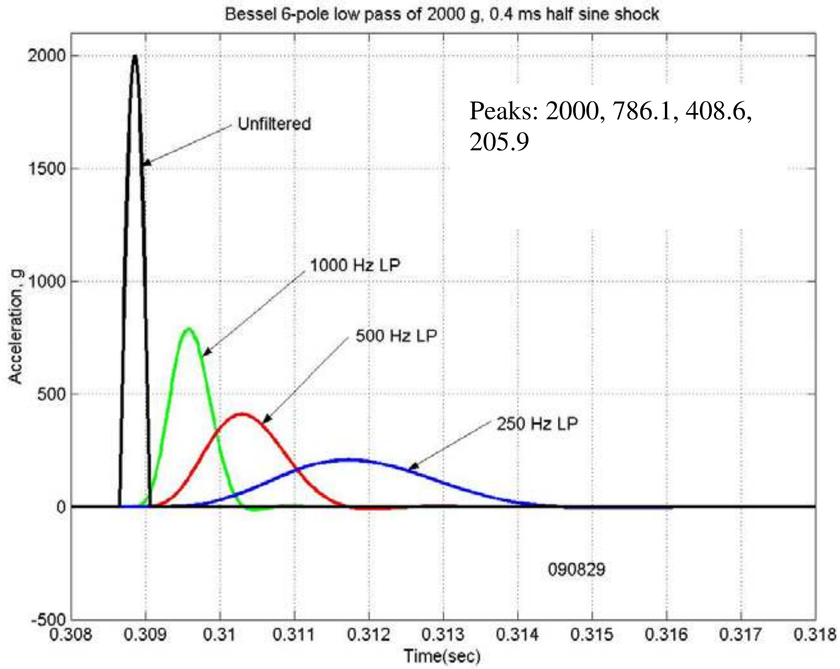


Figure 8. PVSS of 2 pole Bessel filtered high frequency half sine shock. Smoother droop zone.

Figures 7 and 8 show the time histories and the PVSSs for the 2-pole Bessel filtered half sine. The time history shows essentially no overshoot, or ringing waviness, and the droop zones in the PVSSs are very smooth. Figures 9 and 10 show the same thing for the 6-pole Bessel filterings. Smoother droop zone; still about the same high frequency plateau hiding.



Peaks: 2000, 786.1, 408.6, 205.9

Figure 9. This shows a comparison of 6-pole Bessel filtered time histories to the unfiltered shock. Notice the drastic effect on the peak acceleration. Black is unfiltered, green is 1000 Hz low passed, red 500, and blue 250 Hz low passed. Smoother droop zone; still about the same high frequency plateau hiding. Maxima of the filtered halfsines: 2000: 786.1, 500: 408.6, 250: 205.9. Shocks are delayed more, flattened, and look symmetrical. No steep rise and gradual tail off. Very slight ringing.

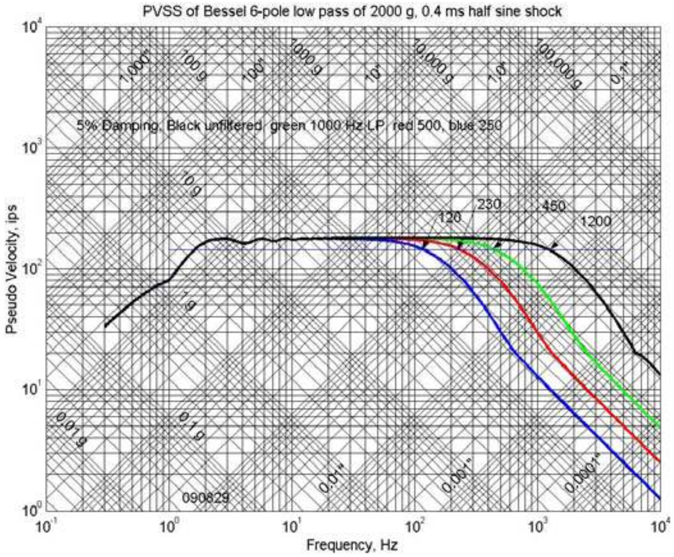


Figure 10. PVSS of 6 Pole Bessel low pass filtered 0.4 ms, 2000 g half sine with cutoffs at 1000, 500, and 250 Hz.

