A new method of designing MIL STD (et al) shock tests that meet specification and practical constraints

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Biography

The author has a degree in Electronic Engineering, is an SEE Member and for many years was a software design engineer and R&D manager developing real time spectrum analyser and shaker controller instrumentation. He is currently the Managing Director of m+p international (UK) Ltd, the Northern European sales and support centre for m+p international.

Abstract

This paper briefly reviews the basic requirements for creating a shock pulse time history suitable for use by digital controllers on electro-dynamic shakers.

In developing a practical test we not only need to meet the various test specification requirements we also require to do so within the limits of the available test equipment.

Although most specs define pre and post pulse amplitude limits they do not define their shape or duration. This provides a very powerful opportunity to choose these pre and post pulses to optimise compensation to suit other system constraints (eg shaker displacement limit) but without excessive shock spectra distortion or other undesirable side effects. However since there are an infinite number of possible solutions this process is far from trivial. Also the symmetrical sinusoidal compensation pulses that are most commonly used may be easy to compute but do not offer much scope for optimisation.

A pulse shape and constraints methodology was put forward in a paper by R.T. Fandrich at Harris Corporation in 1981. Fandrich applied his method to optimising a 30g 11ms pulse for use on a 1 inch displacement shaker but this involved significant manual parameter optimisation. This methodology has been revisited and adapted to provide a more general solution that computes an optimum solution directly from test spec and test equipment parameters.

Keywords

Classical shock, digital control, compensation, optimisation, MIL STD, constraints, Fandrich

Test requirements and equipment constraints

For classical shock testing the following test conditions are normally specified: -

pulse shape, eg halfsine, sawtooth etc
pulse peak amplitude
pulse duration
pre-pulse tolerance, normally a positive and negative percentage of the peak with an additional lead in band
post pulse tolerance with a lead out band[1]

In addition to achieving these test requirements we also have to create a compensated pulse whose acceleration, velocity and displacement characteristics are within the limits defined by the test equipment being used. The key constraints imposed by our test gear that are to be considered here are: -

a) initial and final conditions, ie zero acceleration, velocity and displacement
b) shaker peak velocity capability
c) shaker peak to peak displacement capability
d) shaker and amp minimum operating frequency
e) also compensation must add minimal additional damage potential (SRS deviation)

As an illustration in this paper I shall use the classic 30g 11ms halfsine example. This will be familiar to most readers and allows a direct comparison with Fandrich's original paper on this topic.

As well as creating an optimum solution based directly on the above criteria the author set out to find a generalised solution that does not require complex mathematical tools or algorithms and has a minimum of iterative steps.

Common solutions

Of course there are a number of well-known compensation solutions commonly available.

The most frequently used is based on symmetrical pre and post pulses, see Figure 1.

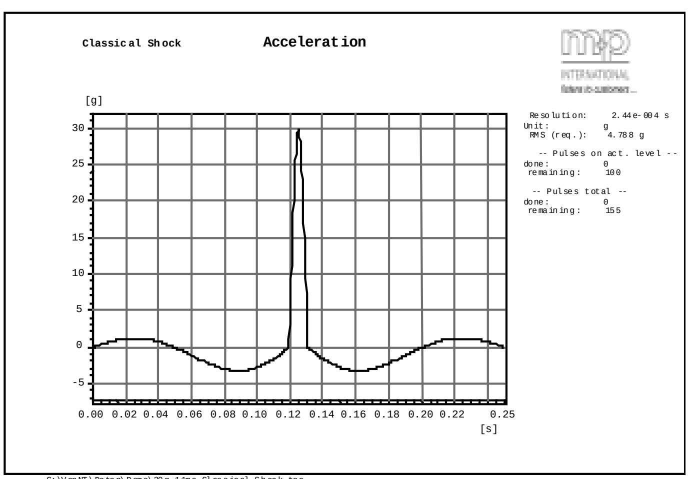

Figure 1 - Symmetrical compensation

[1] Although different positive and negative tolerances are defined in MIL STD only the negative limit is discussed here since the positive compensation pulse levels are always much less in this solution.

