HEALTHCARE PACKAGING CONSORTIUM

Cloud Publications
International Journal of Advanced Packaging Technology
2016, Volume 4, Issue 1, pp. 200-215
ISSN 2349-6665, doi 10.23953/cloud.ijapt.24

Research Article **Open Access**

Simultaneous Multi-Translational-Axis Motion used in the Evaluation of Product Component Frequency Response and Unit Load Stability

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Publication Date: 14 July 2016

DOI: https://doi.org/10.23953/cloud.ijapt.24

Abstract The motion of packaged product transport vehicles can be described with six axes of motion: three translational (vertical, lateral, longitudinal) and three rotational (pitch, yaw, roll). Laboratory simulation of six axis motion is complex and typically requires expensive equipment with many moving parts. For these reasons, the packaging industry has focused laboratory simulation on the one axis that contains the most energy, the vertical translation axis. Analysis of three axes translational motion in truck, rail, and air transport reveals that although the vertical motion often contains more overall energy, the lateral and longitudinal motion is equal, or even higher, in intensity than that of the vertical motion within particular frequency ranges. In this study, a relatively cost effective way of reproducing simultaneous three-axis-translational motion is used to evaluate the vibration frequency response of a product's components. In addition, the stability effect of multi-translational-axis motion as compared to single-axis motion is evaluated on both a unit load and a single stack of packaged products. The value of simultaneous multi-translational-axis vibration testing is demonstrated through literature review and results from laboratory testing of unit loads, single stacks of packaged products, and the analysis of the frequency response of a product's components.
Keywords *Packaging Dynamics; Multi-Axis Vibration; Transport Vibration Testing; Frequency Response; Load Stability*

1. Introduction

The motion of packaged product transport vehicles occurs in multiple axes all at the same time; motion along the lateral, longitudinal, and vertical axis, and rotation about these axes: pitch, yaw, and roll, Figure 1. This fact makes laboratory simulation of this complex motion challenging and expensive. Based on the typical depiction of motion in a truck bed, it is often assumed that the most intense packaged product input exists in the vehicle in the vertical axis, thereby simplifying simulation in a laboratory to reproducing only the fully constrained single-axis vertical motion. This paper highlights a study that supports the assumption that vertical motion is always the most intense motion is incorrect. It is shown that at particular frequencies, the lateral and longitudinal motion of vehicles can exceed levels of the vertical motion.

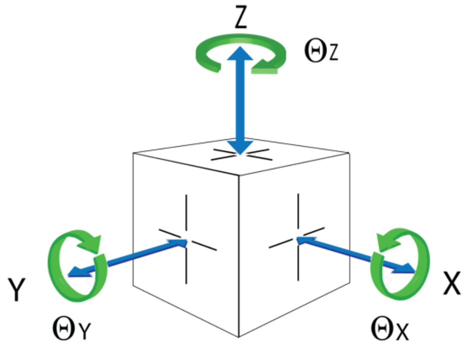


Figure 1: *Six axis motion*

Single axis vibration is the packaging industry standard for simulation of the distribution environment and the fragility evaluation of products. Different electrical/mechanical/fluid mechanisms are used to produce the motion of the platen each with their pros and cons. Due to its relative simplicity as compared to multi-axis motion systems, single-axis systems are less expensive and easier to maintain. However, development of the technology related to reproducing and controlling a vibration table's motion has made simultaneous multi-translational-axis vibration a more reasonable consideration. This study utilizes an electric servo-motor driven multi-axis shaker resulting from this development.

It is logical that the frequency response of a component inside a product and the stability of a unit load or stack of packages is dependent on the axis of motion. If single-axis motion is used to simulate a multi-axis environment, would the component and packaged product response differences be? This study answers this question by comparing the response of a product, a unit load, and a stack of packaged products when subjected to single-axis motion versus simultaneous multi-translational-axis motion.

Additionally, this paper addresses different industries employing the technology of multi-axis vibration. Several industries currently use simultaneous multi-axis vibration. Interest has grown since the mid 1980's [1] and facilities with this equipment are located around the world. This paper provides a brief overview of which industries are using multi-axis vibration in laboratory simulation and why they are doing so. Studies showing the inadequacies of single-axis vibration testing and the benefits of multi-axis vibration testing are highlighted.