In Figure 10, I've dropped the plateau cut off line to 20 % just to see the change in the plateau limiting frequencies. The upshot is 1000 Hz LP cuts things off at 450 Hz; the 500 Hz LP cuts it off at 250 Hz, and the 250 LP at 120 Hz.

Table 1. Estimated Intersection values of PVSS with depressed plateau by 10%

Frequency Intersect	Low	unf	1000 Hz	500 Hz	250 Hz
Butter 2 pole, 10 %	1.9	850	520, 52%	300, 60%	150, 60%
Butter 6 pole, 10 %	1.9	850	510, 51%	290, 58%	140, 56%
Bessel 2 pole, 10 %	1.9	850	410, 41%	230, 46%	110, 44%
Bessel 6 pole, 20%	1.6	1300	430, 43%	230, 46%	120, 48%

Table 1 gives a good summary of the drastic effects of filtering. We had kind of thought that a 250 Hz low pass would not distort meaningful content below 250 Hz, and that's simply not true. Butterworth filters hide the plateau at 50-60% of cutoff; Bessel filters hide the plateau at 40-50% of cutoff. Table 2 lists the peak accelerations for the different filters.

Table 2. Maximum values of filtered half sines.

	Unfiltered	1000 Hz	500 Hz	250 Hz
Butter 2 pole	2000	1259.6	702.1	360.5
Butter 6 pole	2000	1058.2	557.2	281.9
Butter 6 pole FF	2000	975.4	507.3	255.8
Bessel 2 Pole	2000	1181.1	621.6	319.1
Bessel 6 Pole	2000	786.1	408.6	205.9

EXPLOSIVE MULTICYCLE SHOCK

Now let's examine the effects of filtering on a non simple explosive shock motion. The results are similar. Figure 11 shows Navy Mil-S-901 heavyweight shock test acceleration and its integrals. The test is done by mounting the equipment in a barge and setting off an underwater explosion nearby to simulate ship shock motions. It makes a good example for this analysis. To filter this shock I used a 2-pole Bessel filter because its linear phase will not affect the time history. Figure 11 shows its time history and integrals.

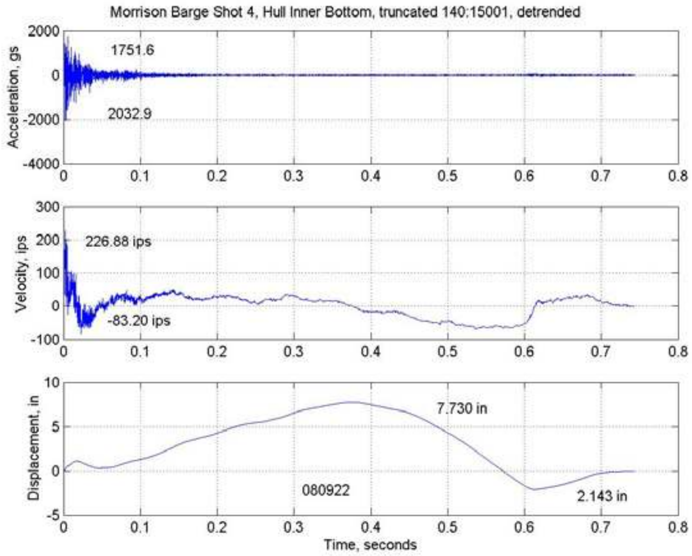


Figure 11. Navy heavy weight shock test example. This is a multicycle real data shock for test of low pass filtering effects. These are often filtered.

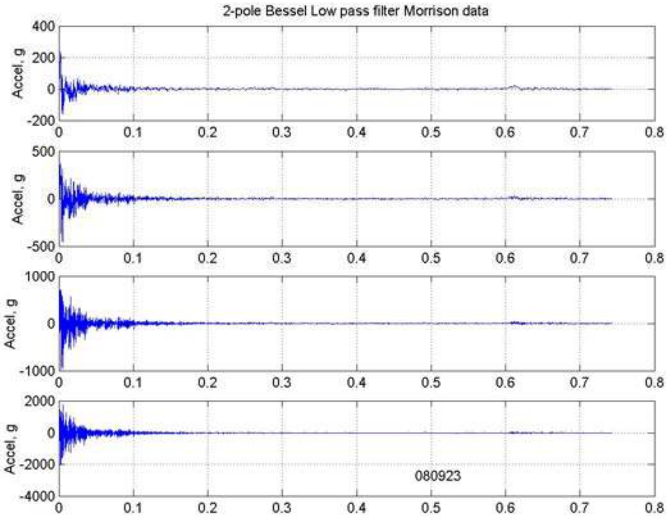


Figure 12 Filtered acceleration time histories. Unfiltered on bottom, 1000 next one up, 500 second from top, and 250 on the top.