Although the most basic half sine solution produces only a single sided displacement solution this is easily modified to create a double-sided result. However the limitation of this compensation type is that for low value tolerance bands (eg the MIL STD 5%) the duration of the pre-pulse compensation tends to be greater than is desirable. This results in poor sample resolution over the main pulse and/or too low a frequency for the shaker/amplifier or most likely produces a higher displacement requirement than is available. This problem is also exacerbated by the symmetry of the post pulse even when post pulse tolerances typically allow higher amplitudes (eg MIL STD 30% that would allow the use a shorter post pulse).

A number of asymmetric variations using sinusoidal pre and post pulse types have also been used. Although these may result in a workable solution in some cases, I am not aware of a generalised solution. Other "optimisation" algorithms are also available which typically only allow either displacement or velocity to be minimised usually at the detriment of the other or another parameter such as amplitude.

For the classic MIL STD 810 tests an optimised solution was developed nearly 20 years ago by R J Fandrich and described in a paper published in 1981(see ref 1). Figure 2 shows the Fandrich solution based on his 30g 11ms example where displacement has been minimised to allow use on a 1" shaker. This pulse shape will be familiar to most readers.

Although Fandrich only produced an optimised solution for the above pulse specification the basic shape can be linearly scaled in both the time and acceleration axes. This feature is commonly used to produce solutions for different pulse duration and amplitudes and works well for the common 60g 11ms and even 100g 6ms MIL STD tests. The common factors that make this possible are that each test shares the same pulse shape (halfsine) and also the same pre and post tolerance percentage bands (5% pre and 30% post). Where these parameters differ from the original, simple re-scaling can not be applied to produce an optimum result. Apart from manual parameter selection and optimisation Fandrich does not suggest a way of optimising other test requirements.

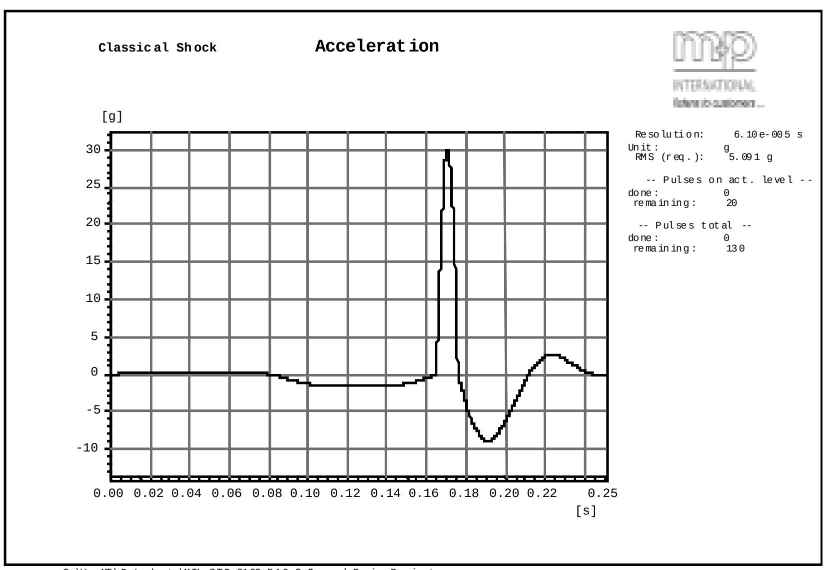

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Figure 2 - Fandrich's MIL STD compensation

The general method described here has been developed to compute a solution from user defined tolerance percentages, shaker displacement and minimum allowable frequency. So rather than produce simply a minimum velocity or minimum displacement result we are able to produce an optimum overall solution that takes advantage of all key system capabilities. It is also possible to change pre and post pulse shapes to either minimise SRS "distortion" or enable larger pulses to be accommodated within a given shaker capability.

Overview of compensated pulse sequence

To help understand the optimisation process it is useful to review the purpose of the compensation pulses as we progress through the sample window. Although I will use the Fandrich example the same basic principals apply to all types of solution.

Referring to Figure 3 we clearly see the main acceleration pulse between lines C and E. The pre pulse is bounded by A and C and the post pulse between E and G.