1.1. Vehicle Motion

The motion of trucks, trains, and planes is stochastic or non-deterministic in nature, meaning that the output can vary for a given set of controlled inputs. This phenomenon is called random vibration. To graphically illustrate this complex motion, the average intensity of the vibration is plotted versus frequency in a power spectral density (PSD) plot. The power density, typically in units of G^2/Hz, represents the average intensity of the motion versus the frequency. This tool produces a "fingerprint" for a given vehicle enabling one to see at which frequencies a particular vehicle vibrates with a higher intensity than at others. The energy represented by the PSD plot can be calculated as the square root of the area under the curve called the overall grms value of the motion. The overall grms value for different PSD plots can be used to compare the overall intensities of the different motions represented. While the overall grms is valuable for comparing PSD plots, it can be misleading in that a peak intensity of the motion of a vehicle over a small frequency range will not have a significant effect on the overall grms. This "averaging out" of the peak can lead to a distorted frequency specific comparison between two PSD plots.

1.2. Multi-Axis Laboratory Testing

Several studies were conducted to examine the effect on results of using single-axis vibration testing to characterize the fragility of a product's component. Two such studies used environmental stress screening (ESS) testing which involved subjecting a post-production product to "stresses which are more severe than anticipated in service. The object of this is to precipitate latent defects into recognizable failures, so that a particular unit does not proceed further in production…" [2]. The results from these studies supported the claim made by Harman and Pickel that "multi-axis testing excites all modes simultaneously with a more realistic stress loading (and) test objects may pass uniaxial testing but fail under actual operating conditions" [3]. Another study cited, "Although test engineers try to build in a safety margin by using high vibration levels, sequential tests still lack the interactive effects of vibration on multiple axes and may fail to excite certain critical modes" [4].

In a study by Whiteman and Berman, the researchers used notched aluminum round bar test specimens fixed on one end and free on the other. The specimens were subjected to random vibration in a horizontal and vertical orientation sequentially. Results were recorded as a number of cycles to failure defined by crack propagation in the region of the notch. Interestingly, by merely changing "the order in which the uniaxial excitation was applied during the test caused a variance in the results" [5].

A second similar study was conducted by French, Handy, and Cooper. In this study, specimens were made from square aluminum beams which were notched on two adjacent sides and tested in a fixed-free configuration. Samples were vibrated on a simultaneous two-axis (X,Y) shaker with a sinusoidal input at 4 g from 10 to 35 Hz. Specimens were tested by two methods: 1) Sequential single-axis testing and 2) Simultaneous two-axis testing. "The two methods produced different failure times, different failure distributions, and different failure modes" [6].

There are benefits to simultaneous multi-translational-axis testing as compared to sequential single-axis testing beyond the aforementioned component failure response differences. One such benefit is time savings. In applications where samples must be vibration tested in the lateral, longitudinal, and vertical orientations, using a single-axis shaker requires that the sample be rotated and retested for each of the three axes. If the goal is to simulate an automobile use cycle, vibration testing lengths can be anywhere from several hours to several hundred hours. Simultaneously testing all three axes can save hundreds of hours in test time over sequentially testing one axis at a time [3].

Several industries currently use simultaneous multi-axis vibration in the evaluation of their products and packaging structures. One of the first large scale multi-axis test facilities was in Julich, Germany in 1983 called SAMSON. This facility was developed primarily to improve experimental qualification of nuclear reactor components and their fitting against seismic events. It was recognized that because of its capacity to test items as large as 25 tons, SAMSON could be used to test building structures and spacecraft components [7].

In its most recent revision of MIL-STD-810G, the US Department of Defense recognized the value of simultaneous multi-axis testing by specifying Multi-Exciter Testing (MET) [8]. Prior to this change, MIL-STD-810F specified sequential Single-Exciter Testing (SET) [9]. The change in specification recognizes the previously mentioned benefits of laboratory simulation improvement and cost and time savings.

