Random Vibration Testing Of Packaged-Products: Considerations For Methodology Improvement

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ABSTRACT

Vibration has always been included in the laboratory testing of packaged-products, in obvious recognition of the fact that vibration of lading is always caused by transport. As the technology of vibration testing progressed, there was generally industry consensus regarding the various methods and approaches.

In the beginning (60 or more years ago) there were only mechanically-driven eccentric cam "vibration" machines, and the resultant test was accepted as an industry standard. While certainly a great improvement over not testing at all, this fixed-displacement, circular-synchronous motion is now recognized as producing "repetitive shock" rather than vibration.

In the early 1970's, broad-frequency sinusoidal vibration began to find application in packaged-product testing. A resonance-search-and-dwell (RSD) method was developed and applied by many leading organizations, often aiding in the solution of problems and resulting in improved products and packages. There was little discussion, however, of the fact that pure sinusoidal motion rarely if ever occurs in actual transport. Today RSD is mostly used for product/package design, not transport simulation.

In the early 1980's, random vibration became practical in packaging laboratories, and tests based on Power Spectral Density (PSD) measurements and control have since become the norm. Random vibration motion produced in the laboratory can be very similar to the motion of actual transport, and often there is good correlation between lab results and "real world" experience. Test protocols based on this technology are published by ISO, ASTM International, ISTA, and many other national and international organizations.

In the last few years, however, it has become recognized that the standard random vibration approach could potentially be improved. Because a single PSD typically represents an average taken over a relatively long time interval, it can omit, or "average out", varying amplitudes, differing vibration features, and infrequently-occurring but nonetheless significant and potentially damaging motions. Visualize a section of rough road or a rail crossing in an otherwise long, smooth truck shipment. Or a relatively brief period of turbulence or a bad landing in an otherwise long, smooth air journey. There is legitimate concern that the submersion of these changing conditions and large events into an overall average may significantly compromise the simulation value of the resultant test.

A number of proposals have been made and test approaches undertaken to address this issue, including creating and running both high-intensity and low-intensity spectra, control of kurtosis and use of non-Gaussian vibrations, synthesis of non-stationary random processes, shock-on-random, and more. However at this point there is no consensus regarding the best methodology.

This paper will describe the issue in detail, and summarize the various suggested approaches in simple terms. Recommendations regarding practical approaches, further research, and possible industry consensus will be made.

Keywords: vibration, random, testing, PSD, simulation

INTRODUCTION

Most typically, laboratory random vibration tests are intended to simulate "real world" transport vibration. Even when the vibration spectrum is taken from an industry standard, at some point there was most likely a relationship to actual measurements of the real world [1]. It is therefore instructive to briefly discuss how field data is translated to simple PSD profiles for use in the lab, because this illustrates the source of the possible need for improvement.

Transportation vibration occurs in the time domain, and is recorded as acceleration-vs.-time data. It is then post-processed into the frequency domain, to a PSD format. In simplified terms, this is accomplished as follows: the acceleration intensity at a particular frequency is averaged (using a root-mean-squared process) over a period of time, and the resultant Grms value is then used to locate a point on the PSD plot at that frequency. This is repeated for each frequency in the analysis band, and a complete PSD plot is thereby created [2].

Averaging is fundamental to the creation of a meaningful PSD. Random vibration is, after all, *random*, and the true characteristics emerge only after data has been observed and computed for a period of time. But averaging, by its very nature, eliminates intermediate variations and masks the extremes.

Consider the two acceleration-vs.-time charts of Figure 1 on the following page. The top chart is actual shipment data from an approximately 700 mile (1125 kilometer) truck transport in the U.S. As can be seen, it has varying vibration amplitudes and characteristics, and a number of quite large superimposed "spikes". If all this data were to be averaged into a single PSD and run in the lab, it would look similar to the bottom chart. The bottom chart is definitely random in nature, but because all data is averaged into one spectrum (and because of the way in which typical lab vibration systems and vibration controllers work), the variances, features, and large spikes are lost.