The first requirement is that the shaker starts and ends at rest (A & G) with zero acceleration and velocity. Displacement is also zero at these end points and I have chosen to assume this zero rest position is mid way between min and max shaker travel (symmetrical double sided).

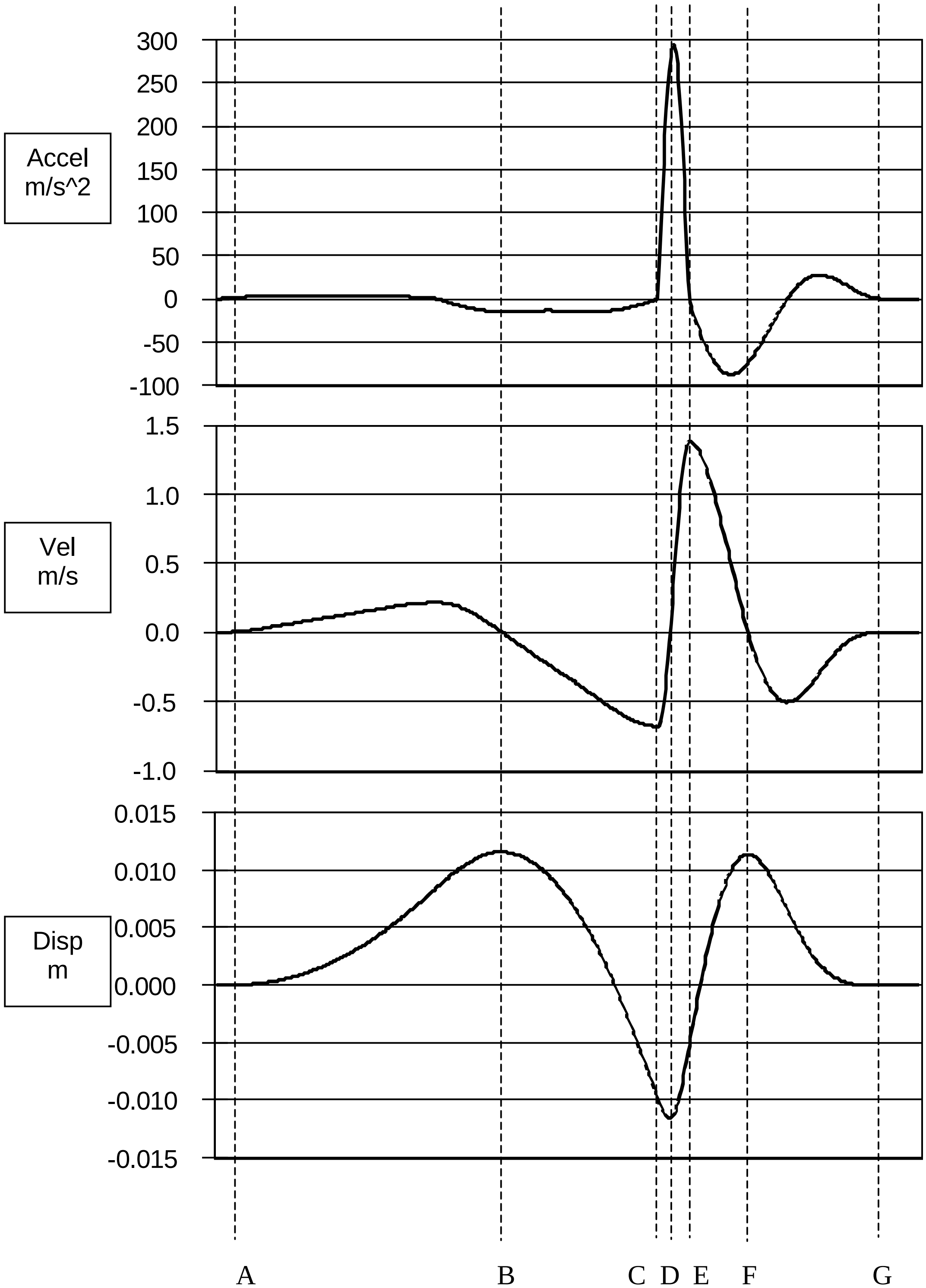

Figure 3 - Compensated pulse sequence (30g 11ms)

Since the main pulse has zero acceleration at its start (C) and its end (E) then it follows that both the pre and post pulse must also be zero at these points.

