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COMPARISON OF VARIOUS ASTM AND NSTA VIBRATION
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COMPARISON OF VARIOUS ASTM AND NSTA VIBRATION TEST METHODS FOR PRODUCT PACKAGING

By

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ABSTRACT

COMPARISON OF VARIOUS ASTM AND NSTA VIBRATION TEST METHODS FOR PRODUCT PACKAGING

By

Atiwadee Pichyangkura

This study investigated the effect of three different vibration tests recommended by ASTM and NSTA for package testing. The vibration levels were measured in the instrumented packages located on the top and bottom of a column stack. The sinusoidal vibration and random vibration tests were done on an electrohydraulic vibration test machine as recommended by ASTM. The NSTA vibration test was done on a mechanical rotary vibration machine. The results showed that the NSTA vibration test is less severe than the ASTM vibration test for all package types except those that have a resonant frequency between 3.0-5.5 Hz. The ASTM vibration tests predominantly produce impact only in the vertical orientation while the NSTA vibration test produces a higher frequency of impacts in the side orientation at the top of the stack. These side impacts are significantly more severe than those measured in packages for lateral movements inside trailer shipment.

I would like to dedicate this thesis to:

My parents : Dr. Chart and Dr. Sumalee Pichyangkura for their love, hard work, and support throughout my life.

My grandmother and my grandfather, and my two brothers for their love and encouragement.

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I would like to express my gratitude to Dr. S. Paul Singh for his guidance, support, and understanding while serving as my advisor. I would also like to thank Dr. Gary J. Burgess and Dr. Galen Brown for serving on my committee.

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1.0 INTRODUCTION

The purpose of this study was to investigate the various vibration test methods that are recommended by the American Society for Testing and Materials (ASTM, 1992) and the National Safe Transit Association (NSTA, 1992). The two societies have developed test methods to simulate the effect of vibration forces that are encountered during transportation of packaged goods. The purpose of testing shipping containers is to obtain necessary information that is useful in reducing damage and costs. By using appropriate tests, information about the protective capabilities of the container can be obtained. Real life test shipments are cumbersome, slow, and expensive, and usually delay the introduction of new products to the market. Laboratory simulated tests provide critical information in a short period of time and can in most cases pinpoint the precise cause of failure. Laboratory tests are used to simulate the various conditions found during actual handling, storage, and shipping of packaged products.

The NSTA vibration test using the mechanical rotary table is more economical due to the low relative costs of the equipment. However it does generate severe motion in the lateral direction. The ASTM vibration tests using the electrohydraulic vibration table are more expensive due to the very high cost of the equipment. These machines also produce vibration movement restricted in the vertical orientation. Real life shipments will have both lateral and longitudinal vibrations along with the vertical vibrations. The three or more degree of freedom electrohydraulic vibration tables are extremely expensive and therefore cost prohibitive to be used in package testing.

A number of organizations have worked on developing packaging test standards in the United States. The oldest and largest of these is the American Society for Testing and Materials, Committee D-10 on Packaging. Operating as a balanced consensus group, the ASTM D-10 Committee has generated over a hundred packaging standards since its inception in 1914. The Federal Government also has developed various packaging test methods. Most of these are included in the Federal Test Methods Standard 101C. Some shipping-container test standards have also been developed by the Packaging Institute USA. The National Safe Transit Association has developed performance test criteria for shipping packages since the late 1940s which are continually updated in the document titled " Pre-Shipment Test Procedure". The NSTA has a large representation from the various trucking and transportation carriers in its membership. The Technical Association of Pulp and Paper

Industries (TAPPI) has developed various standards for the use of paper and corrugated in packaging applications.

This study specifically investigated two types of vibration test methods. These are the sinusoidal vibration test and the random vibration test. The sinusoidal test uses a single frequency of excitation and the packages are subjected to this frequency for a specific time period also referred to as " dwell time ". The amplitude of vibration is also held fixed during the entire dwell time.

The ASTM D 999-91 is the " Vibration Testing of Shipping Containers " test method using sinusoidal vibration. The test standard allows using two separate apparatus to test packages. These are the Vertical Motion test machine and the Rotary Motion test machine.

The vertical motion machines are usually electrohydraulic actuators that provide a sinusoidal oscillation for frequencies ranging from 2 Hz - 100 Hz and acceleration levels up to 1 G.

The rotary test machines consist of a cam operated device that provides a rotary motion to the table. The frequency of these types of machines is varied by changing the speed of the drive motor. These machines usually vibrate at frequencies ranging from 2 to at least 5 Hz and have a stroke of 1 inch. In some machines the stroke can be varied up to 2 inches using different size cam offsets.

The second type of package vibration tests use random vibration. ASTM D 4728-91 " Random Vibration Testing of

Shipping Containers " test method recommends the use of Power Spectral Density Spectrums to control the vibration of the table. During a random vibration test, the table generates continuously changing frequency and acceleration levels that over time approximate the demand Power Density Spectrum. Random vibration tests have shown to approximate damage from real life shipments (Singh, 1992).

Ostrem and Godshall (1979) evaluated the common carrier shipping environment and developed data to be used for package tests. Andress (1981) developed some of the first random vibration test methods used for package testing.

Pierce et-al (1992) compared the leaf-spring with air-cushion trailer suspensions. The results showed that the air-ride suspension when maintained gives lower power density (PD) levels on all road surfaces studied. A damaged air-ride suspension and leaf-spring suspension are very similar in response frequencies, although the damaged air-ride produces higher vibration levels at lower frequencies.

Another study was done to compare the levels of lateral and longitudinal vibration to vertical levels measured in the same truck trailer traveling over interstate highways (Singh et-al, 1992). The results show that below 20 Hz, lateral and longitudinal vibration levels were generally much lower than vertical levels, but at frequencies above 20 Hz, the vibration levels were similar in all axes. The more heavily loaded trucks showed higher lateral and longitudinal levels of vibration than lightly load ones.

