UNDERSTANDING TODAY'S TRANSPORT ENVIRONMENT MEASURING RECORDERS

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ABSTRACT

Within the last decade, sophisticated electronics and computer technology has permitted the design and manufacture of compact, powerful, and accurate instruments for measuring the transportation environment. This paper focuses on the latest generation of devices that typically measure and calculate shock, vibration, drop height, temperature, and humidity, and explains their basic principles of operation and applications.

Various classes of transport measuring instruments are briefly discussed (mechanical, chemical, electronic, etc.), and electronic recorders are differentiated in terms of their measurement approaches; i.e., numerical monitors and full-waveform recorders. The remainder of the paper will then concentrate on the full-waveform electronic instruments.

Knowing what the instruments do and the essentials of how they do it then leads to a discussion of the primary applications, meaningful presentation of the data, and use of the information to create realistic laboratory simulations of the transportation environment.

INTRODUCTION

The packaging and transportation of goods is a multi-billion dollar activity worldwide. Inevitably, some of the goods are damaged in shipment; the total cost of these losses is estimated in various ways, but most certainly is over a billion dollars annually. A great deal of effort is expended by packaging and logistics engineers to minimize transportation damage, and pre-shipment laboratory testing of products and packages has been commonplace for many years. But the test *levels*, *intensities*, and *protocols* are always a point of discussion or controversy. The fundamental question of "what really goes on out there?" during transportation and distribution has been difficult to answer with statistical confidence, certainly because of the extent of the systems and the many variables involved, but also because of inadequacies in measuring instrumentation. Only in the last 10 years or so has technology been able to adequately satisfy the need for transport environment measuring recorders which provide adequately useful, meaningful, and accurate information.

MANY TYPES OF RECORDERS

There are dozens or perhaps hundreds of instruments and devices which fall into the general category of “shipment recorders” or “transportation monitors”, only few of which are shown as examples in Figure 1.

Figure 1: Examples of Transportation Recorders

The simplest and least expensive devices are those which change color or configuration when something happens, e.g.: a chemical turns red at a certain temperature; a steel ball is dislodged from its spring holder upon impact; magnetic attraction is overcome at a particular acceleration level. These devices are often quite cleverly designed, using chemistry, magnetism, mechanical, material, or physical properties to “sense” and “store” information. However, they usually indicate at only one “trip point” of the measured parameter, and have no way of recording the date and time of occurrence. But they find application in the shipment of goods when only the simplest information is desired. Often their most useful function is that of a very emphatic “caution” message — to proclaim that the shipment is especially sensitive, fragile, and important.

Going back 40 years or more, mechanical “impact” or “vibration” recorders were available incorporating spring-mass systems which responded to input motion, with a pen or stylus attached to the mass writing data onto a paper chart. The accuracy of these instruments suffered from the fact that the spring-mass systems necessarily had resonances within the frequency ranges that they were trying to measure, and their ruggedness was often an issue. These devices are rarely seen today.

The most modern approach, of course, is the *electronic* “transportation recorder”. These are completely self-contained, incorporating sensors, analog and digital circuitry, batteries, and means of data storage and readout. The most straightforward units measure static or slowly-changing parameters like temperature and humidity, at regular time intervals. Although conceptually simple, the best of these demonstrate an amazing sophistication of engineering in terms of low power consumption, small size, ease of use, and data management. They have achieved wide acceptance because of their accuracy, broad measurement range, and time-related data.

The more ambitious electronic units take on the task of measuring the “dynamic aspects” of transport; i.e., shock and vibration. These can be divided into two categories: numerical monitors and full-waveform recorders. The design of numerical units is usually driven by the desire for such attributes as low cost, small size, low power consumption, modest memory capacity, and relative simplicity. The idea is to extract only certain numerical data from the measurements; most common are time-and-date-stamped peak accelerations, but some units provide other information such as duration above threshold, an estimate of velocity change, number of events in an interval, etc. These instruments have found acceptance when the limited data they deliver matches what’s required in particular situations. But they fall short in terms of being able to *fully* characterize the transport environment, and in being able to provide meaningful data which can be used to enhance the realism of laboratory shock and vibration tests.

FULL-WAVEFORM RECORDERS

The subject of this paper is what we will call “full-waveform” recorders. These units measure and store entire acceleration-vs.-time waveforms of the shocks and vibrations which occur during transport. They also often measure temperature, humidity, and other parameters. Since complete information is available for subsequent analysis, these instruments represent the most powerful and sophisticated for the purpose. Data can be analyzed in both the time and frequency domains, or compiled statistically. The instruments are always computer-based, meaning not only that they have internal microprocessors and computer-like architecture, but that they use a host PC running their companion software program for setup, information retrieval, data analysis, file exports, and report generation.