In Figure 12, I tried to show the filter effect on peak acceleration, but it is not as clear as I like. The graphs are auto-ranged so you have to look at the scale on the ordinates. What I did in Figure 13 is to repeat the above, but only for the high intensity first 10 ms and not auto-range to show the dramatic effect on the acceleration. It is interesting to see how the peak accelerations are reduced and yet the PVSSs of Figure 14 are unaffected at low frequency and gracefully reduced at high frequencies.

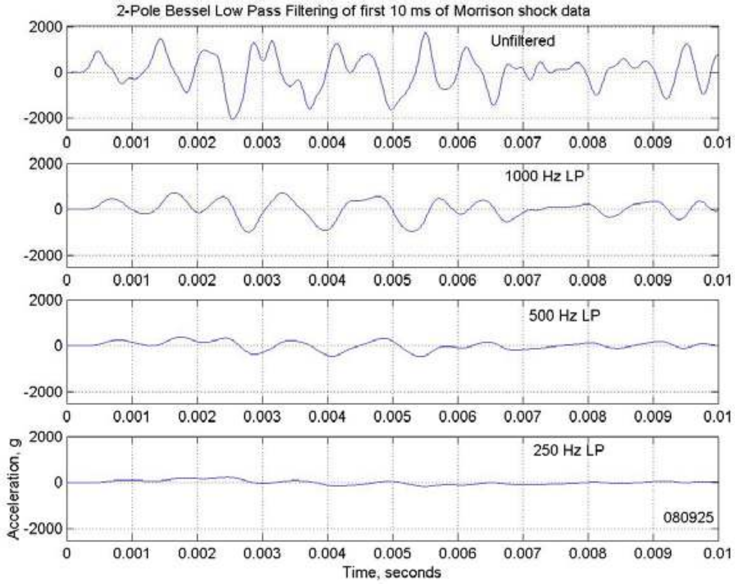


Figure 13. I think the thing to notice is that the peak acceleration is surprisingly reduced by low pass filtering,

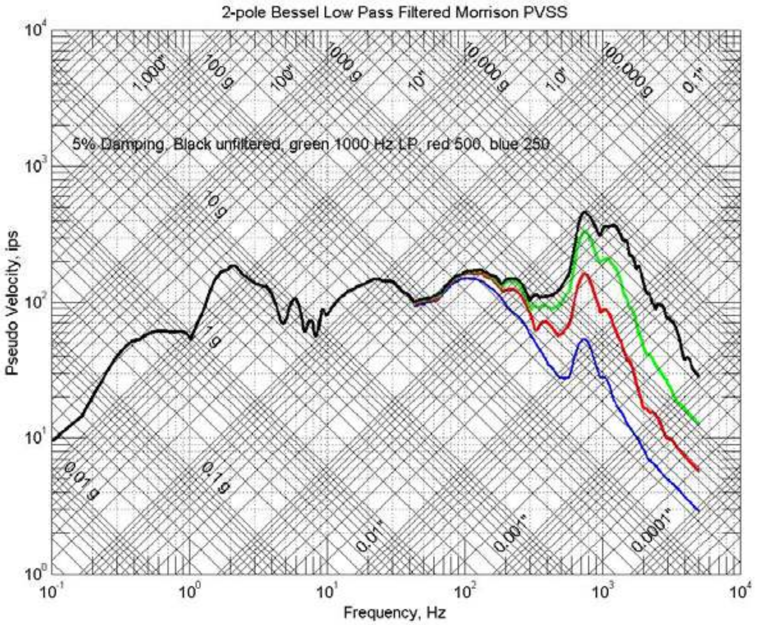


Figure 14 Estimating the frequency at which the filter has reduced the PV by 10%, the 250 Hz low pass reduces the PV by 10% at about 90 Hz; the 500 Hz low pass at about 200 Hz, and the 1000 Hz low pass at about 300 Hz.