Singh and Marcondes (1992) investigated the vibration levels in commercial truck shipments as a function of suspension and payload. They found that leaf spring suspension trailers have the highest vibration levels between 3 and 4 Hz. Fully loaded trailers have lower vibration levels than partially loaded trailers. They also observed that the most severe vibration levels recorded in all cases were vertical and occurred at the rear of the trailers.

This study evaluated the various vibration test methods and measured their effect on vibration levels observed in test packages specifically this study had the following objectives.

1) To compare the vibration levels observed in instrumented packages using sinusoidal and random vibration test methods.

2) To compare the severity of vibration as a function of package resonant frequency (size and weight).

3) To compare the electrohydraulic versus mechanical vibration test machines.

2.0 EXPERIMENTAL DESIGN

In order to achieve the objectives of this study, two Environmental Data Recorders (EDR) were used to instrument the packages. These units and their measuring capabilities are discussed in the following section.

2.1 Environmental Data Recorder:

The EDR-1 is designed for measuring and recording acceleration-time data (EDR manual). The EDR-1 has a built-in tri-axial accelerometer that can measure the acceleration level in each of the three independent axes. The EDR1S software program is provided a means for communicating with the EDR using a personal computer. The EDR electronics consists of a microcomputer system, which has the ability to continuously sense and selectively record acceleration waveforms. The EDR commands allow the various setup conditions necessary to monitor and record acceleration levels. These commands are transferred from the EDR1S computer program to the EDR via a RS-232 serial interface. After the data is recorded the RS-232 serial interface is used again to download the data into the personal computer.

The acceleration waveform data is recorded and stored only when a pre-set acceleration criteria is met. The EDR records an event when any one or more of the three acceleration input channels exceed a preset G trigger level (positive or negative). In addition, the trigger duration may be specified for which an acceleration event must continuously be above a pre-set trigger duration, before the event will be recorded.

The EDR contains a microprocessor-based data acquisition system, which is interfaced with a 10-bit analog-to-digital converter (ADC), converting analog acceleration signal voltage to discrete digital numbers for storage. The conversion and storage process is called *data acquisition*. In addition the EDR also contains 1 megabyte of DRAM (dynamic random access memory). The DRAM is used for storage data memory, as well as storage of user documentation information.

During the ACTIVE mode, the ADC is controlled by the microprocessor to continuously sample each of the three accelerometer input channels sequentially and repeatedly while the microprocessor is continuously checking if any of three signal channels has a voltage level above the trigger level that is set before recording. When the trigger level is exceeded, the event will be detected by the microprocessor and the acceleration waveform data of this event will be recorded and stored in the EDR memory. The number of data samples taken by the ADC on any one channel per unit time is called the *sampling frequency*.

2.2 Vibration Test Machines:

The two types of test equipment that were used for this study are specified below:

1) Electrohydraulic Vibration Test Machine.

Manufacturer : Lansmont Corporation, Monterey, CA

Model No. : 10000-10

Table Size : 60" x 60"

2) Mechanical Rotary Vibration Test Machine.

Manufacturer : L.A.B. Corporation, Skaneateles, NY

Model No. : 4000 SNLVMIT 6

Table Size : 60" x 60"

2.3 Vibration Test Methods:

In order to compare the vibration levels for sinusoidal and random vibration tests using the electrohydraulic and mechanical rotary vibration test machines, three different vibration test methods were used which are described as :

1) Method A : Sinusoidal vibration test using an electrohydraulic vibration test machine.

2) Method B : Random vibration test using an electrohydraulic vibration test machine.

3) Method C : Sinusoidal vibration test using a mechanical rotary vibration test machine.

2.4 Package Types:

Four different types of packages were instrumented in this study and are described below:

1) Package A : Regular slotted container (RSC), Double wall B/C corrugated boards.

275 lbs/sq. inch burst strength.

Min. combine wt. of facings 110 lbs/M sq. ft.

Size limit 90 inches.

Gross weight of package = 8 lbs.

2) Package B : Full telescopic half slotted box (FTHS), Single wall corrugated board.

200 lbs/ sq. inch burst strength.

Min. combine wt. of facings 84 lbs/M sq. ft.

Size limit 75 inches.

Gross weight of package = 8 lbs.

3) Package C : Regular slotted container (RSC), Double wall B/C corrugated boards.

The specifications of the corrugated board are the same as Package A.

Gross weight of package = 22 lbs.

4) Package D : Full telescopic half slotted box (FTHS), Single wall corrugated board.

The specifications of the corrugated board are the same as Package B.

Gross weight of package = 22 lbs.

The inside dimensions of various packages are shown in Figure 1 and Figure 2.

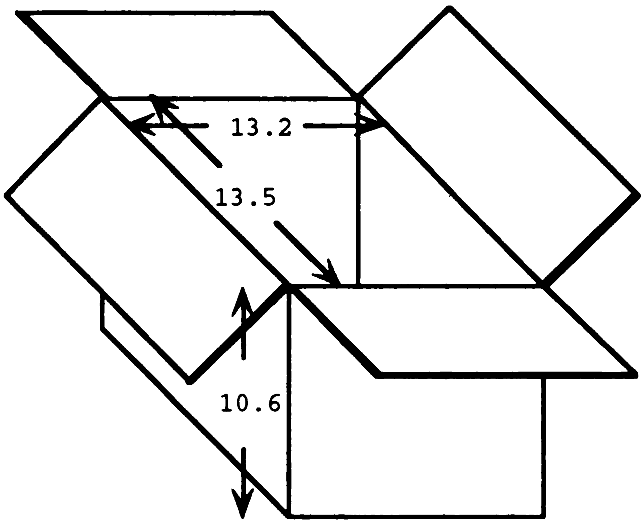

Figure 1 : The inside dimensions of the instrumented RSC (All dimensions in inches).