GENERAL DESCRIPTION, BASIC BLOCK DIAGRAM

These instruments are compact — typically about half the size of a brick and weighing 2-3 lbs. Small and light enough to be put into a package for shipment, or unobtrusively fastened to a vehicle or to a container. But they contain a complete acceleration (and often temperature/-humidity) data system with its own transducers, battery power supply, memory, and communications port. Typically the accelerometers are internal (although external sensors are often optionally available).

The specific circuits and features of full-waveform recorders vary between manufacturers, of course, but they share a basic concept and measurement approach. Figure 2 is a generic block diagram showing the major elements common to all instruments.

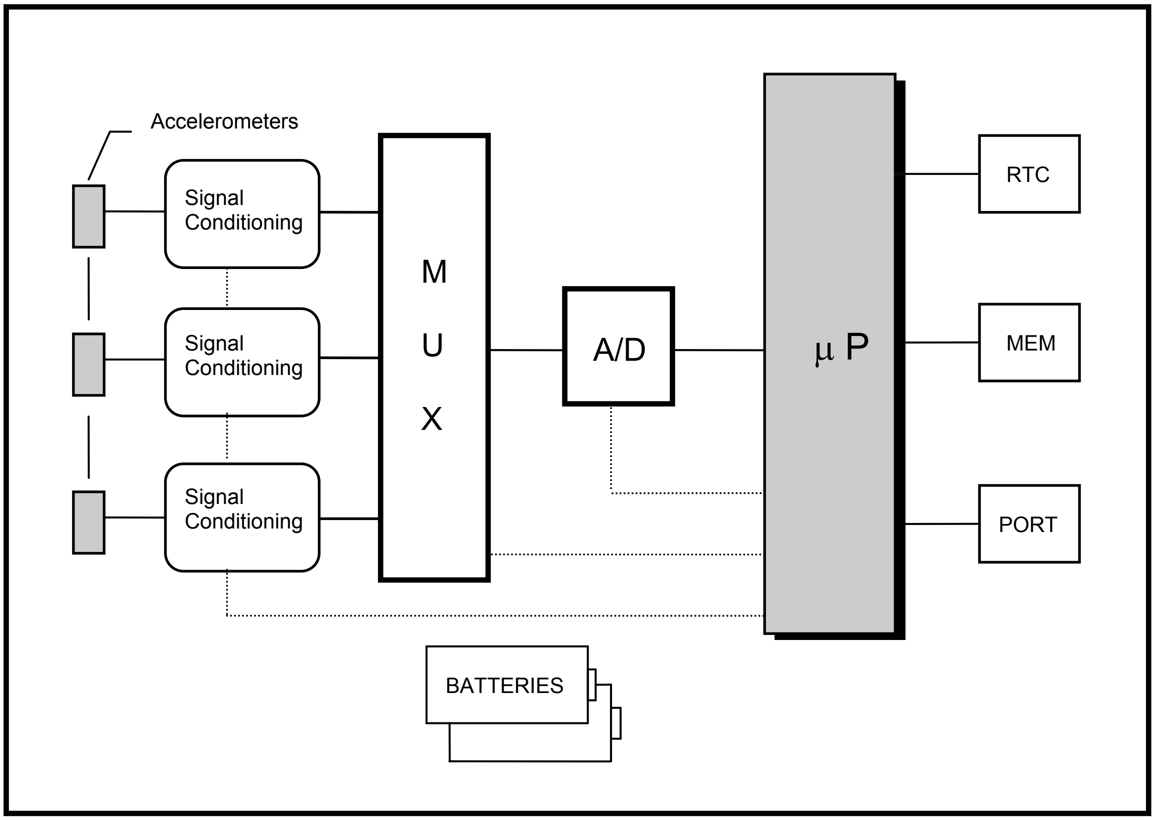


Figure 2: Basic Block Diagram

The shock and vibration sensors are typically three accelerometers (or a “triaxial” accelerometer — three sensing elements in one case), to measure in the X, Y, and Z axes. This allows 3D vectors to be calculated, resulting in “omni-directional” measurement capability. The accelerometers are followed by circuitry which amplifies and filters their signals, to make them suitable for recording and to prevent aliases. These conditioned signals are then connected to a multiplexer (MUX), and the MUX output is connected to an Analog-to-Digital (A/D) converter. The MUX is like a switch, which alternately switches the multiple inputs onto a single output so that only one A/D converter is needed. Compared with having an A/D converter for each channel, this saves space, power consumption, and cost. The A/D is connected to a microprocessor which not only handles the data, but controls the entire instrument operation. There’s digital memory for data storage, a real-time clock (so that the data can be time-and-date stamped), and the computer communications port. All this is powered from batteries and power supply circuitry.