The purpose of the pre pulse is two fold. First to minimise the armature velocity requirement it should accelerate the armature to a maximum negative velocity where the ideal is half of the main pulse velocity change (approx. -1m/s for the 30g 11ms example). Second to utilise the maximum shaker travel the displacement should be symmetrical around the rest point. However the displacement at the end of the pre-pulse must be a little higher than the lowest level since it is still travelling at maximum negative velocity at this point and will be slowed to the maximum point only during the main pulse (point D).

Following the main pulse the purpose of the post-pulse is to simply return the armature from its maximum positive velocity and residual displacement point (E) to its rest condition for all three acceleration, velocity and displacements.

Generalised pre-pulse

Typically we require to maximise velocity and minimise displacement with a given maximum pre-pulse amplitude. Since this maximum amplitude is a limited fixed value we are only able to vary the duration ($1/F_{pr}$) or the shape of the pre-pulse to create this maximum velocity compensation. Since velocity increases in proportion to the duration while displacement increases as a square of the duration it is not surprising that the displacement limit often limits the maximum velocity compensation attainable.

To counteract this the shape of the pre-pulse can be chosen to improve the velocity compensation for a given pre-pulse duration. Velocity is simply calculated as the integral of the acceleration curve. Hence for a given amplitude the maximum velocity would be obtained in a minimum time using a square wave pre pulse. This would also give us the minimum displacement solution since the length of the pre-pulse could also be minimised. So for high energy main pulses where maximum compensation is required to meet equipment constraints then this method can be applied with square wave pre and post pulses that produce ~60% greater velocity compensation compared to the sinusoidal solution.

However a square wave has the major disadvantage of introducing broadband harmonics and increased unwanted damage potential. To overcome this problem Fandrich proposed a "near" square wave solution that is built up from one cycle of the fundamental plus the third harmonic component. The lack of high frequency components satisfies the minimal damage potential criteria (see later) but the new shape adds usefully (~25%) to the velocity compensation obtainable for a given amplitude and duration compared with a sinusoid.

The basic pre-pulse with unity amplitude is given by: -

$$f(t) = 1.155 * \sin(2 * \pi * f_{pr} * t) + 0.231 * \sin(2 * \pi * 3 f_{pr} * t) \quad \text{for } t = 0 \text{ to } 1/f_{pr}$$

Figure 4 shows the pre-pulse curve in our 30g 11ms example. Note that the amplitude of the first half of the pulse is lower than the second half. This is adjusted to optimise the negative terminal displacement value, point C, relative to the positive peak displacement at B. The optimum displacement solution is where the positive and negative displacement maxima are equal. For this condition it can be shown that the optimum P_a is (to a first order of approximation) a function of only P_b (pre-tolerance amplitude) and the main pulse amplitude making P_a a good candidate variable for this purpose. However in the general case it is necessary to integrate both the pre-pulse and main pulse together to find an accurate solution.