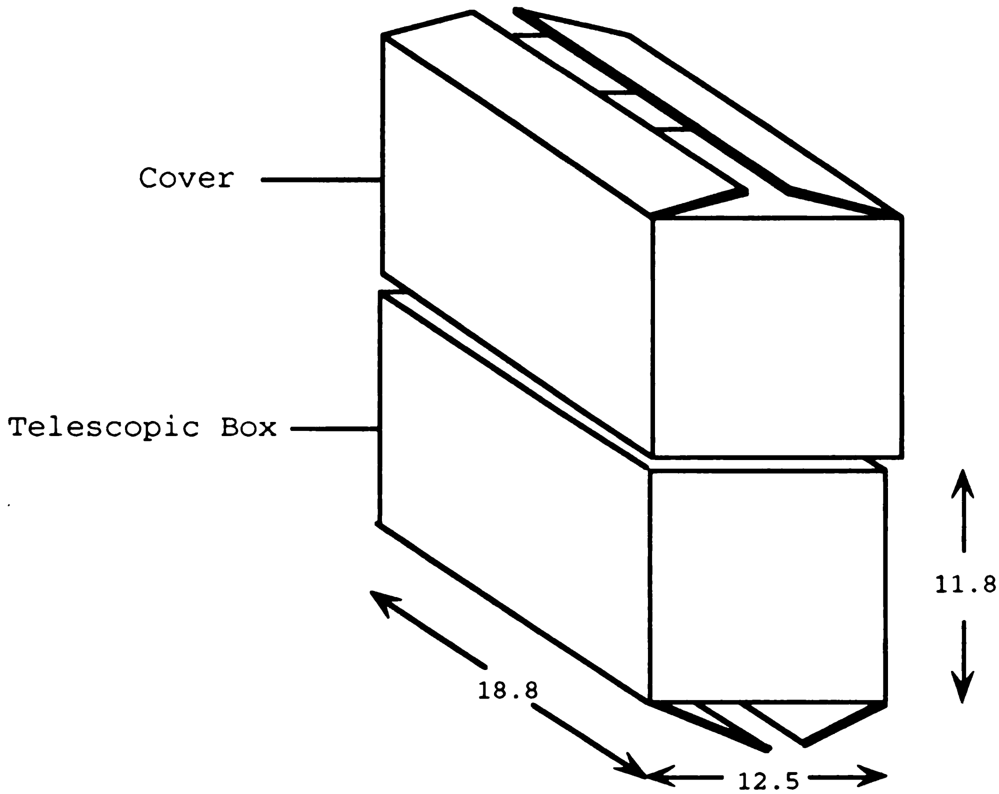

Figure 2 : The inside dimensions of the FTHS instrumented package (All dimension in inches).

2.5 Package Vibration Test Setup:

For the three different vibration tests done on each package configuration, a stack of five boxes were used. The top and bottom box for each test were instrumented using the EDR's. The EDR's were placed on the bottom of the box over two layers of corrugated board (200 lbs C flute single wall). The packages were filled with polyethylene cushions (Ethafoam, Dow Chemical Company) and dummy weight around the EDR's to achieve the total package gross weight.

The two EDR's that were used to instrument the top and bottom packages were set for the overwrite recording mode, with a maximum number of recorded events to be 200. This was done to record the most severe events that the packages observed during a test. A trigger level of 1 G was used. The preprogrammed recorders were put into the top and bottom boxes and the five boxes were column stacked. Figure 3 and Figure 4 show the schematic of the vibration test setup on the electrohydraulic vibration table and the mechanical rotary vibration table respectively. The model EDR-1 200 Serial # 0038 was placed in the bottom box whereas the EDR-1 200 Serial # 0035 was placed in the top box. The stack of packages were first tested with the vibration test Method A using an electrohydraulic vibration test machine. The test was done according to the ASTM D 999-91, method C. The resonance frequency of the stack was determined by using an accelerometer mounted on the top package. The vibration table was run using a frequency scan from 3 to 100 Hz

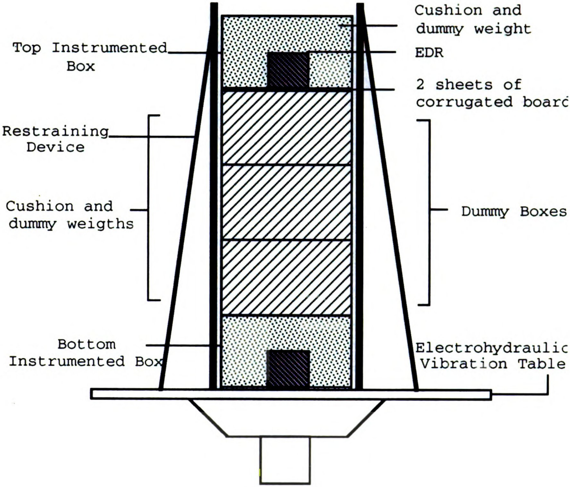

Figure 3 : Package vibration setup on the electrohydraulic vibration table.