It's interesting to note that most recording instrument analysis software, and most vibration controller displays, do not easily present these types of time-domain charts to the user (what they typically display are PSD plots). If they did, comparisons such as Figure 1 might have generated interest in improving simple PSD testing many years earlier. In fact, the top chart was constructed by a painstaking concatenation of individual time-triggered and threshold-triggered data events, and the bottom chart was taken from vibration controller literature.

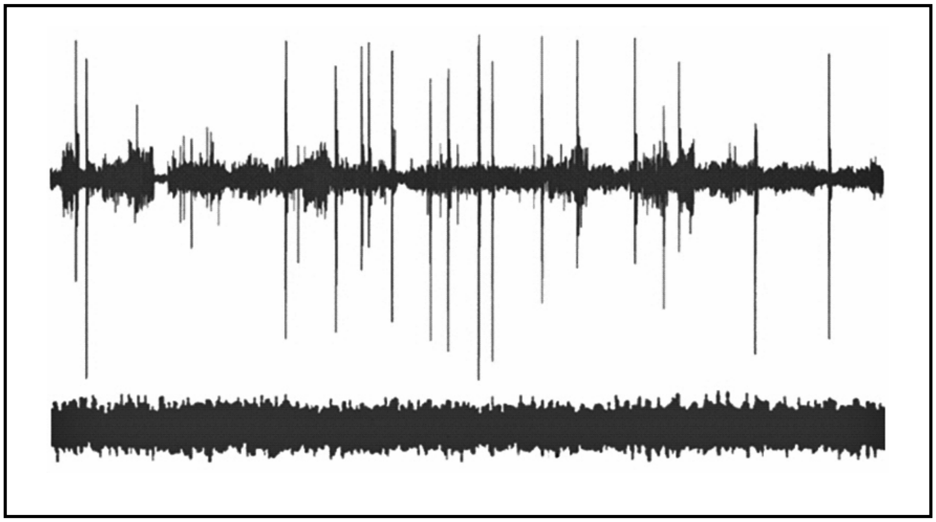

Figure 1. Acceleration-vs.-time (time domain) data. Top chart is data from an actual truck shipment, bottom chart is typical of a lab random vibration test created from a PSD of such data.

Figure 1 prompts the question: "How can we create meaningful random vibration profiles for laboratory testing, while at the same time accounting for, and simulating the effects of, varying amplitudes, different characteristics, and infrequently-occurring large-amplitude motions?

HIGH / LOW / SEPARATED SPECTRA

The high/low/separated spectra approach was actually put forward several years ago, and has been used with some success. It is straightforward and convenient to implement using typical current technology.

The basic technique essentially involves separation of higher-amplitude data from lower-amplitude data, constructing two or more different PSD profiles, and running them individually. Sometimes it's easy to differentiate between high- and low-amplitude data, but often "high" and "low" need a numerical definition. Since the typical software which converts time-domain data into PSDs can usually determine the acceleration amplitude of each data recording, it is possible to separate based upon percentage and/or level. For example, one can sort the recordings according to acceleration amplitude, and then separate the highest 20% from the lower 80%. Or separate recordings having amplitudes above a certain level, like 1g. Once the data is separated, individual PSDs are created from each using standard (averaging) techniques. These PSDs are then run individually in the lab, usually the "high" profiles for relatively short periods of time and the "low" profiles for longer times. Figure 2 on the following page shows spectra created using these techniques [3].

