ACCELERATED RANDOM VIBRATION WITH TIME-HISTORY SHOCK

FOR IMPROVED LABORATORY SIMULATION

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ABSTRACT

Currently, the most accepted way to simulate transport vibration in the laboratory is through the use of a shaped random vibration profile derived from environmental measurements. Power spectral density (PSD) analysis/control of random vibration permit the compiling of quantities of data for statistical significance, and allow "accelerating" the test (increasing intensity and reducing test time). These techniques will be discussed. Then the question of large transient shocks (for example, as caused by pot holes, rail crossings, etc.) is addressed: while not strictly vibration, these occur during transport and may cause damage directly or create a condition whereby vibration causes damage later. Presently, there is no accepted laboratory simulation to account for these shocks. A new technique is suggested that combines transient time-histories with accelerated random vibration for a new, efficient, and effective simulation protocol.

SIMULATING TRANSPORT VIBRATION IN THE LABORATORY

Laboratory vibration tests are performed as part of an overall packaging development process – to design and improve packages, to solve damage problems, (ideally) to *avoid* damage problems, to compare package system performance, certify and validate packages, etc. The idea, insofar as possible, is to "bring the vibration environment into the laboratory", so that vibrational effects can be observed first-hand and under controlled conditions. Better simulation tests lead to improved results and better packages.

There are a number of commonly-used laboratory vibration tests and testing protocols. Not all are good transport vibration simulations, however.

Rotary Motion "Repetitive Shock"

This test is most often performed with a mechanical "shaker", where the table is driven by a system of eccentric cams to move in a circular pattern. As the speed of rotation is increased, the table begins to accelerate faster, in the downward part of its cycle, than the acceleration of gravity. So it begins to move down more quickly than the package, which has been placed on it, can follow. At this speed (approximately 4.6 Hz., 275 rpm) the specimen repeatedly leaves the test surface for part of each rotation – as evidenced by the operator's ability to insert a thin shim under it. Technically this is not vibration, but a repetitive shock ("bounce") test, and is described as such by ASTM D999 Methods A1 and A2[1,2]. This test, with several variations, is called out in a number of ASTM, ISO, U.S. government, and other test procedures. But the majority of these tests are probably conducted in accordance with International Safe Transit Association (ISTA)[3] "Integrity Test" protocols (which reference ASTM). ISTA, in their "Guidelines", state that integrity tests are "not designed to simulate environmental occurrences". So these tests, while useful and very widely conducted, are today not generally regarded as good simulations of actual transport vibration.

A possible exception would be in the case of a specific product/package system and specific modes/conditions of transport where actual field performance is known. Assume that a repetitive shock test was shown to consistently create the same damage or performance as observed during actual transport. Adequate simulation could then be defended on the basis of that particular empirical evidence. But the user should be *very* cautious about extending the conclusion to any other product/package and transport situation.

Sinusoidal Vibration

Sine tests are conducted with broad-frequency vibration systems (most often hydraulically-driven), where the table moves smoothly up and down in a sinusoidal pattern and the frequency is varied to excite responses in the test specimen. The sine test is a very useful tool for engineering and investigative purposes, but is not widely used for transport vibration simulation. ASTM D4169 *does* allow it for package performance testing, but suggests that "random (vibration)… results in better simulation… and is the preferred method."

As with the repetitive shock test, a possible exception would be in the case of a specific product/package system and specific modes/conditions of transport where actual field performance is known. If a sine test were shown to consistently create the same damage or performance as observed in actual transport, adequate simulation could be claimed. But, as before, the user should be *very* cautious about extending this conclusion to any other product/package and transport situation.

Time-History Reproduction

This is an approach which at first look is quite appealing, but unfortunately has some significant drawbacks. The idea is to measure, using electronic field data recorders, the vibration environment in an *actual* transport vehicle during an *actual* trip. This data is brought back into the lab, and a vibration system (usually hydraulic) is used to "exactly" reproduce the motions. Within controller and system accuracies, every pot hole, bump, bounce, and ripple in the recorded data is reproduced exactly. While potentially a very accurate simulation of *that particular trip or trip segment*, this technique has the following shortcomings:

1. One trip has essentially "zero" statistical significance. How does one know if that particular trip was unusually severe, unusually gentle, or truly representative of that general mode and those general conditions of transport? It is too risky to base decisions on what is usually a very small amount of data.
2. There is no valid way to compile time-history data from multiple trips to increase statistical significance. Tests can be run *in series* (one after the other) to simulate more and more actual transit time, but this leads to extremely lengthy tests and still isn't statistically effective.
3. Tests cannot be significantly "accelerated" to compress the testing time. Of course all zero-data ("dead time") is removed, and sometimes even the lower-level data is edited out, but to our knowledge there is no consistent or meaningful rationale for doing this. The intensity of the recorded information cannot viably be increased for testing: there is no accepted protocol; if one attempts to time-compress the vibration by increasing intensity, the large transient (shock) peaks quickly become unrealistic.
4. Because of current vibration controller capabilities, time-history reproduction is limited to frequencies below about 50 Hz. Since it's generally agreed that the transport vibration environment contains frequencies to 100 or even 300 Hz., this limitation is significant.

Frequency-Domain Random Vibration

This is the currently-accepted best approach for simulating transport vibration in a testing laboratory. Here the recorded time-histories are translated into power spectral density (PSD) plots, which are presentations of time-average vibration intensities vs. frequency (Figure 1) [4,5]. This data, while not a *direct reproduction* of the recorded signal, is nonetheless an *accurate statistical representation* of the damaging effects of vibrational motion – fatigue, abrasion, loosening of fasteners, etc.

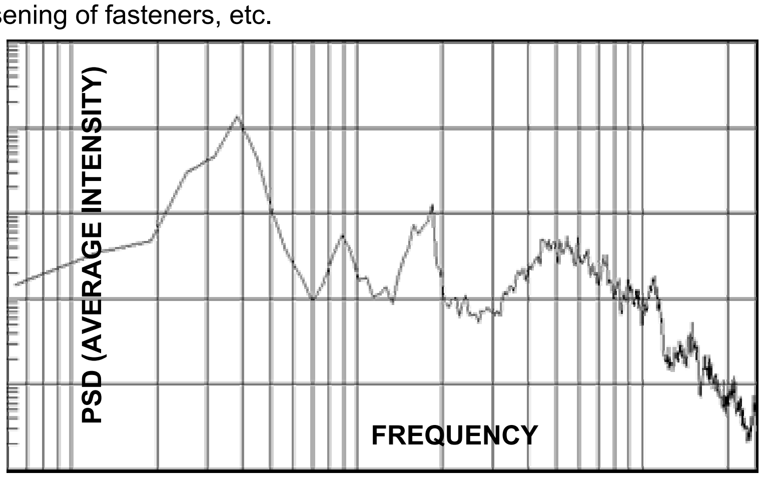

Figure 1. PSD Plot from Single Measurement Trip

In addition, the overwhelming advantage is that PSDs can be compiled to increase statistical significance – *averages* can be *averaged* to create composite spectra. It's important to control variables when taking and compiling data, but multiple trips and measurements can be recorded (for the same transport mode types and conditions), the data converted to PSDs, and those PSDs easily combined into a meaningful composite. Figure 2 shows a compiled, smoothed spectrum derived from multiple measurements having the general characteristics of Figure 1.

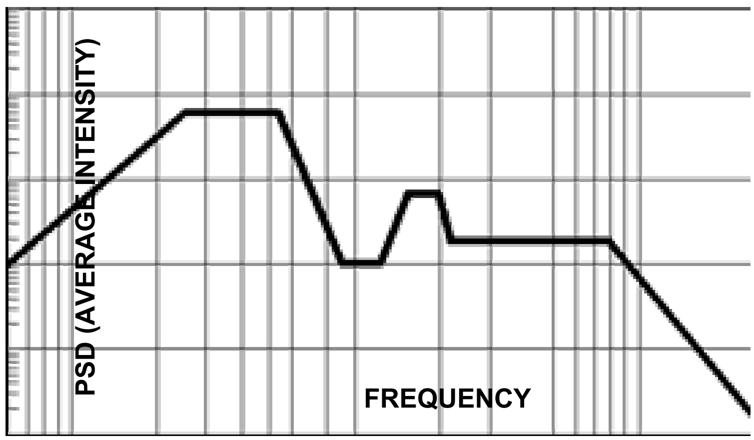

Figure 2. Compiled and Smoothed PSD from Many Measurements

Advantages of frequency-domain random vibration testing include:

1. Individual spectra can be compiled and smoothed into a statistically significant composite, as discussed and shown above.
2. All modern digital and PC-based random vibration controllers can gracefully accept and accurately control random vibration described as PSDs. The operating frequency range easily encompasses that required for transport vibration simulation.
3. There is a protocol for *accelerating* PSD-based tests: increasing the intensity thereby permitting a reduction in the test time, which is the subject of the next section.