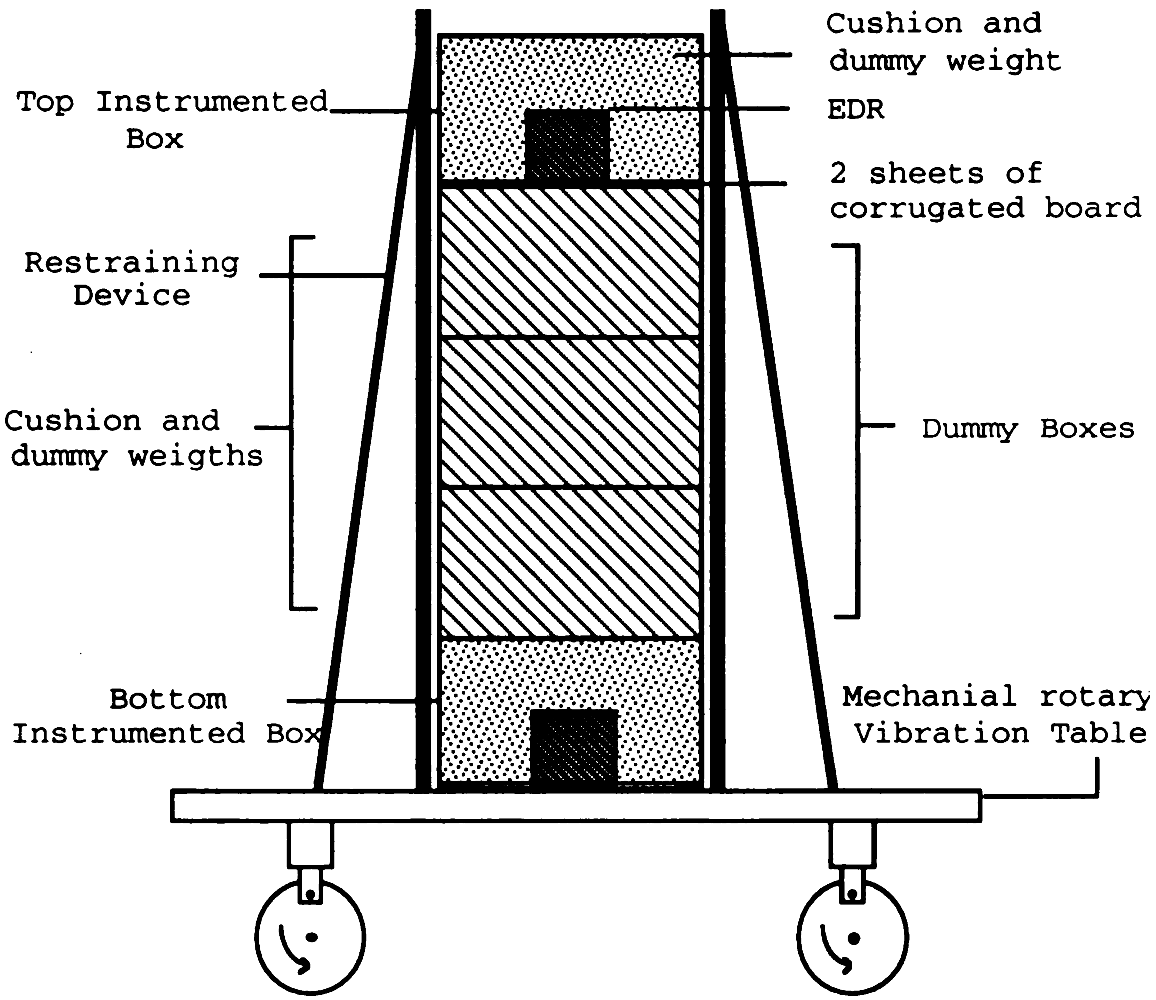

Figure 4 : Package vibration test setup on the mechanical shaker table.

performed at 1 octave per minute. After that the stack was subjected to a dwell at the resonance frequency for 15 minutes. When the test was done, the recorded data in both EDR's was downloaded into the personal computer. The EDRs were again programmed for the next vibration test using the same recording conditions.

The random vibration tests were performed in accordance with ASTM D 4728-91. The PSD spectrum used for this test is the Composite Truck Vibration Summary described in Figure X1.1, ASTM D 4728-91 as shown in Figure 5. The duration of the test was 1 hour.

The vibration tests on the mechanical shaker were performed using NSTA, Project 1A. The NSTA standard requires the packaged-product to be vibrated for a total of 14,200 vibratory impacts. The total duration of test time can be determined by dividing 14,200 by the speed of the rotary drive mechanism.

This study investigated the impact levels in both the bottom as well as the top packages on both types of vibration test machines.

The data and results collected for all the three tests are discussed in the next chapter.

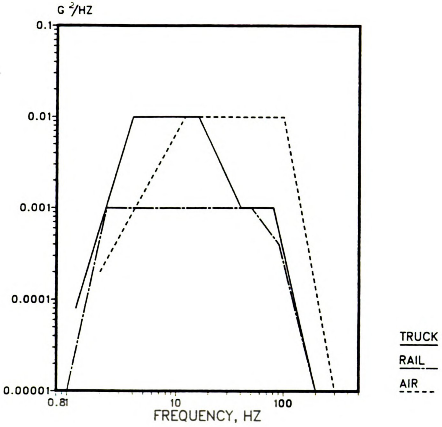

Figure 5 : Commercial transport random vibration spectra summary (ASTM D4728).

3.0 DATA AND RESULTS

The acceleration levels measured in the four package types using the three vibration tests were downloaded on a personal computer and analyzed. This chapter compares the resultant peak accelerations measured over 1G and the orientation of impacts in each package type as a function of the vibration test and package natural frequency.

Before any comparison are made based on the results of the recorded data, it is important to understand the performance capabilities of the two types of vibration tables. Figure 6 shows the acceleration performance level of the electrohydraulic and mechanical (1 inch displacement) vibration tables as a function of table forcing frequency. The acceleration level of a sinusoidal oscillation is mathematically expressed as

$$a = A(2\pi f)^2 \qquad (3.1)$$

where a = Acceleration of table.

A = Amplitude of table (0-peak displacement).

f = forcing frequency.

From this equation it is evident that for mechanical (usually 1 inch) vibration tables, where the displacement of the table is fixed, the acceleration levels sharply increase as the frequency is increased from 3 to 5 Hz. This is graphically shown in Figure 6. It is important to observe that the maximum forcing frequency on these types of tables is limited to 5 Hz, since higher frequencies will result in a very sharp increase in acceleration levels that are very severe and far more excessive than those measured in most conventional transportation modes. The mechanical rotary tables produce acceleration levels determined by equation 3-1 in both the vertical and lateral and lateral directions. The acceleration levels produced in the lateral directions using 1" displacement level are more severe than those measured in real life shipments. In most studies where vibration levels have been measured for various transportation modes (Ostrem et-al, 1979, Sharpe et-al, 1974, Singh et-al, 1992) the peak acceleration levels are usually less than 0.5 g's for frequencies between 2 and 100 Hz in the vertical direction. However in the lateral and longitudinal directions the vibration levels in the 3-5 Hz range are less than 0.1 G (Antle, 1989). The electrohydraulic vibration tables use a servo-valve that controls the displacement of the table. These vibration test machines are usually controlled to provide a fixed acceleration level during a frequency scan, where the displacement of the table is reduced as the frequency increases based on the relationship (3-1). This is shown in Figure 6.