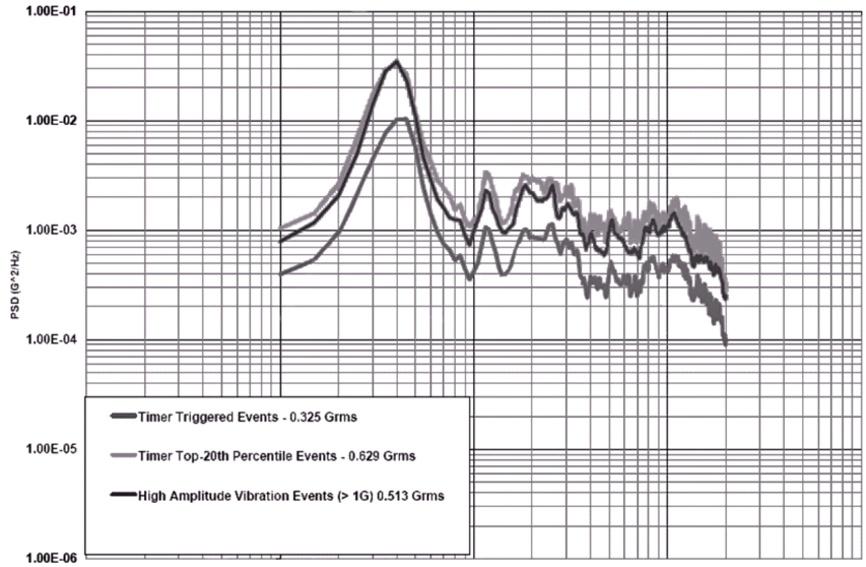

Figure 2: Sample PSD chart from reference 3, showing spectra for all recordings (lower curve), the highest 20% (upper curve), and those exceeding 1g (middle curve).

A variation of this technique is to separate event recordings in other ways. Often “rough road” data can be easily distinguished from “smooth highway” data for truck transport. Or “bad track” data from “good track” data for rail shipment. Or “turbulent air” from “smooth air”. It makes sense to separate these data recordings if possible and create specific “rough road”, “bad track” or “turbulence” spectra to be run as separate short tests.

A related approach has just recently been developed; it shows promise, but unfortunately at this point is unpublished [4]. It utilizes a special software application to construct “probability spectra” from the data population. The program computes the number of times a PSD level was observed at each frequency, then creates spectrum overlays at 80%, 90%, 95%, 99% and 100% “at or below” levels. These spectra represent the probability that an encountered PSD level will be at or below the profile based on all data events recorded. Depending on the degree of conservatism desired, a user can choose a higher or lower probability level, or perhaps test with several spectra of different levels. This approach can be combined with the “specific spectra” idea above for even greater versatility.

The advantages of the high/low/separated spectra and related approaches are an ability to at least partially address the traditional PSD shortcomings in many situations, while using typical existing analysis techniques, data, and vibration system controllers. Popular recording instrument software, without modification, usually supports the required separation and extraction of data events. Vibration controllers are designed to run PSDs of any shape and level (within system capabilities). And certainly conducting higher-intensity spectra for a shorter time, in addition to running a “background” spectrum, can be a good simulation of “rough road”, “bad track” and “turbulence” conditions, and is potentially a step in the right direction toward simulating large-amplitude infrequently-occurring motions.

The disadvantages are that averaging techniques are still used, data separation/extraction criteria often lack good technical rationale, and isolated large-amplitude events are not well simulated.

Assume that a set of data recordings are sorted according to acceleration amplitude, the largest 20% selected, and a PSD profile created from them. That PSD could be subject to the original criticism, namely that larger-amplitude and infrequently-occurring motions are being "averaged out" – the only difference being that the definition of "larger-amplitude" has been increased. Of course the data could be subdivided further: the largest 10%, 5%, 2%, etc. Or the "probability spectra" concept described above could be used, which is more sophisticated in that it looks at individual frequencies. But at some point there might not be enough event recordings to create a meaningful spectrum and/or the appropriate run time may be too short.

Separating event recordings according to their source ("rough road", "air turbulence") would appear to have a sound rationale. But arbitrarily choosing a highest percentage or level does not. Why 20% (or whatever percentage is chosen)? Why 1g (or whatever level is chosen)? Different researchers have used different values, yet the choice can have a significant influence on the tests which are ultimately run in the lab, and the results. The "constructed probability spectra" approach is promising in this regard, as it relates spectrum level to data characteristics.