Notice in Figure 14, How the high frequency plateau is successively reduced by the filtering, while the low frequency is unaffected. The filtering was done with a Bessel 2 pole filter which has a linear phase and is not supposed to affect the time history or the PVSS.

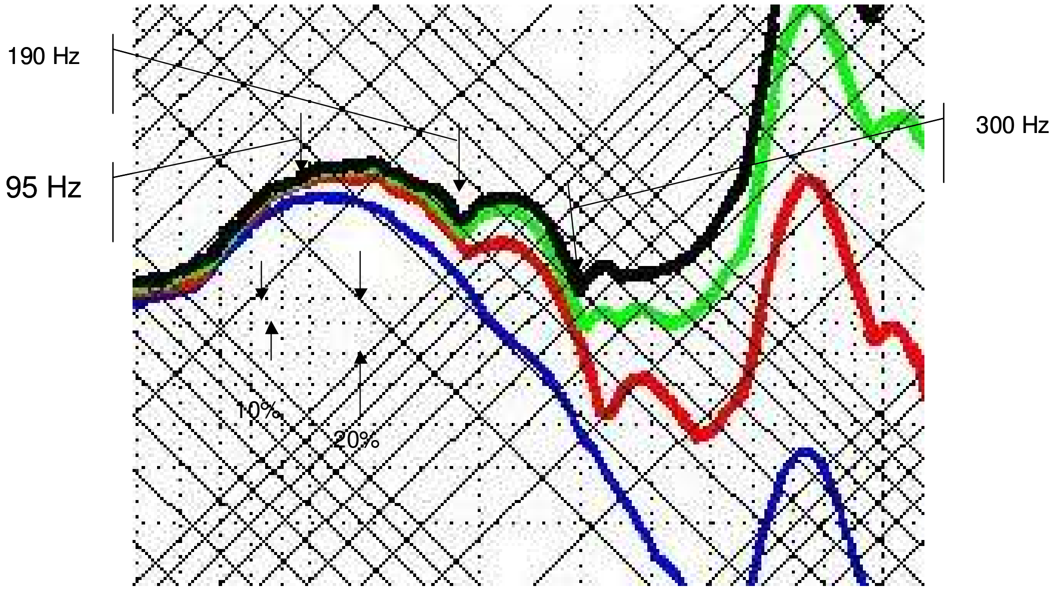


Figure 14a. Expanded view of high frequency plateau region as it is affected by the three different low pass filters. Notice the 4 vertical arrows that show the height or distance representing 10 and 20%. Green is a 1000 Hz low pass, red: 500, and blue 250 Hz.

Figure 14a, is an expanded view of the affected high frequency plateau region portion so we can estimate the frequencies at which the filterings cause a 10% reduction on the plateau. The blue or the 250 Hz low pass reduces the PV by 10% at about 95 Hz; the red or 500 Hz low pass causes a 10% reduction at about 190 Hz, and the green or 1000 Hz low pass at about 300 Hz. The upshot is that a 500 Hz low pass does not mean you are only cutting content above 500 Hz at all. It's much worse. The content appears in the spectrum but at deceptively low levels.

I want to emphasize this; the:

1000 Hz 2-pole Bessel low pass causes a 10% plateau depression at 300 Hz, 30% of 1000 Hz
500 Hz 2-pole Bessel low pass causes a 10% plateau depression at 190 Hz, 38% of 500
250 Hz 2-pole Bessel low pass causes a 10% plateau depression at 95 Hz, 38% of 250

So rather than the PVSS being affected at 67% of the cutoff frequency indicated in [5,6], it is affected by 10% at about 35% of the cutoff filter frequency.