The transportation environment produces vibration levels over a wide range of frequencies at relatively low intensity levels. Electrohydraulic vibration systems allow a closer laboratory simulation of the actual shipping environment as

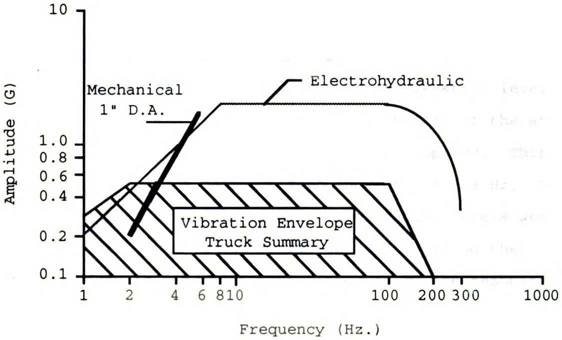

Figure 6 : Vibration environment and test machine performance capabilities.

compared to the mechanical vibration systems because they can operated at fixed acceleration levels versus fixed displacement levels over a frequency range.

The different vibration tests and their effect on the package systems tested in this study are discussed below.

3.1 Package A, Light Weight RSC:

Figure 7 shows the resultant acceleration levels measured in the RSC light weight box on the top of the stack. The three different vibrations tests were compared. This package column had a resonant frequency of 6.5-6.8 Hz. Based on the recorded data, the highest acceleration levels were measured during the random vibration (9.9 G) using the electrohydraulic vibration table followed by the resonance dwell test (5.9 G). The NSTA vibration test produced the lowest resultant acceleration levels (1.9 G). Figure 8 describes the percent occurrence of the orientation of impacts during the three tests. The sinusoidal dwell and random vibration tests predominantly produced impacts in the vertical orientation (99.5%) indicated by the top and bottom channels. The NSTA vibration test however produced a high percent of impacts (95%) in the side rotating orientation indicated by the left and right channels. This was visibly evident during the test where the vibration machine generated a severe rocking motion in the sideways orientation.

Figure 9 shows the resultant acceleration levels in the bottom package. Figure 10 describes the percent

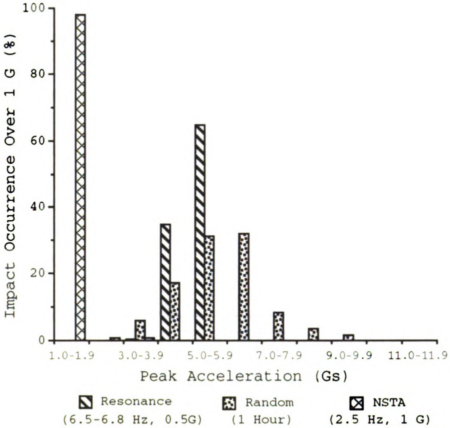

Figure 7 : Acceleration levels measured in the light weight RSC on top of the stack.

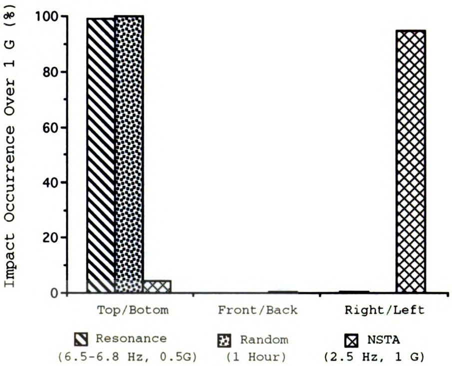

Figure 8 : Orientation of impact for light weight RSC on the top of the stack.

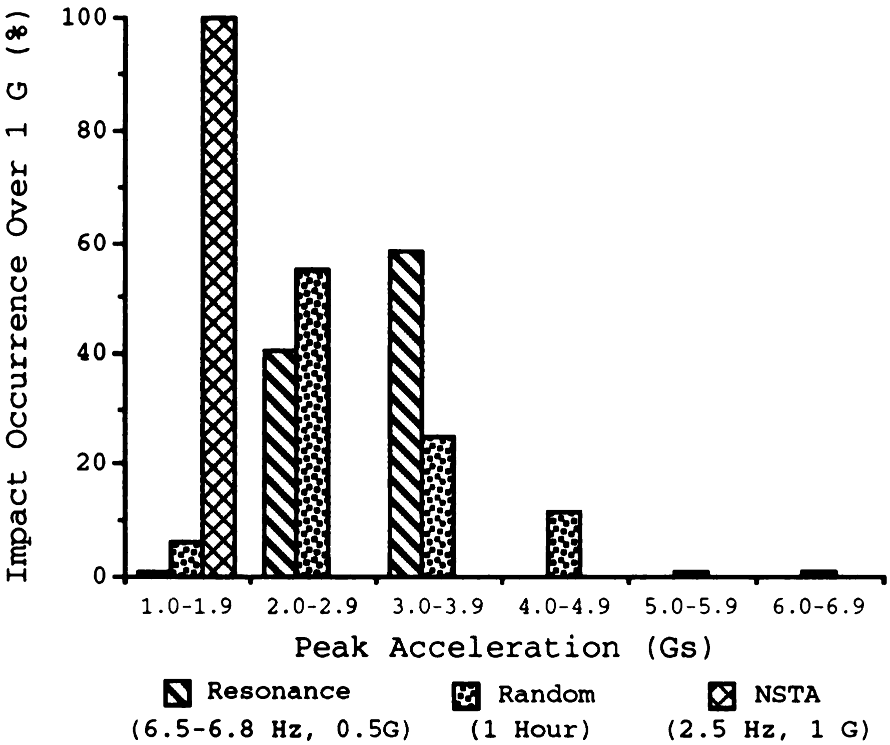

Figure 9 : Acceleration levels measured in the light weight RSC on bottom of the stack.