It is noteworthy to comment on the automotive industry's quest for the use of multi-axis vibration technologies. In the automotive industry, the lack of published standards has not prevented the use of multi-axis testing procedures. The continued search for improved product quality and reduced warranty has led to the development of a number of multi-exciter, multi-axis test systems [3].

No literature was found on the use of multi-axis vibration by the packaging industry even though packaged products undergo this complex motion in transport vehicles. ASTM D5112 specifies a horizontal product frequency response test and ASTM D3580 specifies a vertical product frequency response test [10, 11]. Both tests utilize either sinusoidal or random vibration input and both tests are performed in the single axis only. ASTM D999 and D4728 specify frequency response testing of packaged products in the vertical axis only [12, 13]. The only place vibration testing is specified for packaged products in more than one axis is the sequential three-axis testing of packaged products going into a less-than-truck load (LTL) or small parcel delivery system environment [14, 15]. In these distribution systems, packaged products could be oriented with any of the three product axes positioned vertically in the vehicle. In other words, this is still only a vertical vibration test for a packaged product that could be placed in a vehicle on any of its six faces.

Singh et al. conducted a multi-axis vibration study of the truck transportation environment to compare lateral, longitudinal, and vertical vibration generated by a commercial truck with heavy and light loads. The results showed that below 20 Hz, lateral and longitudinal vibration levels were generally much lower than vertical levels, but at frequencies above 20 Hz, all three were similar. The more heavily loaded trucks showed higher lateral and longitudinal levels of vibration than the lightly loaded ones [16]. These results indicate that if a product or packaged product system had critical modes above 20 Hz, vertical axis only vibration simulation would miss an important part of the vibration intensity input to the system. Such glaring omission in the full spectrum of vibration intensities is alleviated by using multi-axis vibration in testing.

2. Materials and Methods

2.1. Vehicle Motion Axis Comparison

Power spectrum density profiles from several vehicle types were compared. The average intensity of the vibration and power spectral energy from each of the axes (lateral, longitudinal, and vertical) were compared at different frequencies. The comparisons were used to show whether lateral and longitudinal vibration input was significant as compared to the assumed more intense vertical motion.

2.2. Single-Axis versus Multi-Translational-Axis Testing Comparison

A fully constrained simultaneous three-translational-axis vibration table from Kokusai, Inc. was used to perform this testing, Figure 2. This vibration table is powered by six servo motor driven screws (two in each axis) forcing motion of the platen along linear bearings in each of the three axes. The machine is capable of vibrating loads up to 200 kg in weight, has a frequency range of 1-300 Hz, and a peak-to-peak displacement of 51 mm. A Vibration Research VR9500 three-axis controller enabled the input of both sinusoidal and random vibration to all three axes simultaneously.

Figure 2: *Kokusai, Inc. three-axis electric servo motor vibration table*

2.3. Product Frequency Response

The frequency response of the compressor and condenser in an Electrolux upright refrigerator/freezer unit (Model: FRT18S6JW4) was recorded using a three-axis accelerometer attached to each component. The frequency response was obtained from a vertical input and compared to the frequency response from a sequential lateral and longitudinal input. The unit was strapped to the vibration table to isolate motion of the critical components inside, Figures 3 and 4. For each axis, a sinusoidal sweep was performed at 0.25g from 1 to 100 Hz at a sweep rate of 1 octave/min per ASTM D3580 [11]. A transmissibility versus frequency plot was generated for each axis of each component when excited with sequential vertical, lateral, and longitudinal input. The transmissibility plots were compared for analysis. An environmental stress screening test was performed on the unit using only vertical input at each component's fundamental natural frequency at an acceleration level of 0.25g. Then each component was subjected to simultaneous three-translational-axis input at the vertical, lateral, and longitudinal fundamental natural frequencies at an acceleration level of 0.25g. Component acceleration response was recorded for comparison.