ACCELERATED VIBRATION TESTING

Figure 2 could represent a "statistically significant" truck traveling over a "statistically significant" road. But the truck is still traveling in "real time"; i.e. one hour of a Figure 2 test would equal one hour of the represented transport motion. If the trip took 15 hours, for example, we'd need to run Figure 2 for 15 hours to simulate it – not a very attractive prospect. This is where the concept of *accelerated* vibration testing comes in.

In a 1971 Shock & Vibration monograph, Curtis, Tinling, and Abstein of the Hughes Aircraft Company postulated a methodology for the time-compression of vibration tests[6]. In 1993, Dennis Young of ISTA referenced that in his paper "Focused Simulation"[7], where he presented a formula for calculating the amount of acceleration increase corresponding to a test time decrease. Restated, the formula is

$$I_T = I_0 \sqrt{T_0 / T_T}$$

Where I_T = the test intensity in Grms (the overall intensity of the PSD profile)

I_0 = the original intensity (overall Grms of the original profile)

T_0 = time duration of the original profile

T_T = the test time

Grms (root-mean-square acceleration) is graphically equivalent to the *area* under a PSD plot. Root-mean-square can simply be thought of as the mathematical process by which the time-average intensities are calculated.

A time-compression ratio of not greater than 5:1 is recommended to preserve validity. Based on the T_0 / T_T ratio chosen, a new test intensity is calculated from the formula. The *shape* of the profile remains unchanged; it simply gets translated *up* on the PSD plot to increase its intensity (graphically, to enclose more area).

As an example, the overall intensity of Figure 2 is 0.245 Grms. Assume that we wish to simulate a 15 hour trip, using the maximum recommended time-compression of 5:1. That means a 3 hour test in the lab, and we'd increase the intensity to 0.245 $\sqrt{5}$ = 0.245 x 2.236 = 0.548 Grms. This is shown graphically in Figure 3 – the PSD shape remains the same, it's simply translated *up* the plot to increase the intensity (enclose more area).

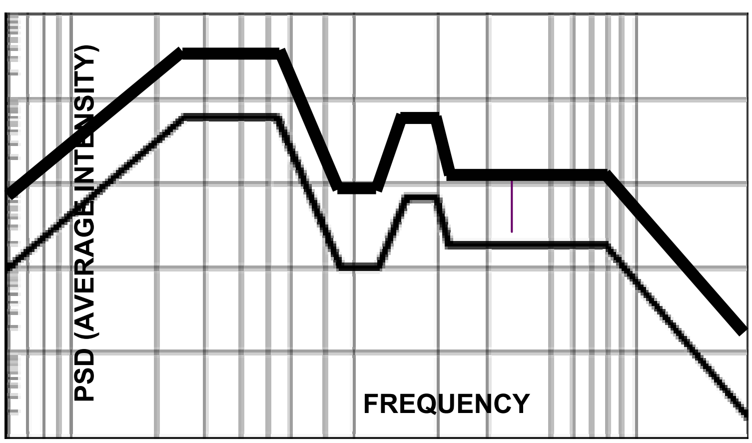

Figure 3. Accelerated Vibration Profile

TIME-HISTORY SHOCK ON ACCELERATED RANDOM

There is one characteristic of PSD-based simulations which is a potential disadvantage, however. That is, since the PSD values are "average intensities" of the vibrations at each of the frequencies across the spectrum, rarely-occurring but large peak g-levels tend to be "averaged out”. For example, if the measurement of a truck trip included one large “pot hole” in a long, otherwise smooth ride, the pot hole data would be averaged in with so much low-level data that it would, in effect, disappear. This is illustrated in the acceleration-vs.-time records of Figure 4: although the bottom signal contains a huge transient, calculated PSDs (both shapes and intensities) would be essentially the same.

