CUSHION MATERIAL EVALUATION

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I. INTRODUCTION

It comes as no surprise to most of us that products will experience higher levels of shock and vibration in the distribution environment than they are capable of withstanding without some help. This "help" is referred to as a protective package system, which normally uses some type of cushion material to do its job.

Cushion materials are rated according to their ability to provide the necessary protection in terms of inputs such as shock (impact) or vibration. For shock or impacts, this information normally takes the form of a cushion curve which describes the amount of deceleration transmitted through a given thickness of material for a given drop height. For vibration, the information normally consists of resonant frequency plots which describe the spring characteristics of cushion materials when loaded at various levels.

The purpose of this paper is to demonstrate the concepts and techniques by which cushion materials are evaluated and the information presented to those who must use it in a package design situation. A wide variety of cushion types are available, including the plastic foam materials, corrugated and paper crushable materials, air cells of various sorts, flexible membranes, and a wide variety of other cushions. Techniques for developing cushion response data for both shock and vibration input will be covered. The advantages and disadvantages of each method of presentation will also be highlighted.

II. TERMINOLOGY

Certain specific terms will be used throughout this paper and a working knowledge of exactly what is meant by each one is necessary for a complete understanding of the topic area. The terminology list is contained in Appendix I.

III. BASIC SPRING DYNAMICS

Cushion materials can be described as mechanical springs or isolators used to mitigate the effects of shock and vibration on a product. Most people are familiar with the springs used on automobiles which essentially cushion or mitigate the vibration and shock inputs from the road to the passenger cavity resulting in a much smoother and more comfortable ride. In this same way, a cushion material is anything interposed between one object and another to mitigate the effects of shock and vibration on the first object.

In this regard, all cushions or springs work in basically the same way; that is, they deform in response to induced forces. They transform relatively high G short duration shock pulses experienced when two rigid surfaces collide, such as a product dropping on the floor, into a lower G longer duration pulse. This type of event can be visualized such as shown in Figure 1.

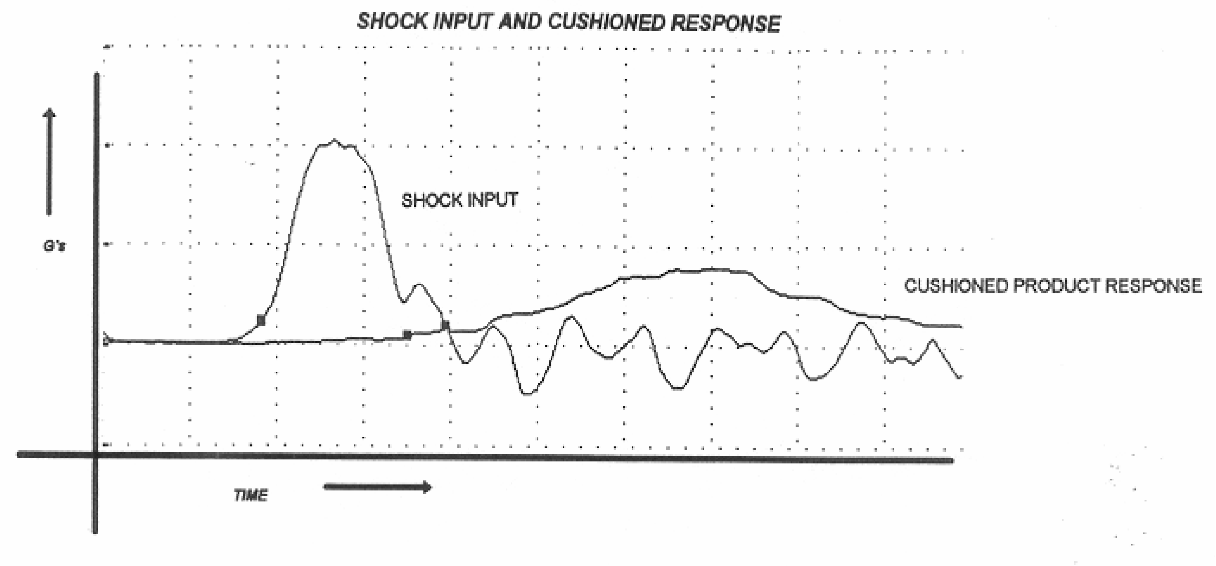


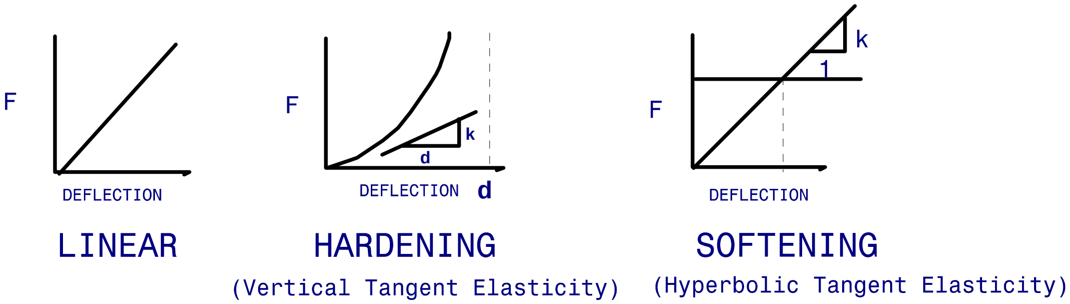
Figure 1 (Source: Westpak, Inc. data)

For package cushioning work, the most important spring characteristics are the spring rate (and creep associated with that rate) and the natural frequency (and damping) built into the spring/mass system.

SPRING RATE

The spring rate of any spring is the measure of the amount and uniformity of deflection in the spring as a result of an induced force or load. Springs are categorized as linear, hardening, or softening springs depending on the shape of the force/deflection curve. For example, a **linear spring** has uniform and predictable deflection characteristic for an applied load or force.