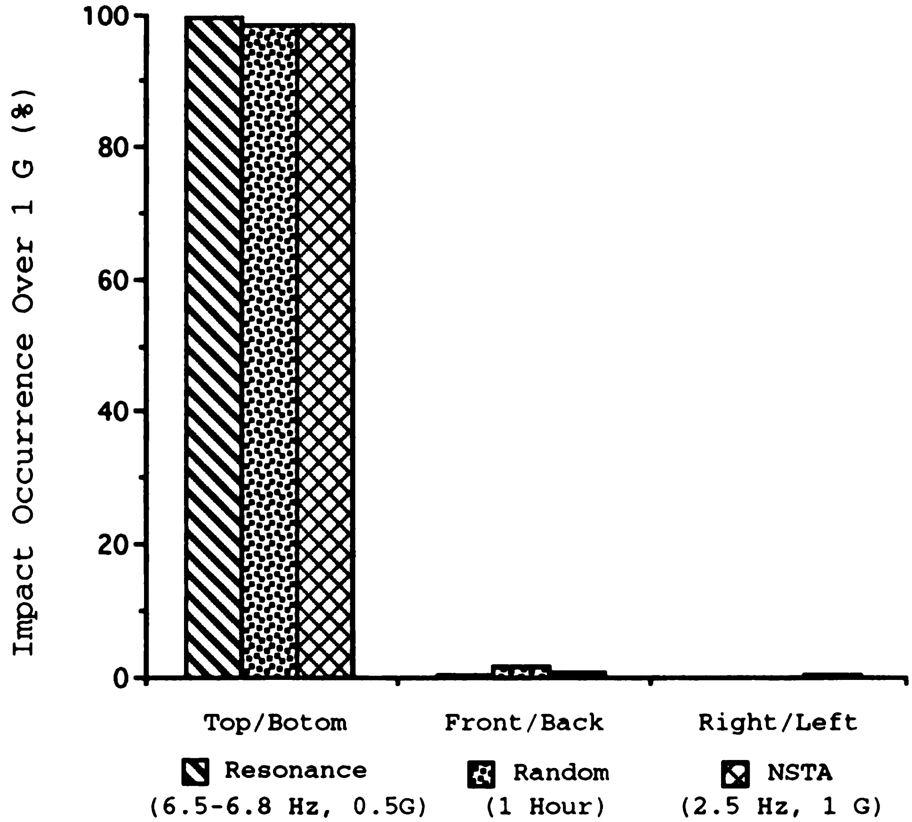

Figure 10 : Orientation of impact for light weight RSC on the bottom of the stack.

occurrence of the orientation of impact. Again in this case the random vibration test on the electrohydraulic vibration table produced the highest acceleration levels (4.9 G) in the top/bottom vertical orientation followed by the sinusoidal dwell test (3.9 G). The NSTA vibration test produced the lowest acceleration levels (1.9 G) predominantly in the vertical orientation (top/bottom).

The results show that in the mechanical vibration test, the top package sees a high frequency of side impacts versus the lower box which sees mostly vertical impacts.

3.2 Package B, Light Weight FTHS:

Figure 11 shows the resultant acceleration levels in the top package of the FTHS light weight box stack. This package column had a resonant frequency of 6.1-6.5 Hz. According to the results, the resonance dwell and the random vibration tests on the electrohydraulic vibration table produced the highest acceleration levels (7.9 G). The NSTA vibration test produced the lowest resultant acceleration (2.9 G).

The percent occurrence of the orientation of impact in the top box of these three tests are shown in Figure 12. The results show that all of the impacts produced during the sinusoidal dwell and the random vibration tests are in the vertical orientation indicated by the top and bottom channels. However, the NSTA vibration test produced a high percent of impact (98.5%) in the side orientation indicated

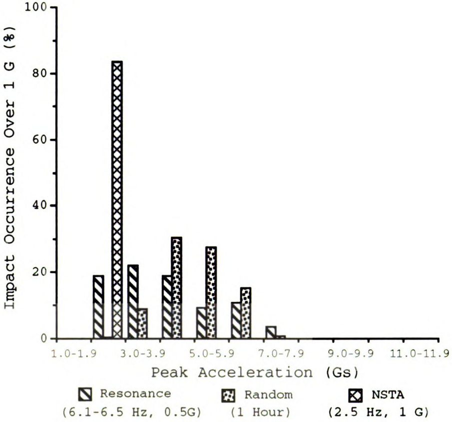

Figure 11 : Acceleration levels measured in the light weight FTHS box on top of the stack.

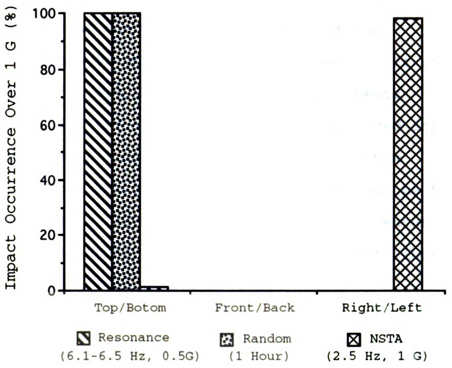

Figure 12: Orientation of impact for light weight FTHS box on the top of the stack.

by the left and right channels for the top package.

Figure 13 shows the resultant acceleration levels produced in the bottom package. From the results, the random vibration produce the highest acceleration levels (4.9 G) followed by the resonance dwell test (3.9 G). The NSTA vibration test produced the lowest acceleration levels (2.9 G). Figure 14 shows the percent occurrence of the orientation of impacts occurred during the tests. It shows that the sinusoidal dwell and random vibration tests predominantly (100% and 98.5% respectively) produced impacts in the vertical axis indicated by the top and bottom channels. The acceleration levels produced during the NSTA vibration test mostly occurred in the vertical orientation (61.6%) indicated by the top and bottom channels followed by the side (Left/Right) orientation (37%).