Small signals produced by the accelerometers are turned into bigger voltages by the signal conditioning circuits, then these are connected to the A/D and converted into digital data points. The points are processed by the microprocessor and stored in memory. At the end of a trip or recording session, these data points are uploaded to the host computer, and the signals are re-created by the host software.

If the instrument records temperature/humidity and other parameters, there may be similar blocks for those.

It‘s obvious from the foregoing that these instruments operate as “sampled” data systems. This means that the incoming value is determined (digitized), processed, and stored at only discreet instants in time, as determined by the “sample rate.” When the data are read back from memory, lines or curves are drawn between these digital data points in “connect the dots” fashion to re-create the original inputs. Fluctuations of the signals which might occur in-between samples will not be recorded or reproduced. Further, if the input signal frequencies are allowed to exceed ½ of the sample rate (the Nyquist theorem), aliases may occur. This leads to several important considerations, which will be discussed in a following section. When the sample rate is high compared to the frequency content of the incoming signals (the typical case), then the digital data points are so close together that any differences between the original and reproduced signals are negligible.

SIZE, WEIGHT, AND POWER

These recorders are designed for small size and light weight, so that they can be used in the widest variety of situations. Size and weight usually don’t matter much if you’re instrumenting a railcar, but if you’re trying to measure the drop heights of a box of cookies, it can make a big difference! This means that the units employ state-of-the-art surface-mount chip technology, multi-layer circuit boards, miniature components, custom cases, and specialized design approaches. Power consumption is also very important, since it’s often desirable to have the instruments record for long periods of time without changing or recharging the batteries. Typically the instruments operate on just a few milliamps of current when active, and use advanced power management features to keep overall consumption low.

NON-CONTINUOUS RECORDING

It’s important to understand a fundamental aspect of how these instruments operate, which is that they *don’t* record data continuously. For example, if you wanted to measure a truck shipment from point A to point B, it might seem most straightforward to turn the instrument on at A, record *everything* during the trip, then turn it off at B. But on further consideration, you realize that during the truck trip there would be a great deal of data that are simply not of interest. If you were recording continuously, you’d have information from the truck standing at the dock, parked in a parking lot, sitting at a truck stop, and so on. The moment you looked at that data, you’d see that it was just “zero”, and you’d discard it. Memory and battery power are too precious to waste on data that are ultimately not going to be of interest.

So what events *are* of interest? Continuing our example of the truck trip, we’d certainly be interested in recording when the truck hits a pothole, goes over a rail crossing, bumps over a curb, etc. For these cases, the units are set up to trigger from a programmable acceleration threshold and record for few seconds to capture just those data. Then they power down much of their circuitry and wait for the next event.

And we'd also be interested in the long-term fatiguing vibrations of the truck just rolling down the highway hour after hour. We can't threshold-trigger in this case, because the threshold would have to be set so low that essentially we'd be recording continuously. The fact is, "monotonous" rolling-down-the-highway data is typically much the same the first minute as it is the second minute as it is the third minute, and so on. We only need to measure enough to characterize the kind of motion that it is, and then determine how long it lasts. The instruments do this by waking up every so often, at programmable time intervals, and taking a few seconds of data. That's enough to know what's going on, and — with a resolution which is equal to the interval between measurements — to determine how long the condition lasted.

So in our example of the truck trip, the instruments trigger from an acceleration signal threshold to get the infrequent, big events, and also trigger on a time interval basis to get the ordinary, long-term data — all without wasting either instrument memory or power. This is shown pictorially in Figure 3, where the heavy line represents acceleration-vs.-time data.