Non-linear springs are categorized as hardening or softening depending on their particular characteristics. Hardening springs result in decreasing deflection as a function of load increase, whereas softening springs result in an increase in deflection with a uniform load increase. These characteristics are shown graphically in Figure 2.



LINEAR

HARDENING
(Vertical Tangent Elasticity)

SOFTENING
(Hyperbolic Tangent Elasticity)

Figure 2 (Source: Westpak, Inc.)

CREEP

Compressive creep is defined as the change in thickness of a cushion under a constant static load over a long period of time. All springs, regardless of their shape or material, will gradually compress under a long-term exposure to a constant load. Worn-out bedsprings and rear ends of cars that sag excessively are examples in everyday life of static and dynamic creep. This characteristic is important to package designers as cushion materials are normally designed close to the creep limit in order to be effective and efficient in the use of materials.

NATURAL OR RESONANT FREQUENCY

All spring/mass systems display a characteristic known as resonance, wherein the response of a mass mounted on a spring to a vibratory input is greater than the input itself. For a totally undamped system, this response level can reach infinite proportions. Real world systems, however, all have some level of damping built into them which limit the excursion. This damping is a measure of the transmissibility of the vibration response at resonance. These characteristics are graphically displayed in Figures 3 and 4.

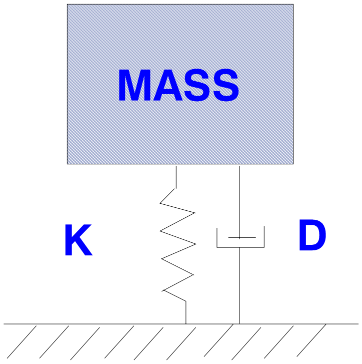


Figure 3 (Source: Westpak, Inc.)

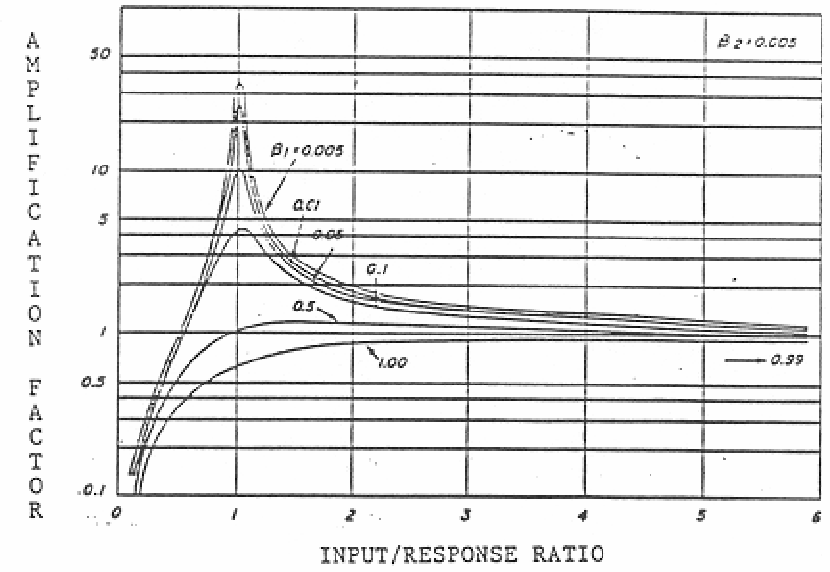


Figure 4 (Source: Steinberg)

IV. CUSHION CURVES

The shock performance of cushion materials is measured using instrumented impacts resulting in a cushion curve such as that shown in Figure 5. The cushion curve describes a level of deceleration transmitted through a given thickness of material as a function of static stress (loading) on the cushion and the height of the drop.

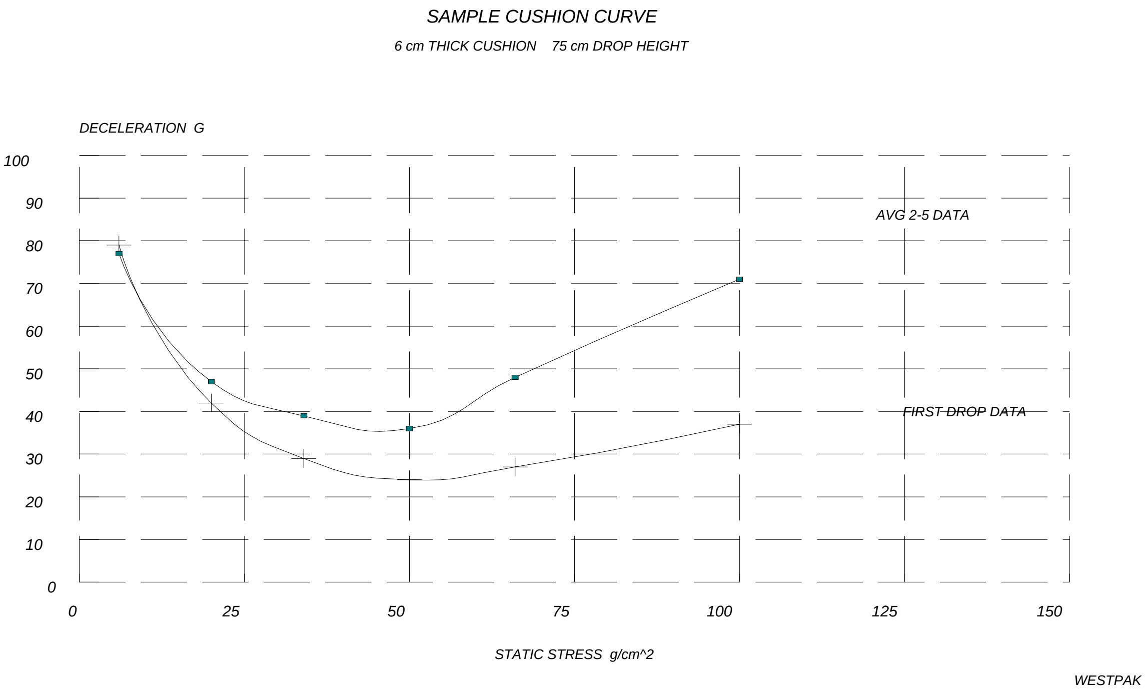


Figure 5 (Source: Westpak, Inc.)