DROP TABLE SHOCK MACHINE TEST SHOCK

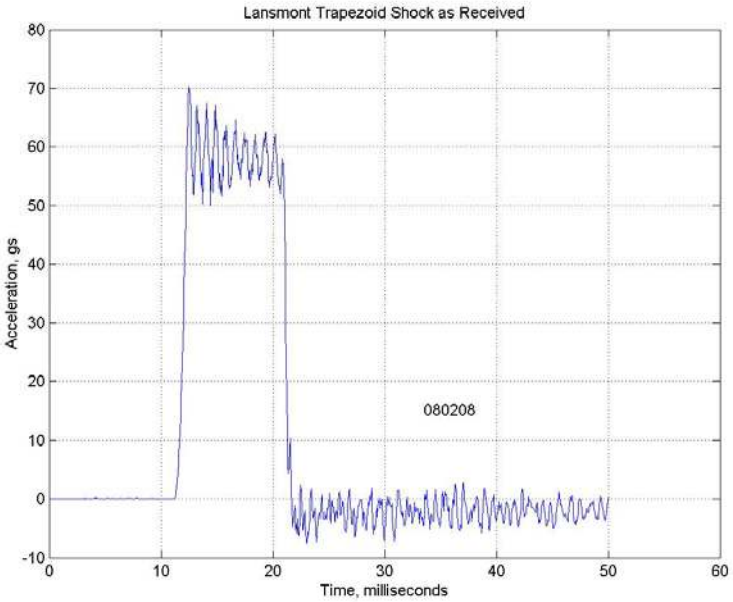


Figure 15 This is an unfiltered 60 g, trapezoidal shock. These are used a lot in package cushioning work.

This is a different problem entirely. Figure 15, shows an acceleration time plot of an actual 60 g ASTM D3332 [9] package cushion testing trapezoidal shock. I filtered this shock many times because I suspected filtering was being used to hide important information. It wasn't, but that testing was instructive to me, and I think it will be interesting to you. In Figure 16, I added a sufficient 1 g drop to the front of the shock so the impact of the shock brings the final velocity to zero. The specification calls for the shock to be “faired” to hide the lumpiness. I'm thinking, if you don’t like it or it raises questions, hide it. Is this a case of deceptive filtering?

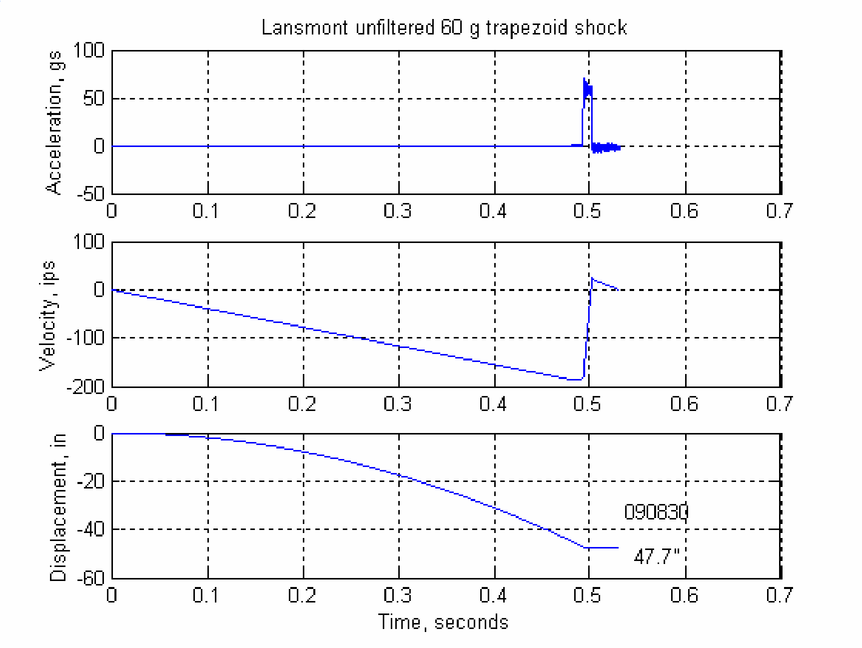


Figure 16. Add a 1 g drop to the beginning to bring the final velocity to zero. Notice this requires a 47.7 inch drop, and the impact velocity change is about 200 ips, so this is a severe shock.

Figure 17 Shows the PVSS of this shock in the red curve, and we see it is quite severe from 1 to 40 Hz.