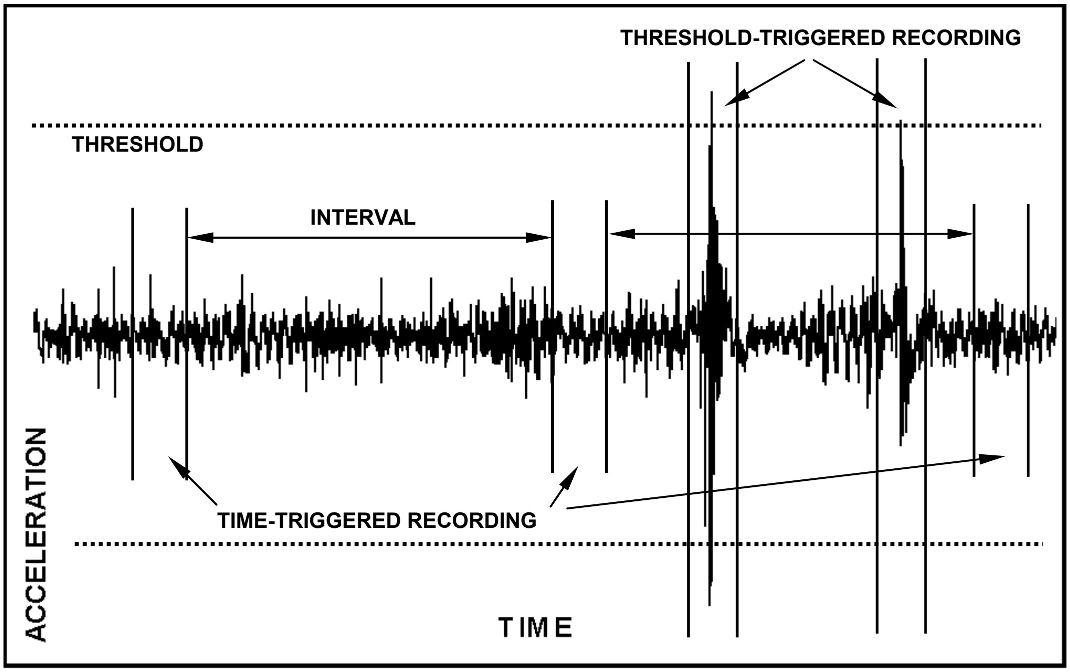


Figure 3: Non-Continuous Recording Techniques

PRE-TRIGGER RECORDING

The instruments can acquire data which occurred _before_ the trigger conditions (threshold, time, etc.) were met. This is to measure the initial rise of a shock pulse, the free-fall time of a drop event, and so on. How can the unit record before it's been told to start recording? The answer is that a portion of the instrument's circuitry is powered and working _all the time_. Visualize a pipeline, with data samples continuously flowing through it. If the trigger conditions are not met, information simply flows into the pipe at one end, and is allowed to flow out of the pipe (and down the drain) at the other end (see Figure 4A). At the instant a trigger occurs, _all_ data in the pipeline are _pre-trigger_ data. So when triggered, more data is allowed to flow in until just the desired (programmed) amount of pre-trigger information remains (the rest of the pipe now being filled with _post-trigger_ data), then the pipe is closed off (see Figure 4B), and its contents are stored in memory.

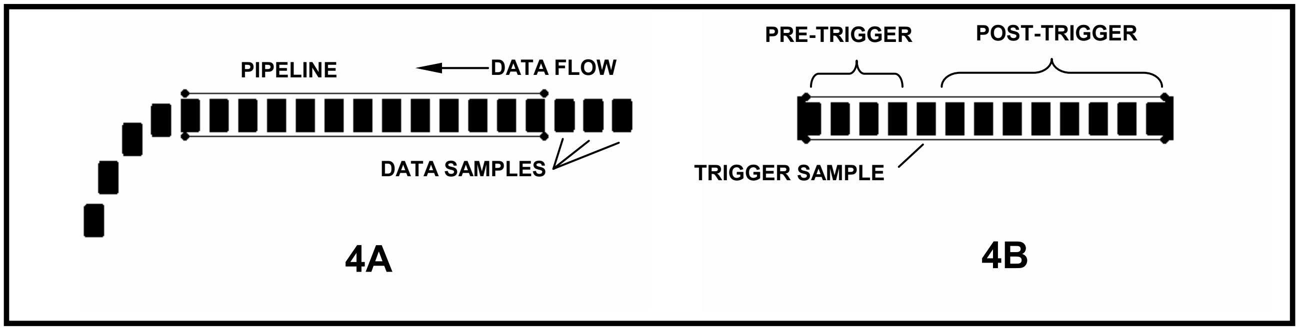


Figure 4: Pre-Trigger "Pipeline"

MEMORY AND DATA MANAGEMENT

An interesting question confronts the instrument designer: how to handle a situation where the unit's memory is full, but a new piece of data comes in? Modern recorders typically have at least three techniques of dealing with this, usually called something like "Fill/Stop", "Wrap", and "Max".