The procedure results in a cushion curve with peak deceleration on the vertical axis and static stress on the horizontal axis. (Static stress = weight / bearing area) Some procedures require that each curve be drawn from a minimum of 5 test points (static stress levels) and that each test point is the average of the last 4 of 5 deceleration readings from the material test at each load level.

Most cushion curves have the general shape of that shown in Figure 5. The left-hand portion of the curve shows a relatively high deceleration level transmitted through the cushion. The center portion of the curve represents a more optimum loading where there is sufficient force to deflect or crush the material or shape and cause the deceleration to be spread over a longer period of time. The result is a lower deceleration level. On the right-hand portion of the curve, the material or shape is overloaded. (It bottoms out.) Thus it approaches using no cushion at all resulting in higher deceleration levels.

It is important to recognize that the procedure used for conducting a cushion curve has a tremendous influence on the data generated as well as the intended end use of that data. Many packaging engineers think that cushion curves are intended to give information on the transmitted deceleration levels in a package design situation. In fact, that may not be the case. Most cushion test standards such as ASTM D1596 (the one most widely used for commercially available materials) were originally intended to provide information to compare cushion materials to one another in a controlled situation rather than to provide data for package design. This may seem like an insignificant difference, but when the data is used for a protective package design, the end result may be very different from the anticipated result.

Consider, for example, how the various tests are conducted. ASTM D1596 procedure uses a test machine with a guided platen that has provisions for adding weights and an accelerometer to the platen to measure the level of deceleration experienced at impact. The machine is equipped with a velocity indicator so that the proper impact velocity can be determined and with rebound brakes to prevent multiple impacts on the cushion.

Five impacts are conducted at each static stress loading, and a new specimen is used for each loading level.

The important feature of the test procedure is the fact that a guided falling platen impacts a cushion specimen resting on the rigid base plate of the machine. The deceleration level at impact is monitored on the platen. Regarding the use of the data for design purposes, the standard cautions that "...data obtained are applicable to the cushioned and not necessarily the same as obtained in completed packs." (1) Earlier versions of this standard contained wording to the effect that data obtained were useful in comparing cushion materials to one another rather than for use in package design applications.

The **enclosed test block method** conducted according to ASTM D4168 (2) is a procedure intended for testing of foam-in-place cushion materials and requires that the test block be surrounded by the cushion material and the entire assembly placed in a corrugated container. The container, with a test block, is then dropped from a known height onto a rigid surface. The deceleration transmitted through the cushion is monitored by an accelerometer mounted inside the test block. (See Figure 6 for more details.)

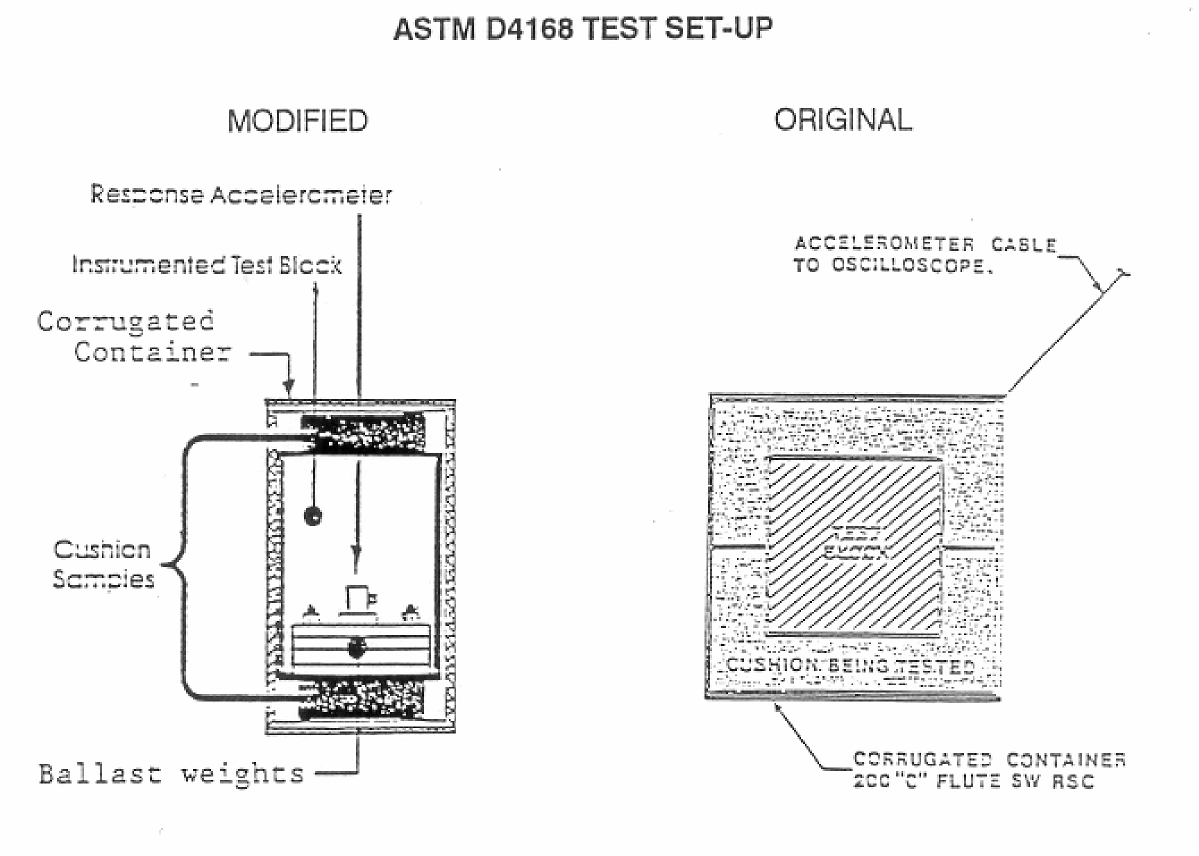


Figure 6 (Sources: ASTM & Westpak, Inc.)