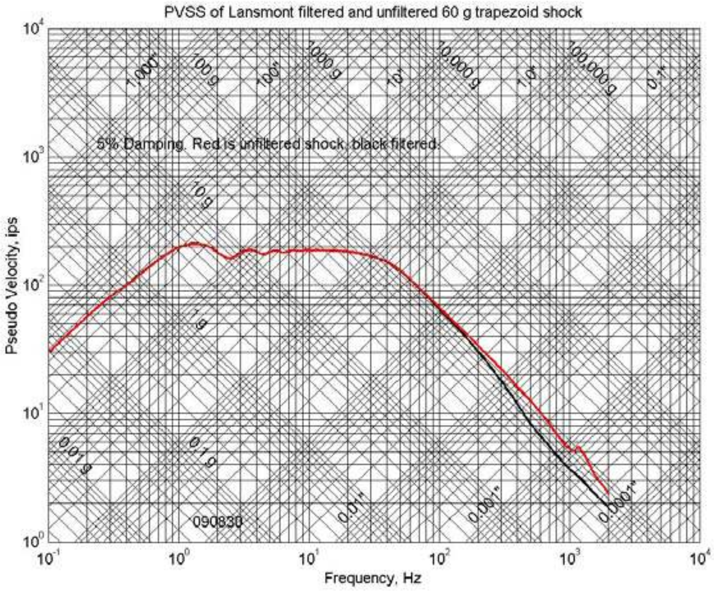


Figure 17. PVSS of the Bessel 2-pole-pole 300 Hz low pass filtered 60 g trapezoid and the red unfiltered shock.

The ASTM Spec [9] talks about a "faired pulse and offers the picture shown in Figure 18. Lansmont Corporation [13] in their "Damage Boundary presentation" shows Figure 18, of a "faired" trapezoidal shock. It is amusing that in the presentation used to develop the Damage Boundary concept, a trapezoidal shock is chosen because its theoretical concept has an almost instantaneous rise time which gives the shock a doubling of the peak acceleration on the normalized SRS that they use to explain the theory. Figure 18 shows an exaggerated slope rise time and completely ignores the instant rise time used in the arguments to develop the theory..

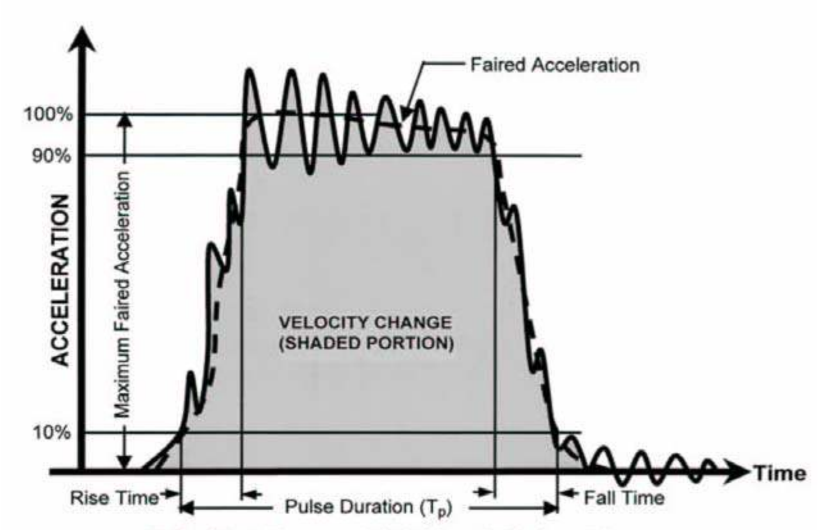


FIG. A2.1 Trapezoidal Shock Pulse Diagram

Figure 18. Diagram illustrating a faired trapezoidal pulse.

Figure 19. Shows an illustration, again from the Lansmont Corporation presentation, of what they consider a faired trapezoidal shock. You can see why my suspicions concerning filtering were aroused. (Available on the Lansmont website, www.lansmont.com.)

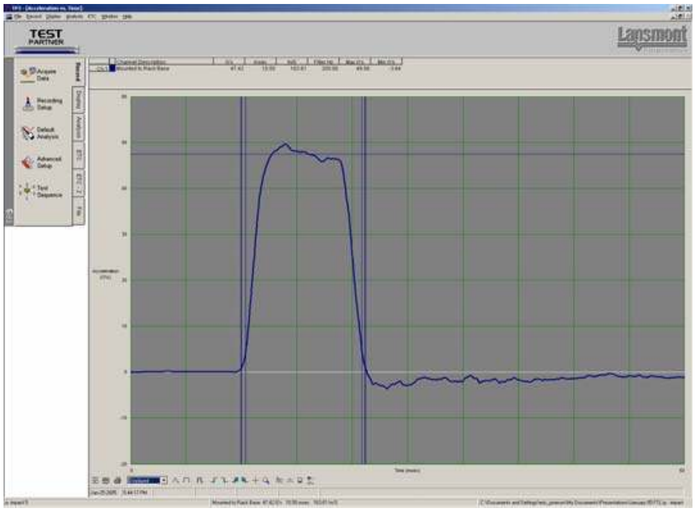


Figure 19. Illustration from Lansmont Damage boundary Presentation illustrating concept of a "faired" trapezoidal shock.