In the Fill/Stop mode, when memory is full and new data arrives, the new data are simply discarded. At the end of the trip, the data remaining in memory will be from the _first_ portion of the trip (before memory filled). This is useful when you know when the trip will start and how long it will last, but _not_ how long it will take to get the recorder turned off and retrieved.

In the Wrap mode, the oldest data in memory are overwritten with the new data. At the end of the trip, the data in memory will be from the _last_ portion of the trip. This is useful when you know how long the journey will last, but not necessarily when it will start.

The Max mode is more complicated, but perhaps most useful. Here, new data overwrites data in memory if they are _larger_ than the _smallest_ of the pre-existing data. As can be imagined, this requires some processor power and computation time, but the result is that at the end of the trip, only the _largest_ events will remain in memory.

The instruments may also manage data in other ways, separating them according to various criteria. These criteria vary among manufacturers, but include *how* the unit was triggered (threshold or time), or *when* the unit was triggered (according to some pre-defined schedule).

SAMPLING RATE CONSIDERATIONS FOR SHOCK MEASUREMENT

The Nyquist criterion requires that the sampling frequency be at least twice the data bandwidth to prevent introduction of aliases. This is a well-known principle for sampled data systems, and will not be covered here. However, there are other considerations when measuring shock pulses. The peak amplitude of the pulse may be under-represented and its waveform distorted if the interval between samples is a significant fraction of the pulse duration. Samples may be taken just *before* and just *after* the peak, but not sufficiently near *to* the peak. And if there are too few "dots to connect", the pulse shape may be inaccurately represented. Figure 5 illustrates these points: the actual shock is well-represented by the solid line when sampled over twenty times during the pulse as shown by the small dots and solid curve. But if that same signal is only sampled *four* times during the pulse, the peak and shape are inaccurately represented by the dashed line.