Various modifications of this test setup are known to exist for testing of other than foam-in-place materials. Oftentimes, the block is modified to accommodate larger test specimens, including corner pads or placed in a container with top and bottom pads only. Provisions are made to allow for air flow between the top and bottom chambers normally by means of corrugated edge pads on the vertical edges of the containers which also function to keep the foam material aligned with the enclosed test block.

The important features which distinguish this procedure from the preceding include:

1. The enclosed test block is in intimate contact with the foam material prior to impact.

2. The effect of corrugated crush and the friction of the container are taken into account.

3. The unknown effects of bearing friction and rebound brake actuation (from the guided platen on the D1596 cushion tester) are eliminated.

The D4168 standard states that the cushion curves obtained by this method "...allow design of cushion systems that can provide adequate and efficient use of foam for protection of goods..." (2) Early versions also noted that this standard was intended to evaluate materials in a manner in which they were used. This is a significant difference from the D1596 procedure.

When using cushion curves, the designer must be cognizant of the procedure used to produce the curves and the potential result that may have on the final package design. One study which investigated this area concluded that the data from ASTM D4168 test procedures came the closest to performing according to the information predicted by the cushion curve in the final package design. (3)

V. VIBRATION RESPONSE OF CUSHION MATERIALS

The vibration performance characteristics of cushion materials are determined by subjecting them to vibrational inputs covering the frequency range typical of the distribution environment. In this case, the cushion and a test block form a spring/mass system which display resonant frequency characteristics important to the package design process.

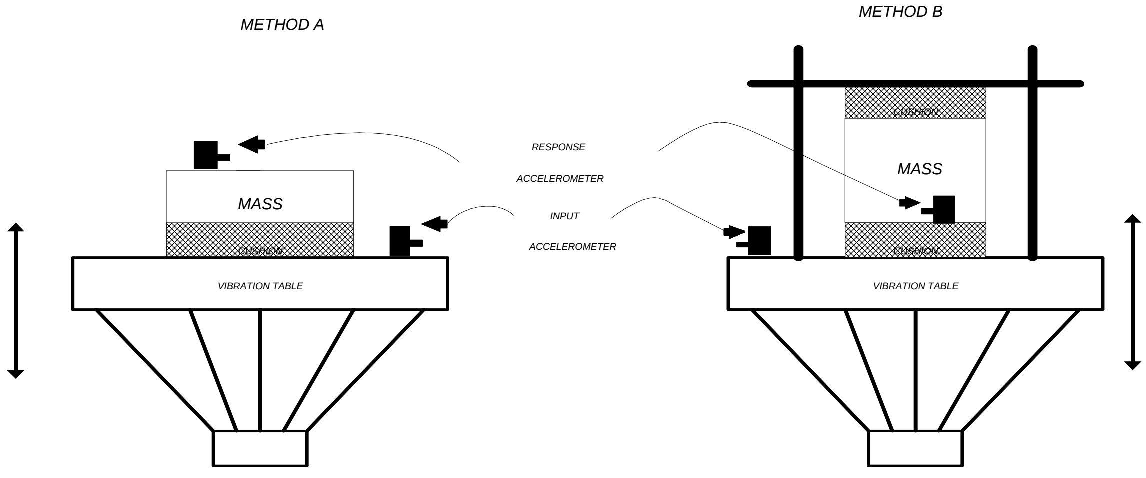
The test setup to produce the data is shown in Figures 7 through 10. The mass of the test block is changed in order to vary the static stress loading on the cushion material, and the test is repeated. Various transmissibility plots are obtained in this fashion. A total of five vibrational sweeps are recommended in order to construct the amplification/attenuation (A/A) plot shown in Figure 10.

The amplification/attenuation plot displays frequency on the vertical axis and static stress (loading) on the horizontal axis. The center portion is that combination of frequency and loading that results in amplification of vibrational input. This is referred to as the **amplification zone**. At lower static stress loadings and frequencies, there is a zone where the response input ratio is approximately one. This is the unity zone where the cushion material neither amplifies nor attenuates vibration input. At higher frequencies and loadings, the cushion material will attenuate (reduce) vibration input. This are is referred to as the **attenuation zone**.

The plot in Figure 10 may be interpreted as follows:

> For a given frequency, the lower static stress loadings result in the same acceleration transmitted to the product as the input. In other words, response/input ratio is approximately 1. As the static loading level increases, there is a range in which the cushion material amplifies vibration input. At higher loading levels, the cushion material attenuates vibration input. That is, the response/input ratio is less than 1.

TYPICAL CUSHION VIBRATION TEST SETUPS



MASS ADHERED TO FOAM
SO THAT THE "SPRING"
(CUSHION) WORKS IN BOTH
TENSION AND COMPRESSION

MASS ISOLATED BETWEEN
2 "SPRINGS" (CUSHIONS)
THAT WORK ONLY
IN COMPRESSION.