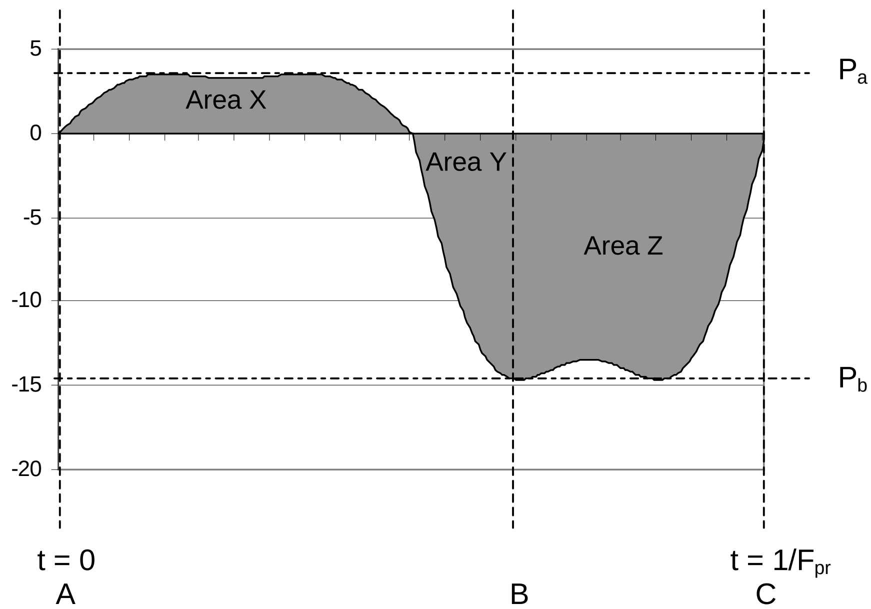

Figure 4 - Pre-pulse acceleration detail

Referring again to Figure 4 it can be seen that for a given P_b and P_a/P_b (ie a fixed shape), that the velocity at any point, which is simply the area under the curve, is proportional to both P_b and t (where $t=1/F_{pr}$). Since the terminal displacement is likewise proportional to t^2 then we also know that we are able to scale the peak displacement at point B in proportion to both P_b and t^2.

Amplitude scaling constants k_v (terminal velocity) and k_d (peak displacement) are calculated by double integrating[2] a sample pre-pulse and normalising the result in terms of acceleration and frequency. Performing a piece-wise integration allows the same code to apply to a variety of pulse shapes.

Then for a given shape, F_{pr} is calculated to define the required pre-pulse where the required velocity = $k_v * P_b / F_{pr}$ and the peak displacement = $k_d * P_b / F_{pr}^2$.

[2] Double integration is performed by creating an acceleration sample array that is sequentially summed to form a velocity array that is summed again for displacement.

The following logic is used to optimise the pre-pulse from the test constraints: -

i) Integrate the main pulse to find the velocity change V_m
ii) P_b = Pre-tol % * Main pulse amplitude ***;tolerance achieved***
iii) Initial $P_a / P_b = 0.24$
iv) For $P_a \pm 0.05$ double integrate the pre and main pulse to find positive and negative displacements
v) Interpolate positive and negative displacements for each P_a to find the value of P_a where they are equal.
vi) For the new P_a double integrate the pre-pulse and calculate k_v and k_d
vii) For optimum velocity $F_{pr} = k_v*P_b/(V_m/2)$ ***;velocity minimised***
viii) Peak positive displacement = k_d*P_b/ F_{pr}^2
ix) If this is > shaker limit then $F_{pr} = \sqrt{(k_d*P_b/ D_{pk})}$ ***;displacement minimised***
x) Check F_{pr} > minimum and limit if necessary.
xi) Repeat once from iv) with new P_a and F_{pr} to iterate to optimum P_a

This sequence uses the maximum amplitude possible to minimise velocity and displacement. Where displacement is minimised then the best sub-optimal velocity result is also achieved.

Although there are several steps required the procedure is easily programmed and does give an accurate result over a wide range of inputs. The routine can also be applied to a range of pre-pulse and main pulse shapes and is also self-calibrating.

Generalised post-pulse

As described earlier the post pulse is simply required to return the residual velocity and displacement following the pre and main pulse back to zero. It must of course do this within the post pulse tolerance levels and without exceeding the displacement constraint.

Fandrich used a single damped[3] sinusoidal cycle: -

$$f(t) = K * t^y * \sin(2 * \pi * f_{po} * t) \qquad \text{for } t = 0 \text{ to } 1/ f_{po}$$

where K is the amplitude scaling and y is the damping exponent.

[3] This function actually increases over time but the function is finally used in reverse producing a decaying sinusoidal post pulse

The function starts at zero acceleration, velocity and displacement. The final acceleration is also zero but of course has non-zero velocity and displacement. Note that the function is actually then used in reverse (ie for $t = 1/f_{po}$ *to* 0) so that it actually starts with the residual conditions and ends with the all zeros. Figure 5 shows the shape of the final acceleration pulse with varying values of *y*.