A related question is how long to run the higher profile(s). Test duration for the "background" profile is often related to the time or distance of the trip to be simulated, but then the higher-intensity profiles are run for an arbitrary duration like 5 or 10 minutes. To date, no rationale has been developed relating these test durations to simulation appropriateness or damage potential.

The final disadvantage of the high/low/separated spectrum approach relates to incorporation of isolated transients caused by potholes, bad landings, etc. These data recordings can be separated by various means and spectra constructed from them, (perhaps, if there is sufficient data) but it seems inappropriate to conduct even 5 or 10 minute vibration tests exclusively representing these motions. In the actual environment, these transients have occurred individually, often with minutes or hours in between – the best approach would be to reproduce or simulate them in a corresponding manner.

KURTOSIS CONTROL, NON-GAUSSIAN VIBRATION

Very simply put, and in the context of this discussion, kurtosis is a measure of how widely the instantaneous peak accelerations of random vibration motion can vary. Low kurtosis means a low range of probable peak acceleration values, while higher kurtosis means a larger range. When the kurtosis value is 3, the vibration is said to be *Gaussian*, where maximum peak accelerations are about 3 times the mean (average) values. Essentially all current packaged-product random vibration tests are Gaussian. Proponents of kurtosis control point out, no doubt correctly, that in the actual transport environment peaks can be quite a bit larger. Kurtosis control (non-Gaussian vibration) is a means of increasing the amplitudes of the peaks without changing the spectrum shape or the overall average acceleration level.

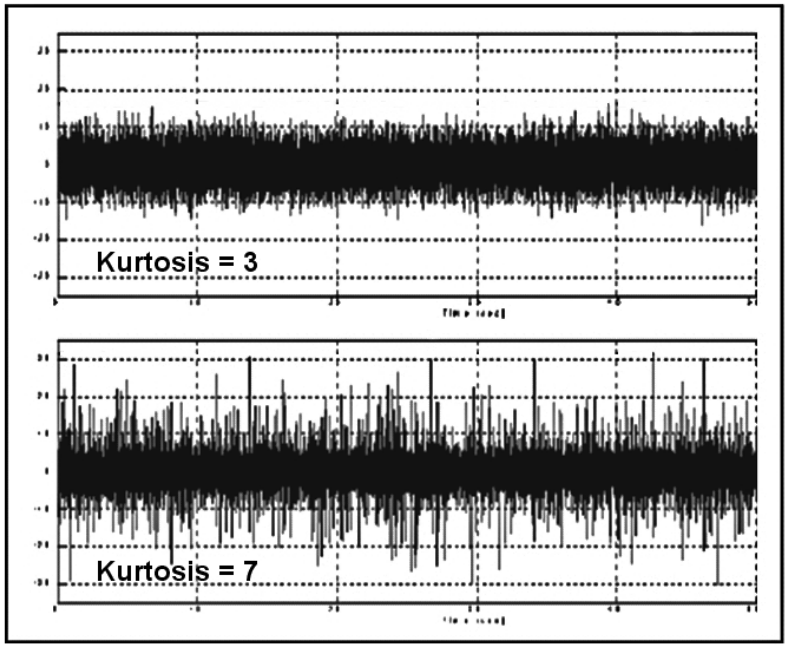

Figure 3: Acceleration-vs.-time histories of same spectrum, same Grms intensity, but with different kurtosis

Figure 3 shows, on the top, the acceleration-vs.-time history of a Gaussian random vibration test (kurtosis of 3), similar to a current standard packaged-product PSD test. On the bottom is data from a test *with the same spectrum shape and average intensity*, but with a kurtosis of 7 (non-Gaussian). It is easily seen that the peaks are higher, and that more test time is spent at higher acceleration levels [5].