Figure 7 (Source: Westpak, Inc.)

CUSHION RESONANT FREQUENCY PLOT (TRANSMISSIBILITY)

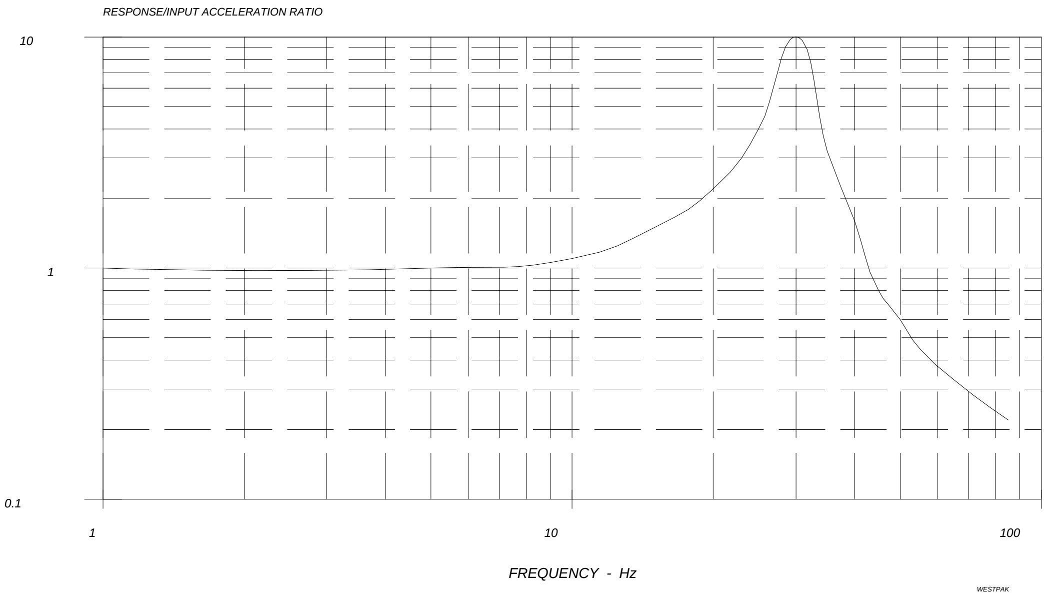


Figure 8 (Source: Westpak, Inc.)

MULTIPLE RESONANT FREQUENCY PLOTS

(different cushion loadings)

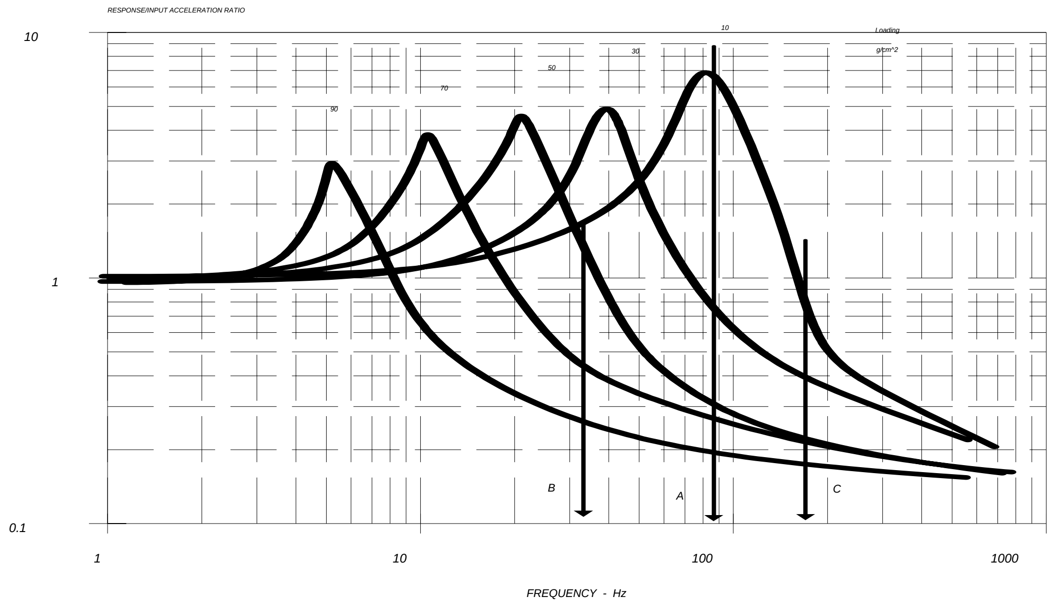


Figure 9 (Source: Westpak, Inc.)