Figure 3: *Frequency response of the refrigerator/freezer unit test setup*

Figure 4: *Refrigerator components tested*

2.4. Unit Load Stability

A unit load of 24 HP printers (Model: LaserJet 1200 Series, product weight: 8.0 kg) was banded and stretched wrapped for truck load shipment. The printers were packaged one per corrugated box, six boxes per layer, and four layers high. Using steel channel, the load was constrained to the vibration table which was allowed to move freely in all three-axes, Figure 5. The unit load was subjected to various vehicle random vibration inputs in the vertical axis only and then in the simultaneous lateral, longitudinal, and vertical axes. Motion of the load and perceived unit load stability was visually recorded for comparison between the two different inputs. The test sequence was then repeated for a single stack of packaged printer's four layers high, unstrapped and unwrapped.

Figure 5: *Unit load stability test setup*

3. Results

3.1. Vehicle Motion Axis Comparison

PSD plots of the motion generated in the vertical, lateral, and longitudinal axes from different vehicles and different vehicle types were evaluated. One typical example from each vehicle type is illustrated and analyzed below. While the PSD plots selected were typical of plots evaluated in this study, they may not be representative of all studies. The PSD plots were used for illustrative purposes.

3.1.1. *Railcar Vibration*

Railcar data revealed that the overall grms of the vertical motion is the highest, 0.20 grms versus 0.11 grms and 0.07 grms for the lateral and longitudinal axes, respectively, Figure 6 [17]. However, the average intensity of the lateral motion is clearly higher than that of the vertical motion between 4.5 – 7.5 Hz and 79 – 132 Hz. This indicates that although the vertical motion contained the highest overall input energy, omitting the lateral motion in simulation would miss simulation of the largest input within these frequency ranges.

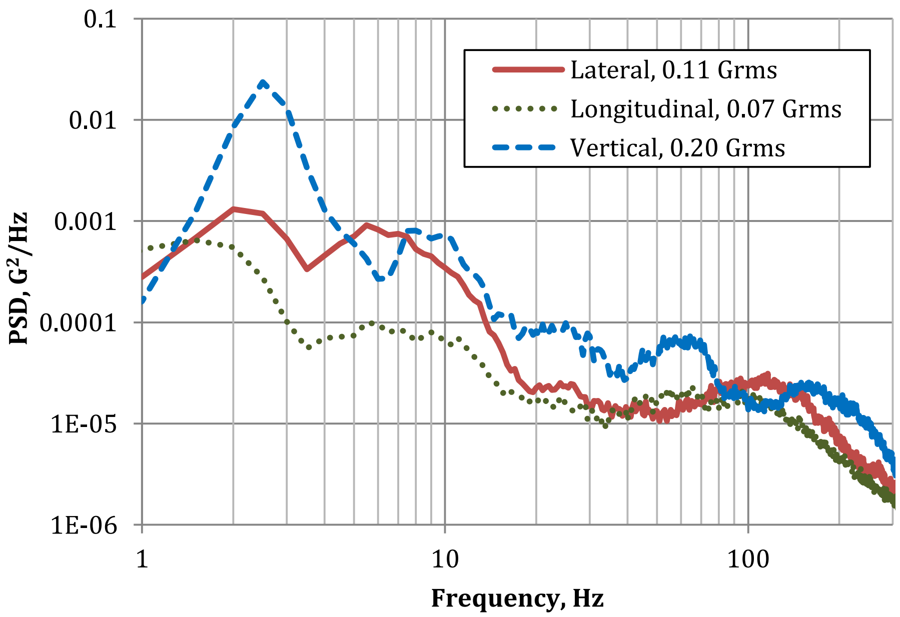


Figure 6: *PSD plot from a railcar, Melbourne to Perth, Australia*

3.1.2. *Truck Vibration*

Analysis of data from a truck revealed that the overall grms of the vertical motion is much higher at 0.14 grms versus the lateral at 0.04 grms and longitudinal at 0.05 grms, Figure 7 [18]. However, the average intensity of the lateral motion exceeds that of the vertical motion between 17 – 25 Hz and the longitudinal motion exceeds that of the vertical motion between 167 – 181 Hz. This analysis supports that found in the railcar analysis where omission of the lateral motion in simulation removes the highest input component in the range 4.5 – 7.5 Hz, and the omission of the longitudinal motion removes the highest input component the 79 – 132 Hz range.