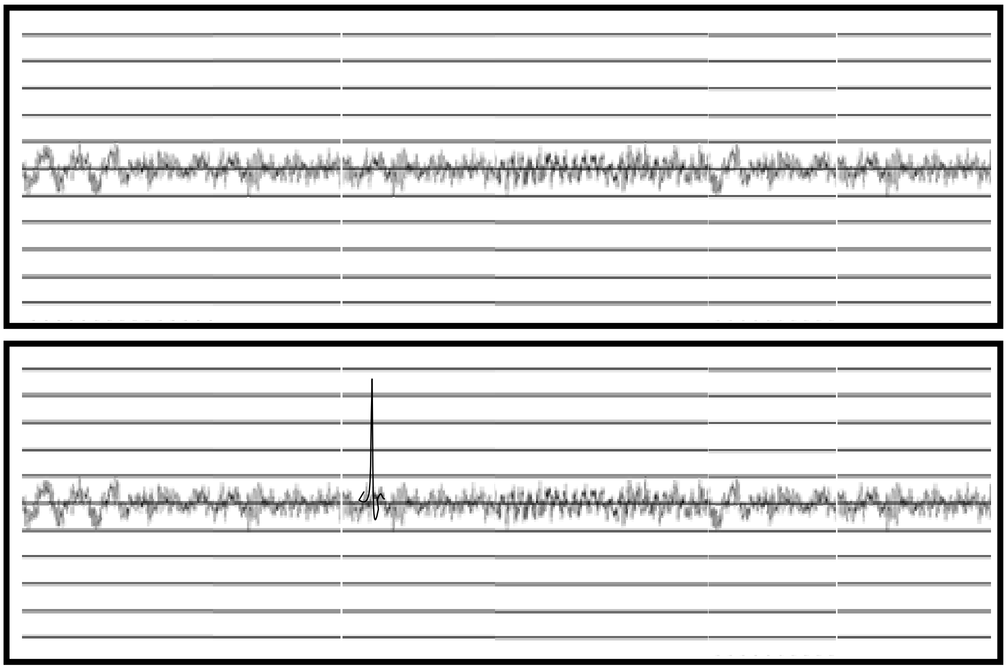

Figure 4: Calculated PSDs, Both Shapes and Intensities, From These Two Acceleration-Time Waveforms Would Be Essentially The Same

But that one “pot hole” could be damaging to the lading, or set up a condition (such as mis-alignment of a pallet load) that would lead to later damage from the low-level motions. This doesn’t invalidate the frequency-domain approach – PSDs represent *vibration*, and the huge transient is a *shock*. It could perhaps be simulated with a separate drop or impact test. Still, it occurred in the vehicle and during the trip, and seemingly should be a part of the vibration test.

Sometimes there’s a temptation to increase the intensity (Grms) of the controlled PSD to the point where such large g-levels occur. In some instances this can replicate the instantaneous damage or damage-potential effects, but the average vibration levels are then so high that the test becomes unrealistic.

The Best of Both

So the frequency-domain (PSD) approach is good for obtaining statistical significance and allows valid time-compression, but does not adequately reproduce large transient motions which may occur in the field. The time-history approach falls short in the first two categories but is good for transients. So why not combine the two, and achieve the best of both? A test consisting of accelerated PSDs as described in this paper, interspersed with actual time-history reproductions of field-recorded data (rail crossings, pot holes, construction zones, curb hops, switches, bad track, rough landings, etc.) could provide an improved simulation. While there would still be issues to address (what *kinds* of transients, how many, what time intervals between them, etc.) , this combination approach would seem to hold promise as a realistic and equivalent, yet efficient and (with today's vibration systems and controllers) practical and attainable testing methodology.

THE BEST DEMONSTRATION OF EQUIVALENCE

Regardless of the methodology used, the best demonstration that a laboratory test or test series is equivalent to some transport condition is *correlation of damage or performance*. If a reasonable test consistently reproduces damage or results that are similar to actual field experience, it's probably a good test – at least for those particular situations. And if it correlates over a broad range of situations, then it's probably a good general test. The transport packaging engineers' work is not done just because the product and package have been designed and the lab testing has been completed. Field performance data should be gathered and carefully studied for proper correlation, and adjustments should be made if necessary.

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