AMPLIFICATION/ATTENUATION PLOT

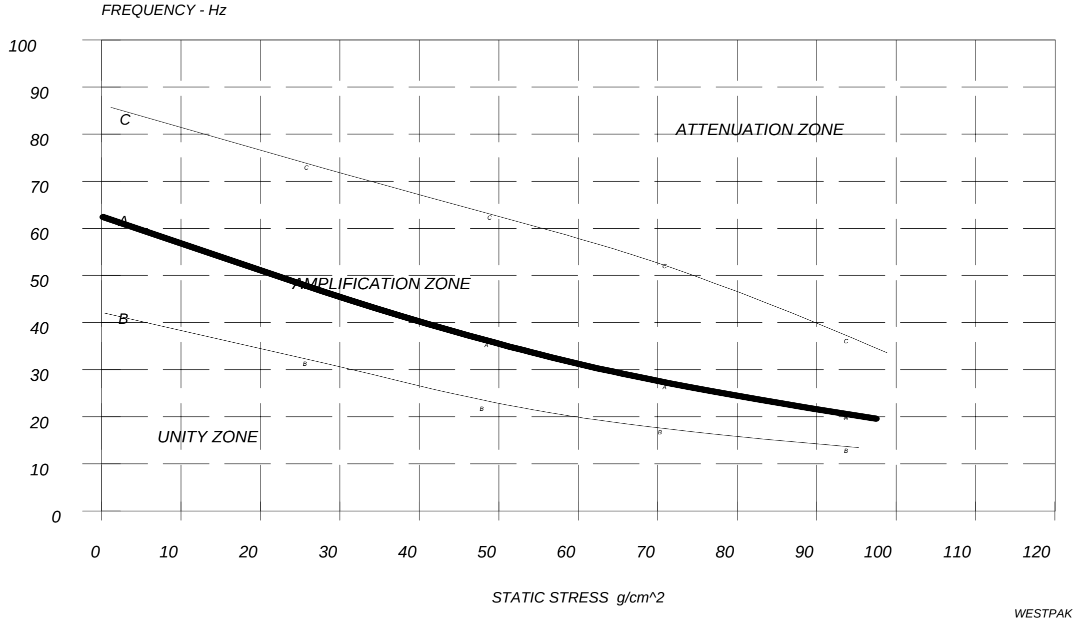


Figure 10 (Source: Westpak, Inc.)

At the present time there is no recognized standard governing the procedure for running cushion vibration tests. Much of the data currently published such as that in MIL Handbook 304B. (4) were produced using the **fixture method**. This fixture is a device for restraining a test block in two axes while allowing it to move freely in the vertical axis. The cushion sample is placed above and below the block, and the entire fixture is mounted to the table of a suitable vibration test machine. A minimum of five vibration sweeps are conducted at different static loading levels in order to determine the response characteristics.

The **enclosed test block method** for determining vibration response characteristics is similar to that described in Section IV. In this case, however, the enclosed test block is placed in a container with a cushion sample above and below it. The container is fastened to the table of the vibration test machine and subjected to the same frequency sweep previously described. The result is a resonant frequency plot for that static loading.

Static loading levels are changed by means of adding weight to the enclosed test block. New resonant frequency plots are conducted at various loadings resulting in a family of curves such as that shown in Figure 10.

Some uses of cushion material, particularly in floating deck crate designs, utilize the cushion as both a tension and compression spring. In this case, the data generated with a fixture or enclosed test block is not appropriate.

Data for floater deck designs can be best obtained by modeling the floating deck with a plywood base and a top on a platen both adhered to different surfaces of the cushion material. The bottom platen is secured to the vibration test machine, and the top platen is used for applying ballast weights in order to change the static stress loading on the cushion. The vibration sweeps are conducted as previously described and the resulting transmissibility plots are converted to an amplification/attenuation (A/A) plot. (See Figure 7.)

It's important to recognize again that the method of conducting the test has a significant influence on the data and its usefulness for design purposes. For example, designing floating deck cushions using compression data only from enclosed test block vibration procedures will be very misleading. In a similar way, designing endcaps for a vibration sensitive product using the tensile/compression method for floater deck designs will be very misleading. The package designer must be cognizant of the method used to generate the data in order to have effective design results.

VI. TESTING NON-TRADITIONAL CUSHION TYPES

Numerous other cushion designs and types are available to the package engineer and methods for testing these various designs and materials lag the introduction of the materials themselves.

For most design purposes, the materials and designs can be tested by having them enclose or support a given mass to which an accelerometer or other sensing device has been mounted. The mass is then secured to the cushion and subjected to a freefall impact. If required by the design, the cushion and the mass can be enclosed themselves in a corrugated container or similar device. The important consideration is that it have a minimal effect on the cushion response characteristics of the material or structure being studied.

By varying the static loading on the cushion material, a series of impact data can be collected which will result in a cushion curve. For many materials and designs, the concept of "static loading" on the cushion material is meaningless because the suspension of the mass inside or on the cushion may not utilize a given amount of "bearing surface" on a deflectable cushion. Suspension packs, for example, will often use air-inflated members or stretchable membranes in order to provided the necessary "give", and therefore, cushioning in a particular design. Designs that utilize crushable members have bearing surfaces that will change dynamically as a function of the crush of those members.

The important consideration for these non-traditional cushion curves is that the maximum transmitted deceleration be monitored as a function of the total mass suspended by the cushion for a given drop height. If this information is known and accurately recorded, then the effective results of using the cushion material or design can be determined and displayed in the traditional cushion curve format.

VII. TECHNIQUES TO IMPROVE LABORATORY DATA

Regardless of which procedure is used to generate cushion response data, the following techniques may help in assuring that the data is accurate and that the results are able to be reproduced in a package design.

A. Be certain to locate the response accelerometer as close as possible to the geometric center of the mass. This is especially important for those techniques that involve a movable mass or the enclosed test block which can rotate or move in more than one axis during cushion deflection. The only way to minimize the effect of this translational movement and achieve reproducible results is to have the accelerometer located in the geometric center of the mass. It is also desirable to have the accelerometer as close as possible to the interface between the mass and the cushion.

B. Be certain that the ballast weights are securely held to the test block and do not rattle during an impact. Loose weights or other loose components on the enclosed test block cause transience or high frequency impacts that may require filtering of the response waveform. The most accurate data comes from unfiltered waveforms, and therefore, the most rigid or solid mass results in the best possible data.

C. When using the ASTM D1596 procedure with a guided platen, make sure that the platen and the impact surface are exactly parallel. This can be accomplished by slowly lowering the platen to the impact surface without a cushion sample in place. The two surfaces must meet exactly parallel.

   In order to determine if the platen and the cushion sample meet the required specifications, it is sometimes instructive to put two accelerometers on the platen; one near each guide rod. Any deviation of the waveform from one accelerometer to the other would indicate a non-parallel condition of the platen at impact, and this must be corrected before data is generated.