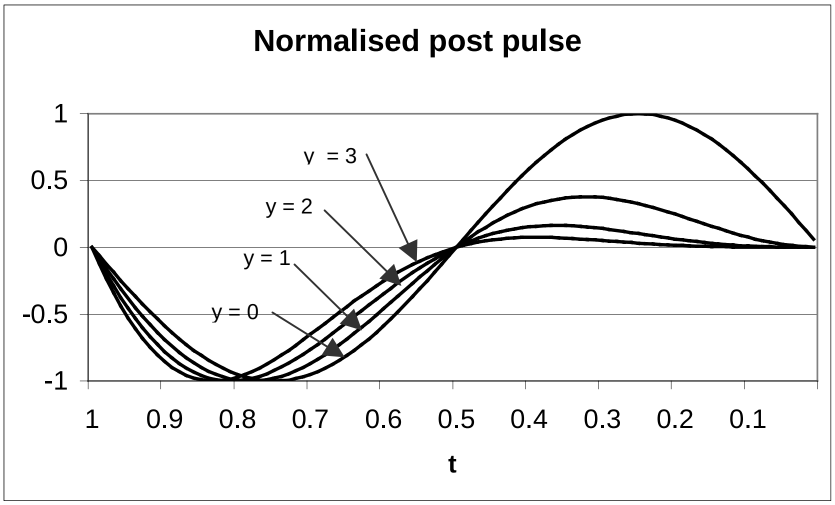

Figure 5 - Post pulse showing acceleration as a function of decay factor y

Varying *y* creates a wide range of terminal velocity to terminal displacement ratio (v_{po}/d_{po}) outcomes - see Figure 6. However the acceleration, velocity and displacement scaling of this function depends not only on *K* and *y* but also on f_{po} in a rather complex way.

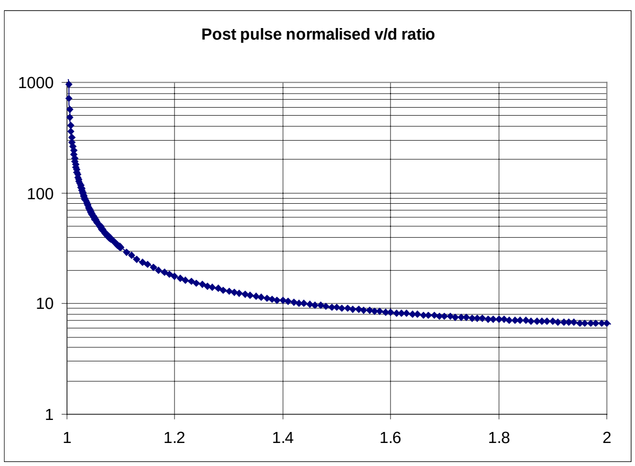

Figure 6 - *v/d* ratio as a function of decay exponent *y*

A simple addition to Fandrich's function greatly simplifies this relationship and hence the calibration of the post-pulse: -

$$f'(t) = K_{po} * (f_{po} * t)^y * \sin(2 * \pi * f_{po} * t) \qquad \text{for } t = 0 \text{ to } 1/f_{po}$$

This function has the same shape and v_{po}/d_{po} properties as the original but for a given value of y the peak acceleration amplitude is now independent of $f_{po.}$ Also: -

$$\text{Since} \quad v_{po} \propto 1/f_{po} \quad \text{and} \quad d_{po} \propto 1/f_{po}^{\;2} \quad \text{therfore } v_{po}/d_{po} \propto f_{po} \text{ and hence}$$
$$\text{duration as well as } y \text{ can be used to scale the pulse to the required } v_{po} \text{ and } d_{po} \text{ values.}$$
$$\text{Also note that as with the pre-pulse } v_{po} \propto K_{po} \text{ and}$$
$$\text{peak positive displacement} \propto K_{po} \text{ and} \propto 1/f_{po}^{\;2}$$

For a suitable range[4] of fixed y values the function *f'(t)* is double integrated to find the terminal v_y/d_y ratio, the terminal velocity to acceleration scaling (K_v), the peak acceleration scaling (K_a) and peak positive displacement scaling for each y.