The question I was asking myself was, "does this fairing hide shock severity from the observers?" If you have a need to hide shock severity from an observer, maybe filtering is a good way. Also I presume "fairing" is low pass filtering, so I'll try it. I'll filter the raw pulse to see if I end up with anything like Figure 19.

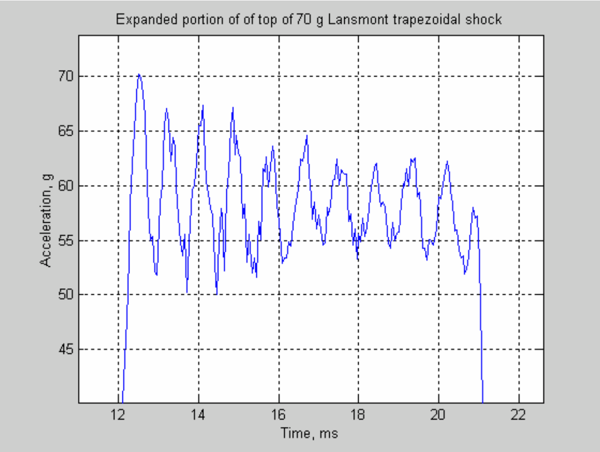


Figure 20 Expanded portion of Lansmont trapezoidal shock of Figure 15. I count 10 valleys between the first and last peak. Time interval is from 12.5 to 21 ms. Frequency is about
10/(21-12.5) = 1.1765 cycles/ms = 1176 Hz.

In Figure 20, I show an expanded view of the top of the trapezoid so we can look at its frequency content. I explain in the figure caption that I estimate that frequency to be about 1170 Hz. I thought maybe to eliminate this I should low pass at 1000, and probably should use a Bessel filter because we don't want to distort the trapezoidal appearance. I used a 2-pole 1000 Hz Bessel low pass, just on the pulse alone and found the result of Figure 21.

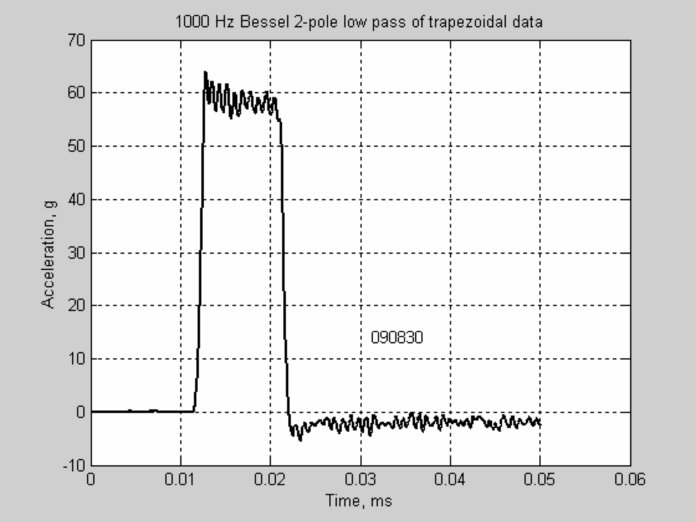


Figure 21. The shows a Bessel 2-pole-pole 1000 Hz, low pass filtering of the shock of Figure 15

I continued to try lower frequency low pass filters until I found a satisfactory result at 300 Hz, and this is shown in Figure 22 superimposed on the unfiltered shock.