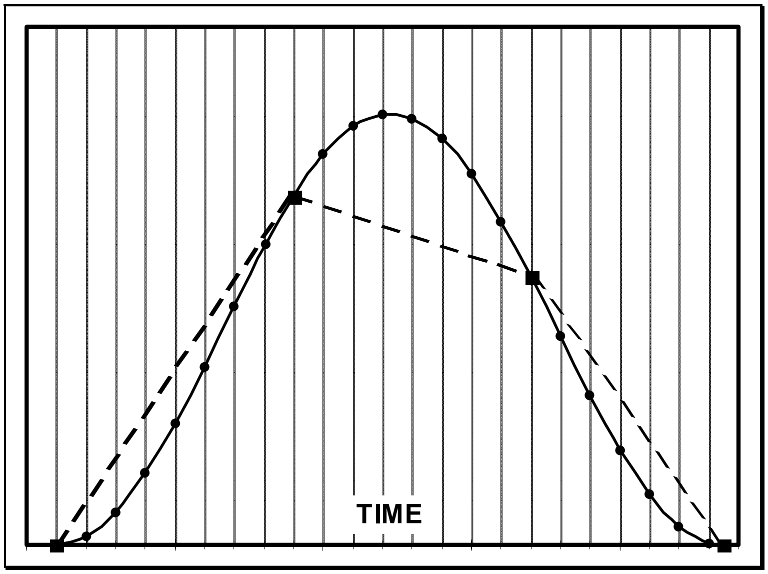


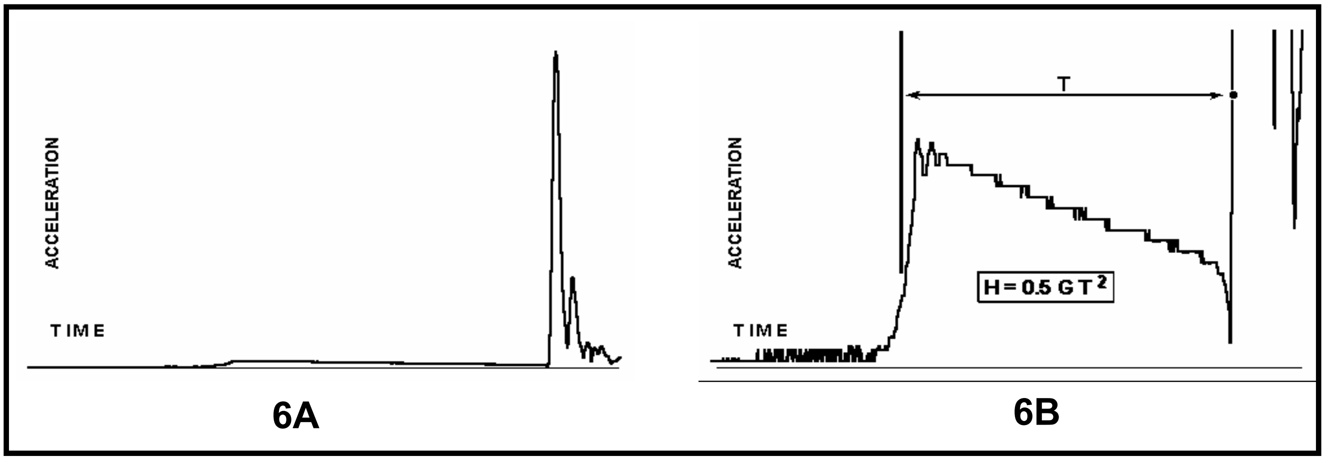
Figure 5: Sampling a Shock Pulse

A good "rule of thumb" is to ensure that there are at least 10 samples taken during the pulse duration. Although this can still result in some small errors, it represents a reasonable trade-off between a high sample rate (which requires more power and consumes more memory) and sufficient accuracy.

DROP HEIGHT CALCULATION

Although several transport recorders are capable of reporting the drop heights of packages in transit, they don't measure drop height directly. They measure *acceleration*, then compute drop height using an algorithm — and this is generally the most difficult sensing and analysis task that the instrument and its software performs. It requires accurate measurement, but (probably more importantly) it also requires an algorithm that takes into account the physics of drops and tosses, instrument characteristics, interactions with the package, and the common scenarios of transportation/distribution.

The software typically looks both at pre-impact accelerations and impact velocity changes to calculate drop height. Pre-impact analysis, a technique known as "zero-G recording" senses the time that the package is in "free fall" to calculate drop height. Figure 6A shows actual acceleration-vs.-time data from a drop test. A recorder was mounted in a package, and that package was dropped, under controlled conditions, in the lab. The instrument was set up for a long "pre-trigger" time, which makes the impact shock pulse appear at the far right of the resulting plot. Notice the small movement of the data during the considerable period prior to impact. In Figure 6B, the plot full-scale has been reduced to clearly show the pre-impact data. In this view the shock pulse goes considerably off-scale, but it's apparent when the shock pulse *begins*, and that's the only point required for this analysis. Where the shock pulse *begins* is where the drop *ends*; the drop *starts* at the near-vertical rise of the pre-impact data (where the package, with recorder inside, transitions from being static at one-G to being weightless — at "zero-G" — during the fall). Knowing T, the time duration of free-fall from start to end, allows calculation of the drop height from the formula given in the figure, where H is the drop height and G is the acceleration of gravity.



6A

6B

Figure 6: Calculation of Drop Height from "Zero-G" Data

Information can be also be extracted from the shock pulse itself, by integrating to get velocity. However, the pulse represents both the impact and rebound velocities, and it is difficult to determine only the impact velocity to allow calculation of drop height. A "calibrated" package can be used to provide additional data for the calculation algorithm; the various manufacturers may use different techniques to enhance the accuracy of their calculations.

APPLICATIONS — RECORDER MOUNTING AND PACKAGING

There are currently three broad measurement applications for transport recorders: to determine the dynamic environment produced by vehicles (often so that it can be reproduced on a testing machine in the lab), to statistically ascertain the drop heights encountered during shipment (for product, package, and test design), and to measure the shocks and vibrations transmitted by a package to a product (for design verification). Each of these requires a different method of recorder setup and mounting/packaging.

If it is desired to monitor the input of a vehicle to its lading, the recorder must be firmly mounted *to the vehicle*. Anything else is a compromise at best. Even mounting to a bottom pallet in a vehicle loaded with product can yield misleading readings when the pallet "bounces" and loses contact with the vehicle floor. If it's ultimately desired have the table of a laboratory vibration machine move like the floor of a vehicle, then true *floor motion* of the vehicle must be measured.

If it's desired to measure drop height, the instrument has to be concealed in a package. And that package needs to look and feel like the "real thing", so that it gets handled (and mis-handled) like the real thing. A "dummy package" is often used — representing the same basic size and weight as an actual package — but with a cushioned, weighted block inside and with the instrument mounted to the block. The cushioning is to protect the recorder — although rugged, it can be damaged by extreme accelerations (usually 500G or more). The block is to achieve the desired shipping weight.