So for any given value of y and a required residual of v_{po}/d_{po}: -

$$f_{po} = (v_{po}/d_{po})/(v_y/d_y)$$
$$K_{po} = v_{po} * f_{po}/K_v$$
$$AccelPk = K_{po} * K_a$$

Figure 7 shows how for our 30g 11ms example with its required v_{po}/d_{po}, the peak acceleration and peak positive displacement solutions vary with different values of exponent y. The increasing curve is peak (negative) acceleration and the decreasing curve is peak positive displacement.

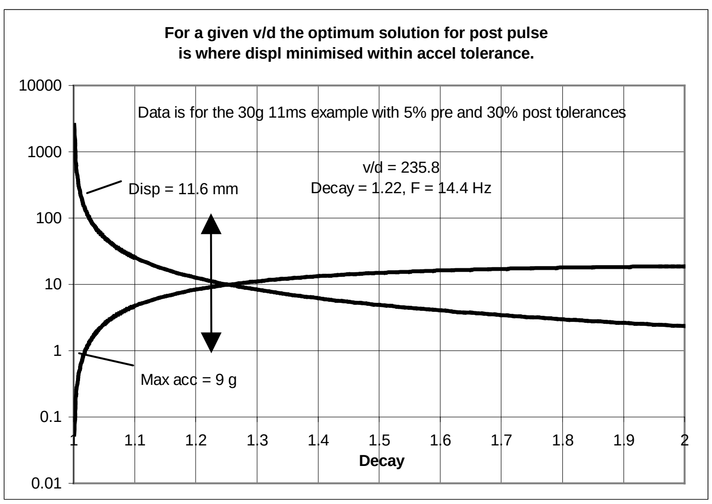

Figure 7 - Selection of an optimal post pulse decay factor

Calculating all solutions from the lowest value of y upwards enables us to find the point at which the peak acceleration is just within the tolerance limit. This will also yield the maximum frequency, ie lowest peak displacement value. Figure 7 shows this solution at y = 1.22 and f_{po} = 14.4 Hz (giving a peak displacement = 11.6mm) for our 30g 11ms example.

[4] By experiment a range from 1.01 to 2 in steps of 0.01 was found to provide an effective range and resolution of velocity/displacement values.

For test specifications such as MIL STD 810 where the positive tolerance is 20% compared with 30% for the negative side note that the positive acceleration peak for the practical range of *y* is typically only one third of the negative amplitude. This is well within the 20% limit and hence does not normally require further consideration.

Other pulse shape options

The methodology described can be applied to any pre, main and post pulse shapes. Figure 9 shows the use of the "near" square pulse as a post pulse that will compensate higher energy main pulses. Figure 10 shows the use of a sinusoidal pre-pulse that would reduce distortion further. Both these examples have been computed using equal pre and post amplitude tolerance constraints that result in near symmetrical pulse shapes with characteristics much like the standard sinusoidal compensation methods.

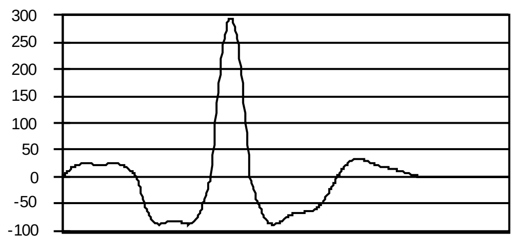

Figure 9 - Post pulse with high velocity pulse shape

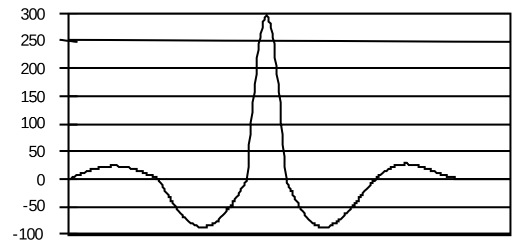

Figure 10 - Pre pulse with sinusoidal shape

Assessing pre and post pulse contribution

Adding any pre and post pulse does of course add additional energy into the test. Whether this is significant is of course test specification and test item dependant and as discussed above the amplitude and shape of the compensation both contribute to the non-ideal solution. Typically there will be various compromise solutions possible depending on what system constraints need to be met.