3.3 Package C, Heavy Weight RSC:

The resultant acceleration levels measured in the RSC heavy weight box on the top of the stack using the three different methods are shown in Figure 15. Figure 16 describes the percent occurrence of the orientation of impact. This package column had a resonant frequency of 5.5-5.8 Hz. Based on the results, the NSTA vibration test produced the highest acceleration levels (up to 9 G's)predominantly (93%) in the side orientation followed by the resonance dwell and the random vibration tests. These side impacts produced are significantly more severe than

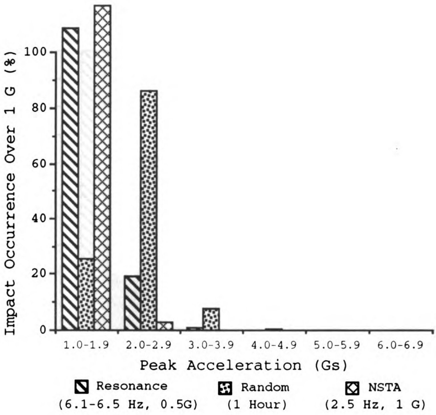

Figure 13 : Acceleration levels measured in the light weight FTHS box on bottom of the stack.

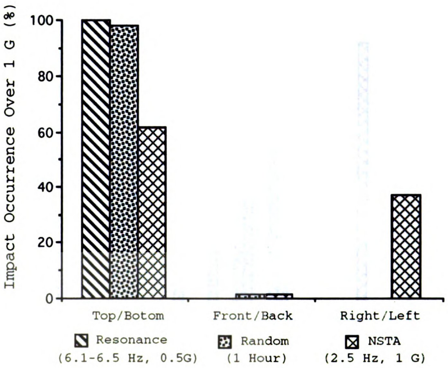

Figure 14 : Orientation of impact for light weight FTHS box on the bottom of the stack.

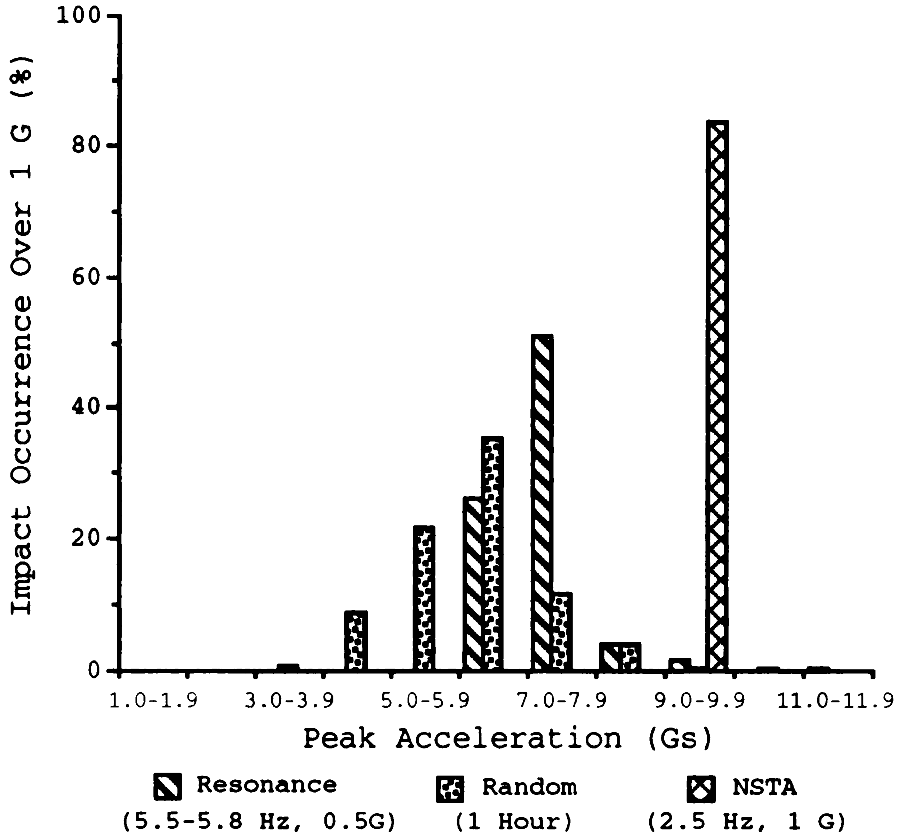

Figure 15 : Acceleration levels measured in the heavy weight RSC on top of the stack.

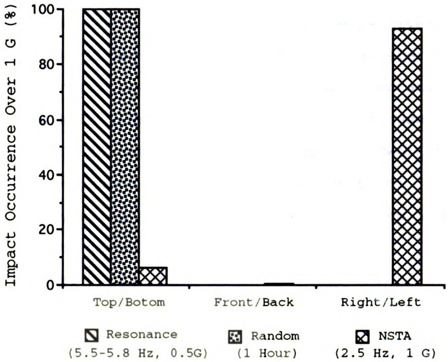

Figure 16 : Orientation of impact for heavy weight RSC on the top of the stack.

those measured in packages for lateral movements inside trailer shipments (Antle, 1989). The sinusoidal dwell and random vibration tests produced all impacts in the vertical orientation (100%).

Figure 17 and Figure 18 show the resultant acceleration levels and the percent occurrence of the orientation of impact in the bottom package respectively. The random vibration test produced the highest acceleration levels (4.9 G) in the top and bottom vertical orientation followed by the NSTA vibration test (2.9 G) and sinusoidal dwell test (1.9 G) respectively. The sinusoidal dwell test again predominantly produced impacts in the vertical orientation however the NSTA vibration test produced a high percent of impacts in side (54%) and vertical (38%)orientations.

3.4 Package D, Heavy Weight FTHS:

Figure 19 shows the resultant acceleration levels measured in the FTHS heavy weight box on the top of the stack, and Figure 20 shows the resultant acceleration levels in the bottom package. For this package type, the NSTA test could not be performed due to very high acceleration levels that were developed in the top packages causing the restraining devices to fall apart. This is due to the fact that this package column had resonance frequency of 5.0-5.5 Hz and resulted in severe magnification levels when the NSTA test was being performed. According to the data, the random

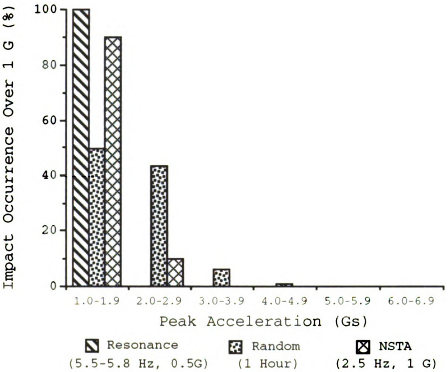

Figure 17 : Acceleration levels measured in the heavy weight RSC on bottom of the stack.