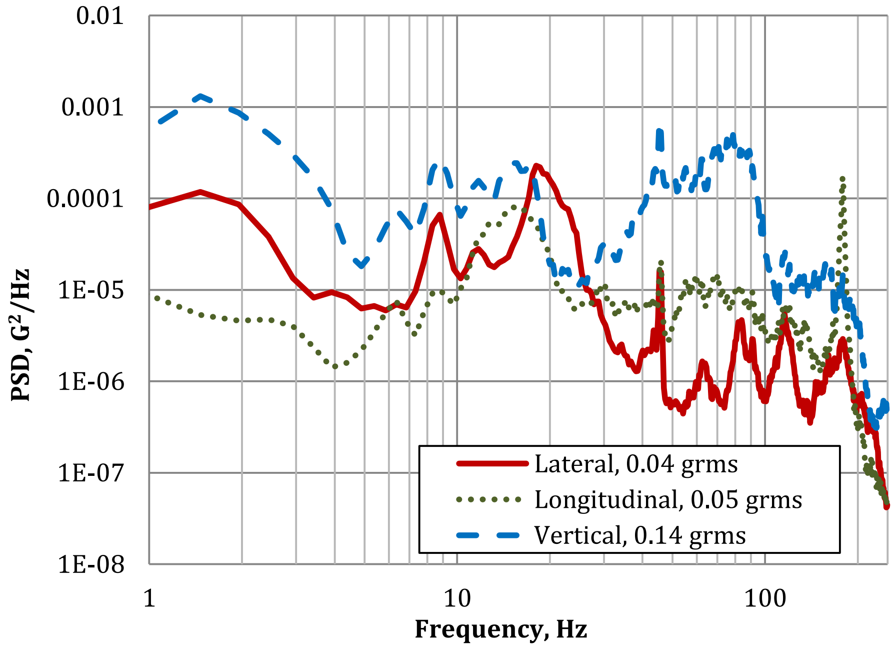


Figure 7: *PSD plot of a leaf spring truck*

3.1.3. *Airplane Vibration*

Analysis of the airplane vibration data revealed that the overall grms of the motion in all three axes was exactly the same, 0.10 grms, Figure 8 [19]. Even the average intensity of the motion contributed by each of the three axes was very similar over the entire frequency range. These results indicate that each of the three axes contribute nearly equally to the packaged product input and are all significant for consideration in laboratory simulation.