The advantages of kurtosis control are obvious in Figure 3 – more and higher acceleration peaks. Since one of the issues is submersion of peaks into an overall PSD average, anything which increases those peaks should be an improvement. And unlike the high/low spectra approach, the high amplitudes are not grouped together and run as a separate test, they're scattered throughout the test duration in perhaps a more realistic manner. Since the value of kurtosis is implemented entirely with the laboratory vibration test system and its controller, standard data recording, analysis, and PSD creation techniques can be used. But of course, the ideal situation would be to determine the kurtosis of the actual recorded field data and then match that for the lab test.

Even with kurtosis control (non-Gaussian vibration), it is still advisable to separate data based on different known or identifiable conditions within the trip, and to create separate tests. Higher kurtosis is no substitute for constructing and running different spectra when appropriate, such as those which might be associated with a rough road or a period of air turbulence.

The disadvantages of non-Gaussian vibration are that standard instrument software does not calculate kurtosis, few packaging laboratory vibration controllers have the kurtosis control feature, high peaks require higher vibration system performance, and very isolated large-amplitude events are not well simulated.

If kurtosis control is to be used to best advantage, it should be set to a value which relates to actual transport vibration. Unfortunately, the companion software for typical packaging-application field data recorders does not include kurtosis calculation. This can often be accomplished with the kurtosis control software, but involves additional effort and complexity.

Since kurtosis control is a relatively new development in testing, it is not within the capabilities of a majority of packaging lab vibration controllers. Some of these will allow adjustment of “sigma clipping” values (closely related to kurtosis), but the maximum setting is often only 4 or 4.5 – probably not sufficient to adequately simulate the transport vibration environment. The purchase of a new vibration test system controller, or an add-on or upgrade to an existing controller would be required to implement adequate kurtosis control.

Currently for packaged-product random vibration testing, a spectrum is considered to be adequately described by its shape and overall Grms – under the assumption that laboratory vibration will be Gaussian. But if this is *not* the case, if a kurtosis other than the (unstated but nearly universal) “standard” value of about 3 is used, it must be clearly and prominently recorded in all test documentation. This is because, even with the same spectrum shape and overall Grms, *a test with significantly different kurtosis may represent a significantly different test*. It is quite possible that a packaged-product might pass a test with lower kurtosis and fail what appears to be the “same test” (based only on spectrum shape and Grms) but with higher kurtosis.

A further disadvantage of kurtosis control (non-Gaussian vibration), at least in terms of currently-installed vibration test systems, is that greater performance is required to conduct the “same test” at kurtosis values significantly greater than 3. This is because those high acceleration peaks demand higher force output from the system (and perhaps higher displacement and velocity as well). For example, if a vibration system is near its performance limit for a particular test (because of a combination of the spectrum shape and intensity, and the test specimen weight) with a kurtosis of 3, it may not be able to properly run the “same test” with a kurtosis of 7. In effect, system maximum performance may appear to be reduced as kurtosis is increased.

The final disadvantage is much the same as for the high/low/separated spectrum approach, regarding incorporation of very isolated transients. Kurtosis control creates high acceleration peaks according to its own statistical rules. Non-statistical high-level events with minutes or hours in between (such as caused by potholes, bad landings, etc.) may not be adequately simulated.

SYNTHESIS OF NON-STATIONARY AND NON-GAUSSIAN RANDOM

Stationary random vibration is defined by statistical properties which do not change with time. In the transportation environment, such a condition might be approximated by a truck traveling long distances over the same type of road at the same speed, or an airplane flying for hours through relatively smooth air. But if the road surface or vehicle speed changes, or if there is air turbulence or other differences, the statistical characteristics are altered and we have *non-stationary* vibration. Obviously non-stationary vibration is a part of every real transport environment.

Vincent Rouillard of Victoria University has put forward the hypothesis that non-stationary (and non-Gaussian) random vibrations can be decomposed into independent random Gaussian elements with varying amplitudes, standard deviations, and durations [6]. As an illustration, consider Figure 4 below. This is the same as the top portion of Figure 1, but with the large "spikes" removed (they will be discussed in the next section) and with the vertical amplitude increased to show more detail.