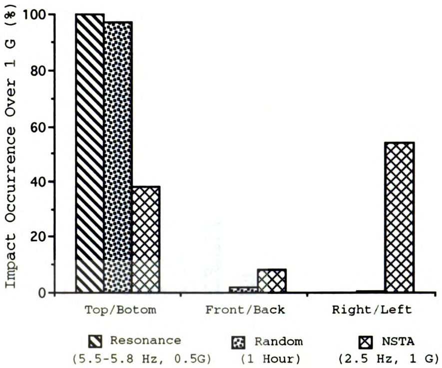

Figure 18 : Orientation of impact for heavy weight RSC on the bottom of the stack.

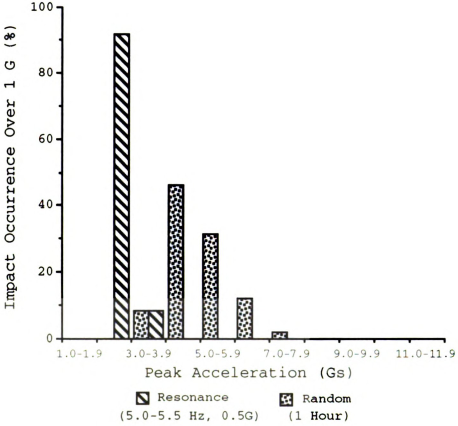

Figure 19 : Acceleration levels measured in the heavy weight FTHS box on top of the stack. (See foot note in next page)

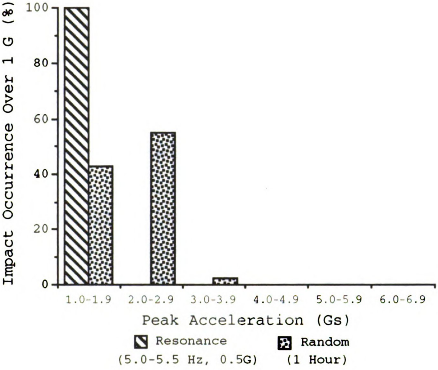

Figure 20 : Acceleration levels measured in the heavy weight FTHS box on bottom of the stack* .

* NSTA test could not be done due to very severe vibration levels

vibration test produced the higher acceleration levels in both top and bottom boxes compared to the sinusoidal dwell test (3.9 G versus 1.9 G) on the electrohydraulic vibration table.

Figure 21 and Figure 22 describe the percent occurrence of the orientation of the impact in the top and bottom box of the stack respectively. For both top and bottom boxes, the random vibration test and sinusoidal dwell tests predominantly (99.5% or more) produced impacts in the vertical orientation indicated by the top and bottom channels.

To summarize the results, the sinusoidal and random vibration ASTM tests are more severe for packages that have resonant frequencies outside the 3.0-5.5 Hz when compared to the NSTA test. The NSTA vibration test is more severe for packages that have resonant frequencies between 3.0-5.5 Hz, since during this entire scan, the packages are vibrating in-phase with the table and always produce a magnification factor greater than 1. It also evident from figure 6 that for a table frequency greater than 3.1 Hz, the mechanical rotary table produces acceleration levels higher than 0.5 g.

Also for both the sinusoidal and random vibration tests 95% or more of the impacts are in the top/bottom orientation for the top and bottom packages in the stack. However for the NSTA test, 95% or more of the impacts are on the side faces for the top package. For the bottom package the impacts majority of are on the top/bottom and right/left of

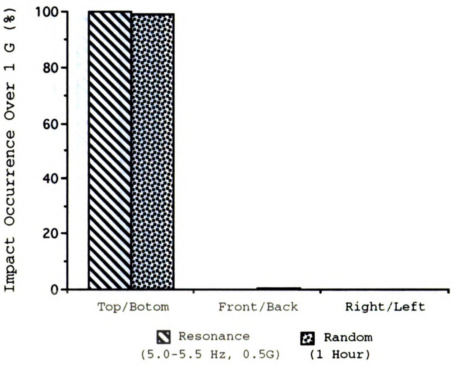

Figure 21 : Orientation of impact for heavy weight FTHS box on the top of the stack.

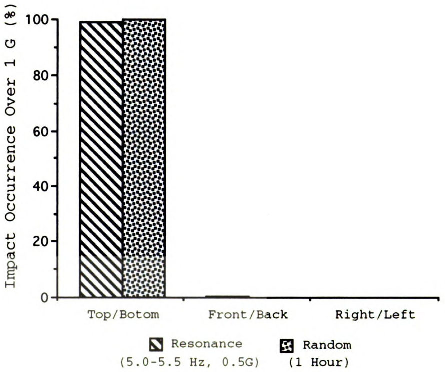

Figure 22 : Orientation of impact for heavy weight FTHS box on the bottom of the stack.

sides the package.

4.0 : CONCLUSIONS

Based on the results, the following conclusions can be made.

1. The NSTA vibration test is less severe than both the ASTM vibration test for all package types except those that have a resonant frequency between 3.0-5.5 Hz.

2. The NSTA vibration test produces a higher frequency of impacts in the side orientation at the top of the stack. These side impacts are significantly more severe than those measured in packages for lateral movements inside trailer shipments (Antle, 1989).

3. For the ASTM vibration tests 95% or more of the impacts are in the vertical orientation for the top and bottom packages in the stack.

4. The column stack vibration test using a mechanical shaker can result in very severe acceleration levels beyond what are found in actual shipments and can be hazardous if the packages have a resonant frequency between 3.0-5.5 Hz.

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