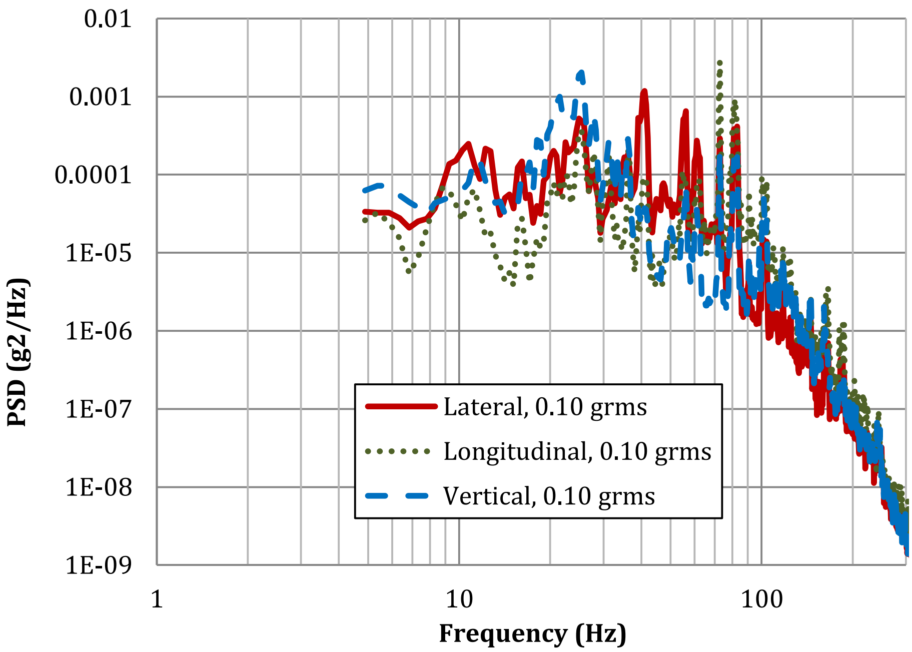


Figure 8: *PSD plot of a typical turbo-prop airplane*

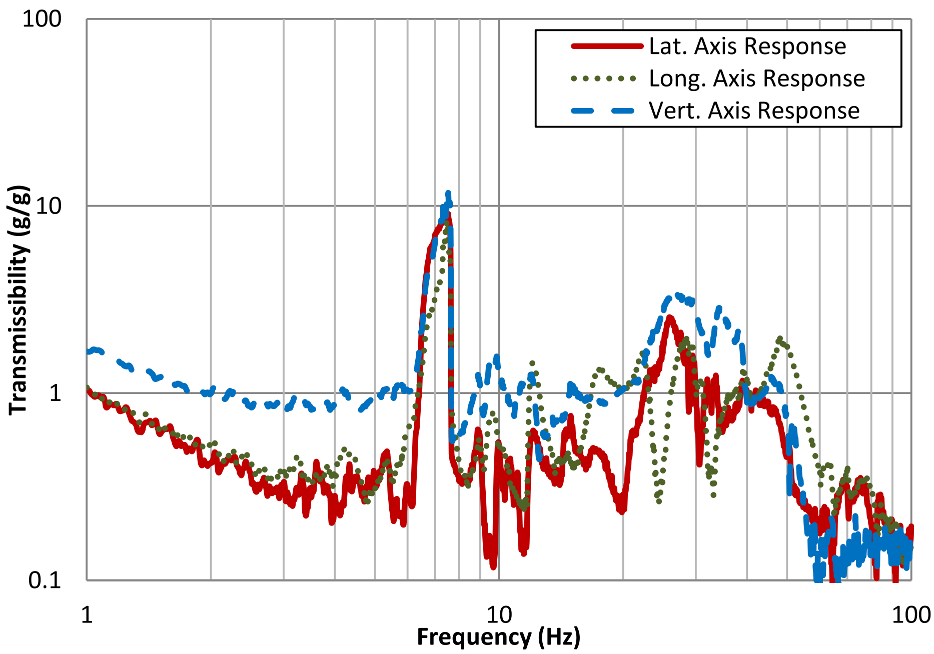
All three PSD plots analyzed in this paper show that the lateral and longitudinal motion exceeds the vertical motion at frequencies above 40 Hz. The data support the results observed by Singh et al., where results showed that above 20 Hz, lateral and longitudinal vibration levels were similar to the vertical motion [16]. Since protective package systems are typically soft in nature, the natural frequencies of these systems are typically less than 40 Hz. Therefore, the damage potential for packaged products and their components is greater at lower frequencies. The PSD plots analyzed in this study illustrate that the intensity of the lateral and longitudinal motion can equal or exceed the vertical in this particularly damaging frequency range of less than 40 Hz and even at frequencies less than 20 Hz.