D. For cushion materials that function at high static stress loadings or those that are relatively thin, the enclosed test block method with a corrugated shipping container around the mass and the cushion may not be appropriate. The reason for this is that the corrugated material in the shipping container will itself function as a cushion under the right conditions. This will result in erroneous readings and ones that are not reproducible in a package design situation.

   In cases like this, the use of a plywood or other rigid container may be appropriate for the exterior dropping mechanism. When using a rigid exterior container, great care must be exercised to make sure that the impact is exactly flat on the base of the drop test machine.

E. The use of a shock test machine in place of a freefall drop tester may be desirable in situations where the cushion is relatively thin or the loading is relatively high. The shock machine should be set to produce a 2 msec half sine shock pulse with a velocity change equal to the impact velocity from the freefall drop height being considered. For example, a 24-inch freefall drop can be simulated by a velocity change equal to 136 in/sec, which is equal to the impact velocity from a 24-inch drop height. It is important that the duration of the shock pulse be relatively short in relation to the duration of the cushioned response of the system being tested. A new ASTM standard about to be released gives further guidelines for use of the shock machine in place of a freefall drop tester.

   During a recent test of molded paper pulp corner cushions, Westpak found the use of the shock test machine invaluable in producing repeatable and accurate results. Total thickness of the cushion material was approximately .75 inches. (5)

F. For vibration testing of cushion materials using the fixture method, the level of pre-loading on the cushion systems has been found to be important in the overall test results. Westpak recommends a fixture design wherein a constant and repeatable preload can be applied to the cushion systems by means of a dead load placed on the top platen of the device.

G. For vibration testing of materials using the enclosed test block method, it is important to allow free air movement above and below the test block. This is normally accomplished by using corner or edge guards in the container to allow the enclosed test block to move freely up and down but allowing sufficient space on the edge of the container for passage of air.

H. For vibration testing of cushions in the tension/compression model, it is important that the mass placed on top of the cushion be secured to the top of the material and that it be as close to the material as possible. The use of tall test masses will tend to deflect the cushion in an edgewise manner especially at the heavier loadings. This can result in erroneous readings, especially with open cell materials that tend to deflect unevenly during vibration induced compression.

VIII. USING THE LABORATORY DATA IN A PACKAGE DESIGN

Once the total thickness loading and rib configurations of the cushion are determined, the package must be designed using these numbers. This is the point where both the performance and the integrity requirements of the package must be addressed. Refer to Cushion Material Testing and Cushion Package Design (6) for more discussion of performance vs. integrity.

Other factors also enter into the process of determining the best package design for a particular application. These include fabrication requirements, end user constraints, ecological considerations, flammability, and a host of others. Important requirement for dynamics is a static loading in each product axis which satisfies the product shock sensitivities and does not result in vibration amplification at product critical frequencies.

It is also important to avoid loadings on cushion materials that will result in significant creep or loss of cushion thickness. This is especially true at higher temperatures for certain polymer materials. It is therefore important to have this data available when designing a package. For example, if optimum vibration can be achieved using a loading of 2 psi on a particular cushion material, but that loading produces a 30% creep at 100ºF, the choice of that material at that loading is certainly questionable.

IX. PACKAGE PROTOTYPE TESTING

Once the design is complete and a prototype fabricated, it must be tested for performance and integrity.

For **shock performance** testing, flat impacts are generally used with the deceleration transmitted through the cushion measured by one or more accelerometers mounted on the product. Westpak recommends 3 accelerometers, one for each axis. The test procedure should be that previously agreed to, but in most cases will follow closely ASTM D775 (7) or similar procedures. Take care to ensure flat impacts. This is important! The difference between a flat drop and an "almost flat" drop can be very drastic in terms of response deceleration. Using 3 accelerometers can help determine if the impact was flat.

It is also important that the monitored location (where the accelerometer is mounted) be as rigid as possible and ideally as close to the product/cushion interface as possible. The reason is to determine the package **input** deceleration, not the product **response** characteristics. In many cases these are difficult to separate. If the product were a solid uniform mass it probably wouldn't make any difference where the accelerometer was located; the input from the cushion would be identical to the response of the mass. However, most products have suspended masses and other components which will be excited or put into motion by a shock input. The response of these various suspended components can cause such things as "chattering" or high frequency noise on the response waveform (see Figure 11).

Often the response acceleration peak is well above the input of the cushion. For example, a primary cushion response waveform may have a peak of 40 G's with superimposed high frequency on top of it which may double that number. It is important to be able to separate these two by identifying the difference between package input and product response.

HIGH FREQUENCY "NOISE" ON RESPONSE WAVEFORM (LEFT), FILTERED (RIGHT)