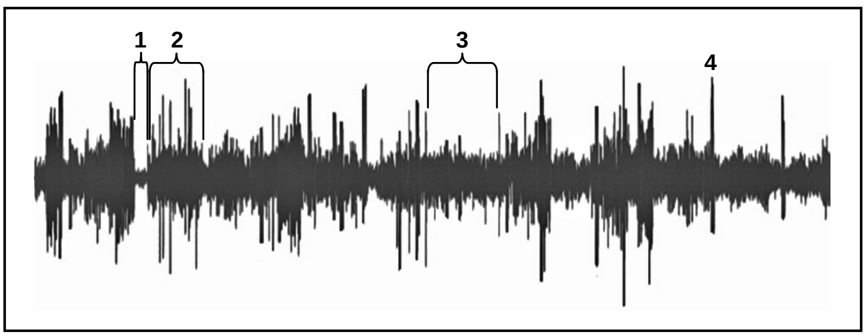

Figure 4: Data from top portion of Figure 1 (actual truck shipment recordings), with the large "spikes" removed and increased amplitude on the vertical axis.

The following is undoubtedly an over-simplification, but visually it seems possible that Figure 4 could be sequences of different Gaussian random vibrations. For example, look at the data in interval "1": it appears to be a very small amplitude, short-duration, low standard-deviation signal. In interval "2" the signal is larger, and has a higher standard deviation. The signal in interval "3" is in-between. Viewed in this manner, it becomes possible to imagine that the entire time history of Figure 4 is simply a sequence of "standard" vibration tests – and this is what Rouillard postulates. (Actual laboratory tests using this approach would probably involve consolidating and running the required spectra, rather than trying to duplicate the exact time history.)

This approach could be compared to separating "rough road" or "turbulence" spectra and background vibrations, but differentiated to much finer detail and to much greater extent. As presented in the referenced paper [6], it required use of a computational algorithm to extract the amplitudes, Gaussian parameters, and times.

Advantages of this concept are similar to the high/low/separated spectra and related approaches, with an added potential to provide significantly better simulations because of the more rigorous approach and finer detail. Existing field-recorded data could be used, but would need to be analyzed with the special extraction algorithm. That algorithm is described in the referenced paper, and possibly could either be duplicated from that or shared by the original researchers. Current packaging-lab vibration systems and controllers should be able to run the resultant spectra (within their performance limitations) if the required spectra time durations are not too short.

Unfortunately this approach, while having been mathematically validated, has not been implemented in a lab with actual test specimens (unlike high/low/separated spectra and kurtosis control). Therefore correlation between lab results and field performance is unknown. Further research and practical trials are required before this can be considered a completely viable approach.

Short time durations could be a problem, and this is acknowledged in the referenced paper. Consider the large-excursion data labeled “4” (and similar events) in Figure 4: these are not only large in amplitude, but are also short-duration. It’s likely that the spectrum parameters are quite different from the rest of the record, but there may not be enough data for proper determination. The motion may be much closer to shock than it is to vibration.

SHOCK-ON- RANDOM

All of the approaches discussed to this point have a common shortcoming: an inability to simulate or reproduce *very* isolated high-amplitude motions (as might be caused by potholes, curb-hops, rail switches, bad landings, etc.). This should not be surprising, since the approaches are aimed at vibration simulation, yet the isolated motions are (or more closely resemble) transient shocks. It could be argued that these motions might be adequately covered by separate shock or impact elements in an overall testing protocol. Yet they occur in the transport vehicles, along with the vibration, so the most realistic simulation would seem to be incorporation into the vibration profile. If the shocks cause damage immediately or directly, perhaps a separate test would yield the same final result, but if the shocks *set up* a condition affecting the damage potential of subsequent vibration (the shock dislodges a part or a package component, misaligns a stack, weakens a container, etc.) then a separate test might produce a different, and less realistic, outcome.