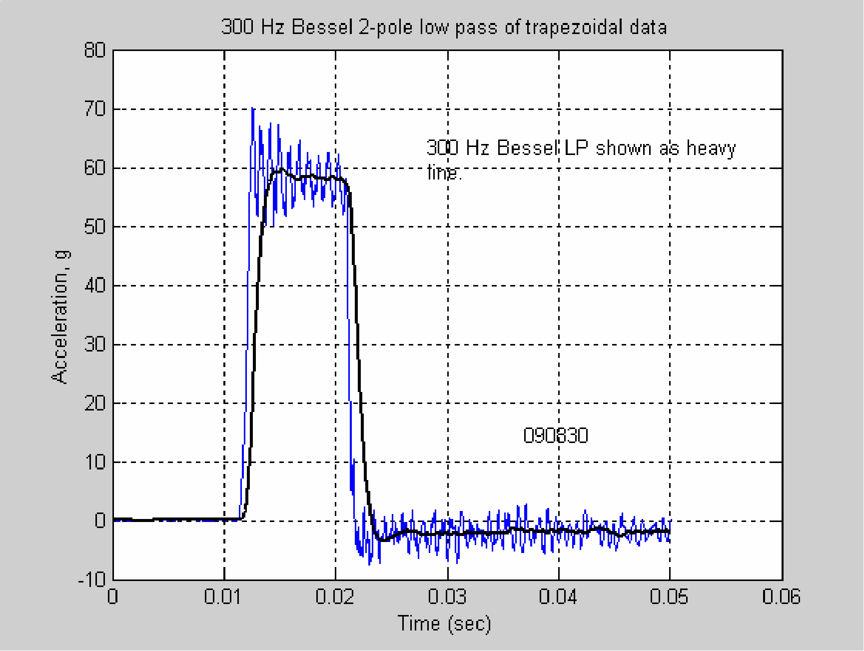


Figure 22. Bessel 2-pole-pole 300 Hz low pass filtering of the shock superimposed on the original shock.

I think this does it. That's faired. This seems good enough Also note the filter definitely changes initial rise time, so it will affect the droop zone. In Figure 23, I present the time history and integrals of this faired shock and it seems indistinguishable from unfiltered the plot of Figure 16.

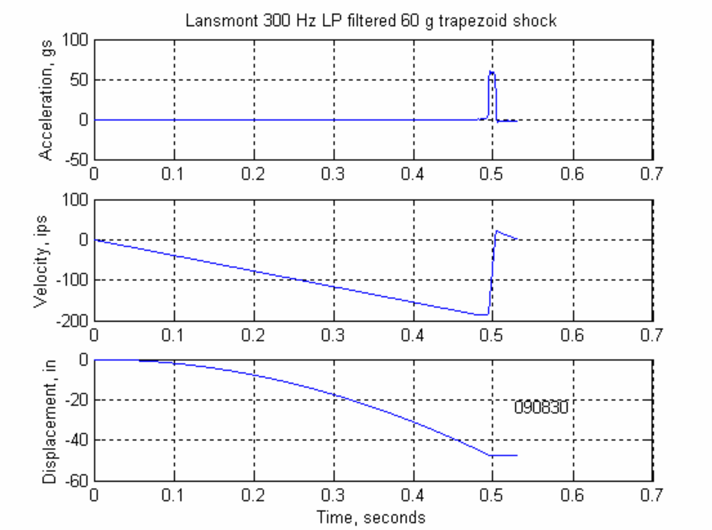


Figure 23 Bessel 2-pole-pole 300 Hz low pass filtered 60 g trapezoid shock with 1 g drop so final velocity is 0.

Figure 17 shows the PVSS of this shock in black and the original unfiltered shock in red. Notice the little 1100 Hz blip in the unfiltered PVSS. That's all the effect that the lumpiness on the trapezoid top causes. The droop zone is considerably reduced, due to the increased shock rise time. The black curve ends up at its 60 g peak asymptote. The red curve has its high frequency asymptote at 70 g where the tops of the lumpiness are. The only change due to filtering is down in the very low PVSS range; the "who cares" region. Fairing and filtering here does no harm and hides nothing bad. My suspicions were unfounded. After having gone through all of this, it finally occurred to me that the severe region of the shock, the high plateau region, is from 1 to 40 Hz as seen of Figure 17. I should not have been surprised that the 300 Hz low pass filter does not alter that severe region.

CONCLUSIONS:

The conclusion has to be certainly that low pass filtering of shock data has a more drastic affect on the shock severity analysis of the pseudo velocity shock spectrum than one is led to believe by the filter cutoff frequency. The PVSS plateau is reduced by 10% at frequencies of about one-third to 60% of the filter cutoff frequency. Standard guidance [5,6] has been that the SRS is good to 2/3 the cutoff frequency. Similarly, antialiasing filters are going to hide true plateau levels at about one third to 60% of their cutoff frequencies. An anitialiasing filter with a cutoff frequency of 20 kHz is likely to reduce the calculated level of the plateau at frequencies above 6.7 - 12 kHz.

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