If measurements are to be made for package design verification (to determine the shock and vibration levels transmitted by a protective package to a product), the usual approach is to make a wooden block the same size, shape, and weight as the product, attach the recorder to it, and place it in the actual cushions and package to be used in normal distribution. The reason for using a wooden block instead of an actual product is because the product can often have ringing, rattling, and component resonances which might degrade the data. And wooden blocks are often less expensive than actual products! Care must be taken to ensure that the cushions and package represent an actual production sample, as small variations can cause significant differences in performance.

PRESENTATION AND USE OF DATA

Transport environment information from full-waveform recorders is typically used to make *decisions* — about package design, transportation logistics, and laboratory testing protocols. Statistical significance is very important: one would typically not base a design or test on a once-in-a-blue-moon occurrence. Enough measurements must be taken, and statistical methods applied, to ensure that the conclusions are valid; data should be periodically re-taken to verify that nothing has changed, and if changes are discovered a thorough new measurement project must be undertaken.

Vibration data are most useful when presented in terms of a power spectral density (PSD) plot as shown in Figure 7. Such data in the frequency domain can be easily compiled across multiple trips for statistical significance, and PSD information is readily accepted by vibration test machine control systems. Different modes of transportation (truck, rail, air, ocean) can have significantly different PSD plots, and variables within each mode (position of lading, type and condition of vehicle, different input conditions, etc.) must be explored.

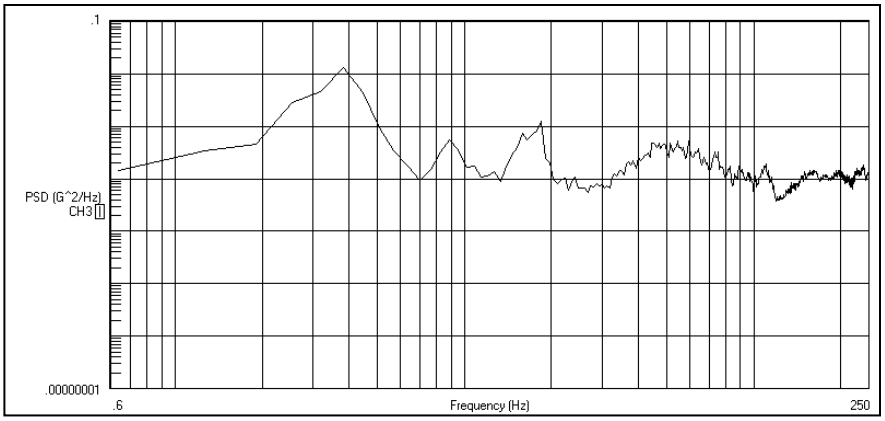


Figure 7: Power Spectral Density (PSD) Plot

Drop height data are often summarized as a histogram, with a cumulative calculation of “percentage of drops at or below” various heights (see Figure 8). This allows a designer to trade off packaging costs against damage losses. For most products, it is more economical to accept some small level of damage than to package for the extreme situation.

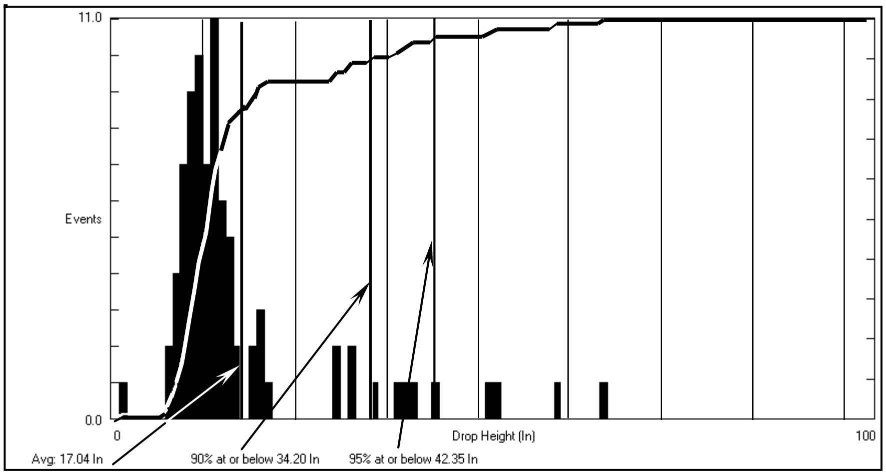


Figure 8: Histogram of Drop Heights

The package orientation at impact should also be measured and reported. This allows a realistic laboratory drop test sequence to be configured — usually a relatively large number of low drops and a smaller number of high drops, at various orientations as indicated by the data.