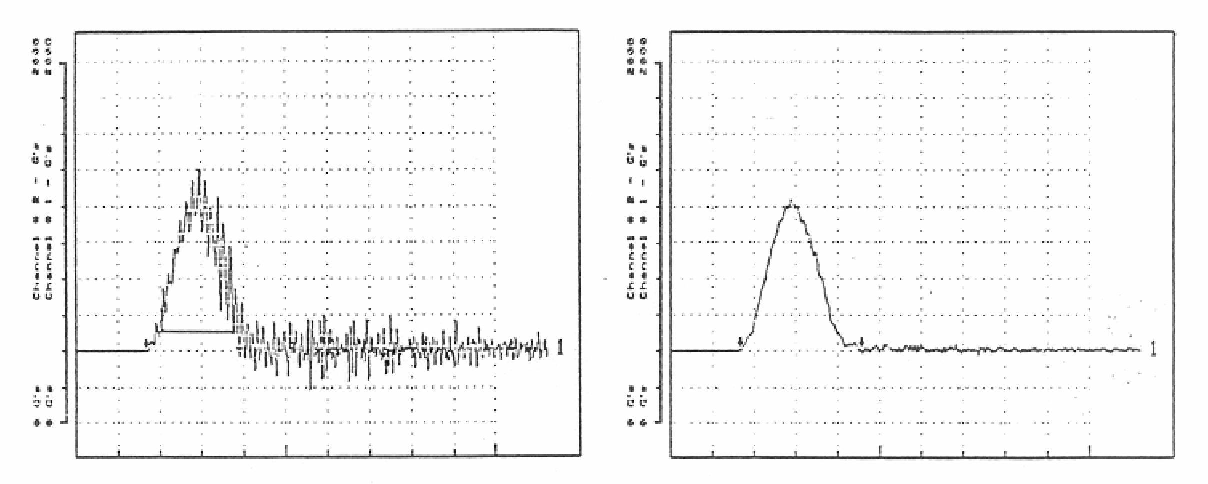


Figure 11 (Source: Westpak, Inc.)

This is one of the most common problems in package response testing. There are several methods of avoiding this problem which should be helpful.

1. Learn to mount the response accelerometer in the proper location, avoiding flexible elements and locating the transducer as close as possible to the cushion material.

2. Understand the use of electronic filters and how they can reduce the apparent affect of high frequency ringing superimposed on the primary response waveform. Exercise care to avoid overfiltering and distorting the response data. (8)

3. If possible, restrict flexible elements within the product in order to make it as homogeneous and rigid as possible. It is sometimes instructive to perform two drop tests; one with the flexible elements unrestrained showing the high frequency response and the second with flexible elements restrained. Note the difference on the product response characteristics.

The **vibration performance** of a package system is verified by subjecting it to a sine sweep over the same frequency range likely to be experienced in the distribution environment. With an accelerometer mounted on a rigid part of the product, the designer can identify the frequencies where the cushion material amplifies vibration input and where it begins to attenuate that input. If the job was done correctly, the package will attenuate (reduce in amplitude) those frequencies where the product is most sensitive.

Package **shock integrity** tests typically involve a series of corner and edge impacts such as those called out in ASTM D4169. (9) This procedure is perhaps the most up to date method incorporating much of the environmental input studies to date. This standard is recommended for package integrity testing.

The **vibration integrity** characteristics of a package system are tested using a sinusoidal dwell test such as that called out in ASTM D999, Method B. (10) Alternately a properly designed random vibration procedure can be used to test both performance and integrity characteristics. Select a suitable random vibration spectrum that "envelopes" the anticipated input from vehicles used to distribute the product. Dwell times vary; some firms use a dwell equal to 5 to 10% of the anticipated time the product will be exposed to vibration input. Thus a 20 hour truck trip may dictate a 1 hour random dwell. Some experimentation in this area will be necessary. Refer to ASTM D4728 for guidelines (11).

Beware of the "mechanical bounce" test, sometimes called a vibration test procedure. The bounce test (conducted on a mechanical shaker) amounts to a series of repeated impacts with very short intervals between events. It may be referred to as a repeated impact test, a bounce test, a fatigue test or something else...but it should not be mistaken for a vibration test. Variable frequency sine testing or random vibration is the only way to test for package natural frequency and product vibration attenuation.

If the package system meets all its requirements, then the job is finished. If not, further package system refinements are necessary.

X. CONCLUSIONS

All cushion systems work in the same way; they trade a high peak short duration shock pulse for a longer duration lower peak shock pulse (See Figure 12). The longer duration depends on the deflection of the cushion. This deflection can be the result of compression, shear, flexure, or other motion of the material. In all cases, the results are the same, namely, the material must "give" in order to change the shape of the acceleration vs. time pulse delivered to the product. The nature of this deflection is predicted by a series of simple physical formulas. Also, the relationship of the variables involved in dynamic package response is straightforward and once it is understood by the designer, it can be of great help in optimizing cushion systems.

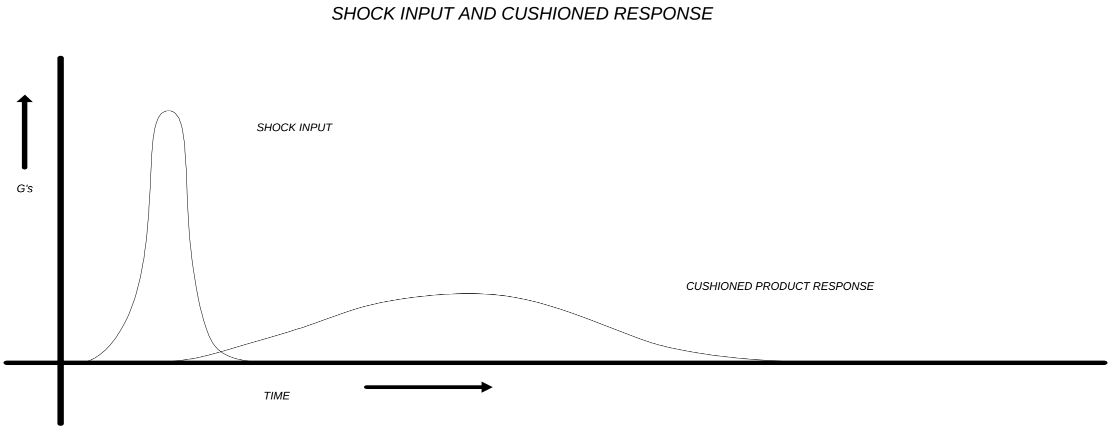


Figure 12 (Source: Westpak, Inc.)

It is likely that package design and testing will become more technical in the future. However, the increased sophistication will simply involve adaptations of a few basic techniques explored in this paper. The designer is encouraged to learn why and how cushion materials do their job and to use this information to design better package systems.

References

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