Shock-on-random, as the name implies, is the combining of shock pulses onto a random vibration profile. The advantage, particularly when combined with one of the advanced techniques described above, could be improved simulation of possibly *very* important aspects of the transport environment. The overwhelming disadvantage is that there is presently no way to try it or to assess its possible efficacy. The idea was broached for packaged-product testing at least 7 years ago [7], but has never been implemented; apparently current vibration controller technology does not support shock-on-random. The problem, as pointed out by Rouillard and Richmond [8], is that closed-loop vibration controllers would attempt to compensate for superimposed shocks, and to some degree would “average out” such transient motions – obviously defeating the purpose. Reference 8 suggests that momentarily opening the feedback loop, so that the system operates in “open loop” mode while the shock is produced, could be a possible solution.

Ideally, the superimposed shocks would be taken from actual recorded data, and added to the vibration test at times and intervals related to what typically occurs in transport. But a reasonable simulation might be achieved by interjecting damped sinusoids or other standard types of shock transients at appropriately periodic intervals.

Of all the approaches discussed, shock-on-random would require the most vibration system performance. Big accelerations require large force outputs, short durations require high-frequency motion and potentially large velocity capability. Yet during most of the test time this performance would not be used – it would only be needed to produce the occasional “spikes”.

CONCLUSIONS

Of the approaches discussed, high/low/separated spectra and kurtosis control are currently available and in use. The former is somewhat proven, and can be implemented immediately by any laboratory which has standard random vibration capability. The latter, kurtosis control, typically requires a new or upgraded vibration controller. More research on its applicability and effectiveness specifically for packaged-product testing would be helpful. Nonetheless, the approach is based on sound principles and should be considered.

The synthesis of non-stationary and non-Gaussian random theory of reference 6 needs more development before its possible merits can be assessed. Certainly it holds promise as potentially the ultimate extension of the high/low/separated approach. But it needs to be refined, actually run in the laboratory, and its results correlated to real world experience.

And finally, it is the author’s opinion that the shock-on-random approach is perhaps the only way to adequately confront the issue of very isolated, infrequently-occurring, large-amplitude transients. It is hoped that future vibration system and controller developments will be able to address this need.

An industry consensus is desirable regarding the shortcomings of current “standard” random vibration tests for packaged-products, and what if any approaches should be adopted to address them. Without a consensus, test results may not be comparable or may be difficult to compare without careful analysis of the underlying methodology.

RECOMMENDATIONS

In situations where there are potential issues with correlation (lab results not adequately reflecting actual field performance, passing the lab tests but having significant damage in the real world), or if it is simply desired to experiment with techniques which might produce better simulations in the lab, then the following approaches are recommended:

- Try the high/low/separated spectra approach. If the vibration test is derived from field data, re-analyze that data to sort events according to acceleration amplitude. Separate the highest 20% from the lower 80% and make a spectrum from each group. Run the lower 80% spectrum in the lab for the normal amount of time, and in addition run 5-10 minutes of the higher 20% spectrum.
- If the field data shows significant time periods of markedly higher intensity, make a spectrum from those events and run it in the lab for an appropriate amount of time. This would be in addition to a "normal" spectrum.
- If a test uses a "standard" spectrum (ISTA, ASTM, ISO, etc.), try adding 5-10 minutes of a higher-intensity spectrum of the same shape to the test protocol. If an ASTM test at Assurance Level II is being used, add a short test at Assurance Level I. If an ISTA or ISO test is being used, multiply frequency breakpoints by 1.5 - 2 to create the higher-intensity spectrum.
- If a vibration controller allows "sigma clipping" adjustments, try higher settings. Run the test "normally" otherwise.
- Look into kurtosis control, perhaps through demonstration of a vibration controller which allows varying the kurtosis. Run the test "normally", but with kurtosis values up to 7 - 10.

In all cases above, assess the test results to determine if correlation is improved.

It is further recommended that all researchers stay aware of further developments in this area (synthesis of non-stationary, non-Gaussian random; shock-on-random) which could affect testing protocols.

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