Figure 11 shows the SRS Maximax for three solutions for our 30g 11ms example.

The lowest amplitude curve is for a simple sinusoidal compensation limited in amplitude to 5% of the main peak. The impractical compromise with this solution is that it results in a displacement requirement of 60mm peak to peak and a 1 second record window (4 times longer than the other two).

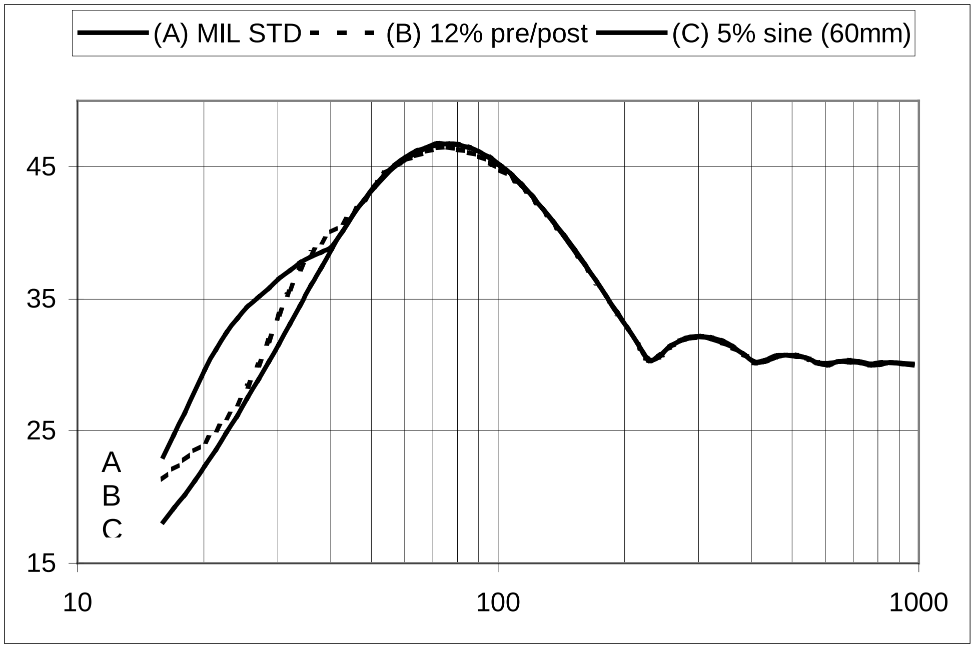

Figure 11 - SRS Maximax (10% damping) for three example solutions

The highest SRS result is from the standard Fandrich MIL STD solution commonly used for the 30g 11ms pulses. This gives about 32% higher levels at 20Hz.

Interestingly the middle curve which follows the ideal much more closely is the result of setting 12% tolerance levels for both pre and post pulses and using the "near" square wave shape (see Figure 9) for both. This results in only 20% increase at 16Hz where levels are in any case at lower levels and about 10% increase at around 38 Hz. The 12% pre and post levels are the lowest equal tolerance bands that result in a 25mm displacement solution.

Conclusions

Using specific test and test system constraints a general compensation calculation method has been described that enables a wider range of compromise choices to be evaluated quickly and easily. Compared to the Fandrich solution this method enables halfsine and any other main pulse shapes to be optimised using a choice of pre and post pulse shapes. As well as computing the standard MIL STD type solutions this will also allow any particular test system to be used over a wider range of test requirements.

References

i) "Optimizing pre and post pulses for shaker shock testing", a paper by R.T Fandrich, Harris Corp, Melbourne FL, USA published in "The Shock and Vibration Bulletin" no 51, Part 2, May 1981 by the Shock and Vibration Information Centre, Naval Research Lab, Washington DC.

ii) VibShockPulse optimisation tool, m+p international.