Shock data are generally presented in an acceleration-vs.-time format as shown in Figure 9, or in a "damage boundary" format as in Figure 10. Since package performance is typically stated in terms of the maximum permissible G-level transmitted to the product, the former is most useful. If the product's fragility has been quantified, the latter presentation allows an engineer to determine exactly which and how many events would have caused damage.

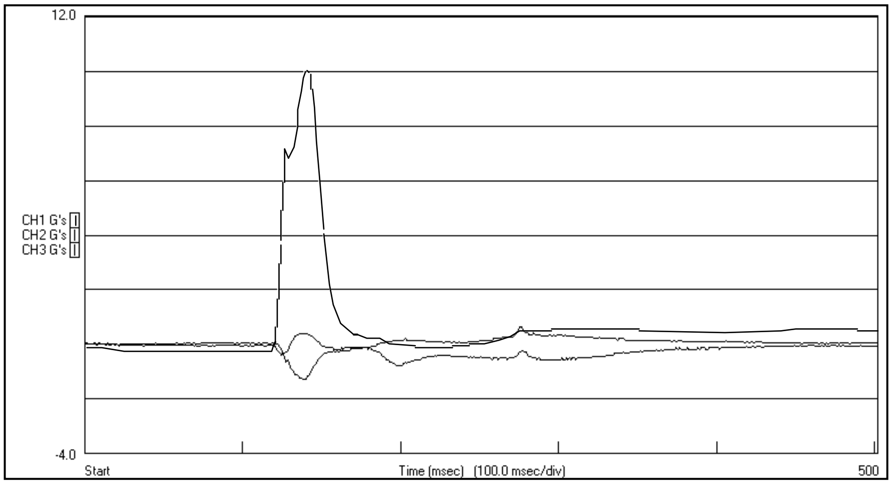


Figure 9: Shock Pulse Acceleration-vs.-Time Display

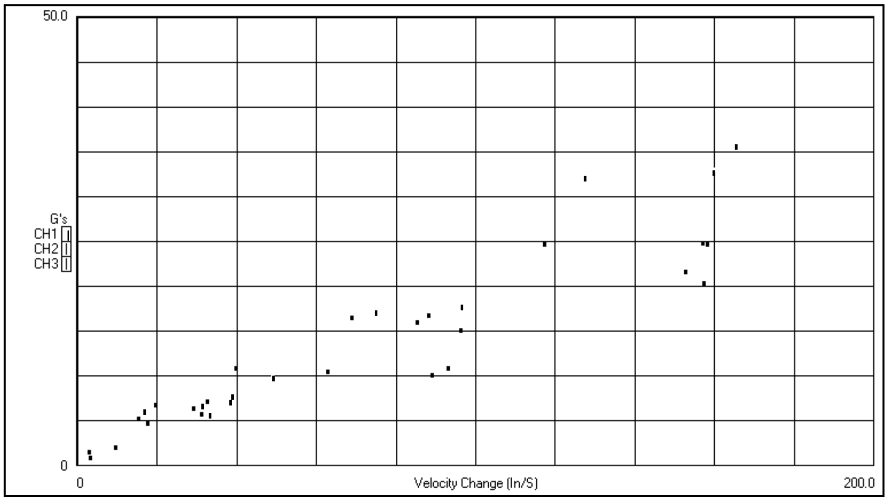


Figure 10: Damage Boundary Display Format

CONCLUSIONS

Today’s full-waveform transport environment measuring recorders are able to furnish the engineer with complete data upon which to base package designs, transportation decisions, and laboratory testing protocols. When making measurements, best results are obtained if the user understands the principles employed by the recorder and its software to gather, store, and analyze data. It is hoped that this paper has furthered such understanding.

Even in the absence of setup or recording mistakes, however, it is nonetheless possible to capture invalid data. For example, if the instrument is still recording when being unfastened from the vehicle or being removed from the package, or if it experiences non-shipment-related conditions of any kind while still recording, those events may corrupt the actual transport data. It is recommended that *every* recorded data event be examined for validity before combining, compiling, summarizing, statistically analyzing, or presenting the final conclusions.