3.2. Single-Axis versus Multi-Translational-Axis Testing Comparison

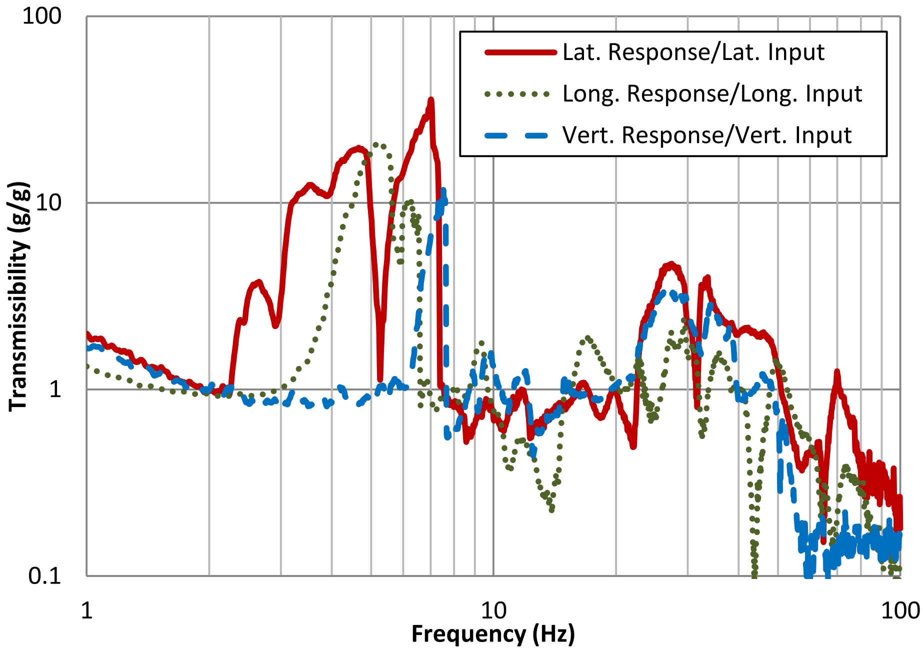
3.2.1. *Product Frequency Response*

Integrity of a refrigerator compressor is a concern during transportation due to its low natural frequency. A visual comparison of Figure 9 reveals the effect the input axis has on the frequency response of the compressor. When tested with vertical input only, as specified in ASTM D 3580 [11], the fundamental frequency is in a narrow band between 6.3 and 7.6 Hz, Figure 9a. However, when subjected to inputs in the vertical, lateral, and longitudinal axes, the fundamental frequency range extends to include a large range from 2.3 – 7.6 Hz, Figure 9b.

The condenser is another critical component during transport and exhibited a similar widening of the fundamental natural frequency range when subjected to multi-translational-axis input versus single axis vertical input. Although not as clear as in the case of the compressor, visual comparison of the vertical, lateral, and longitudinal responses, Figure 10, illustrates the effect. The fundamental frequency range was 6.3 – 14.0 Hz with vertical only input, Figure 10a, but widened to 3.0 – 17.5 Hz when the input was sequentially lateral, longitudinal, and vertical, Figure 10b.

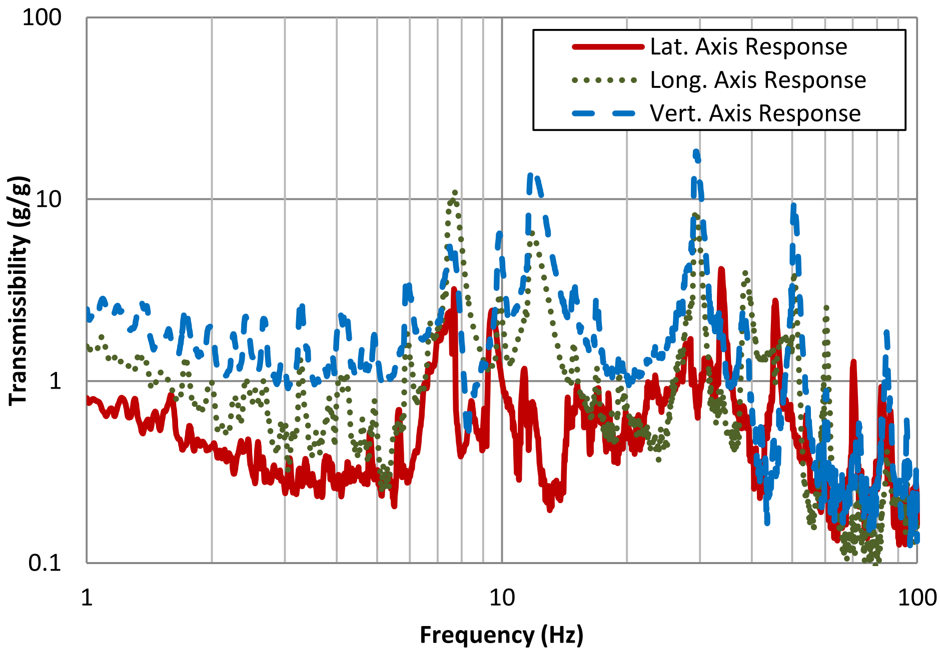


(9a)

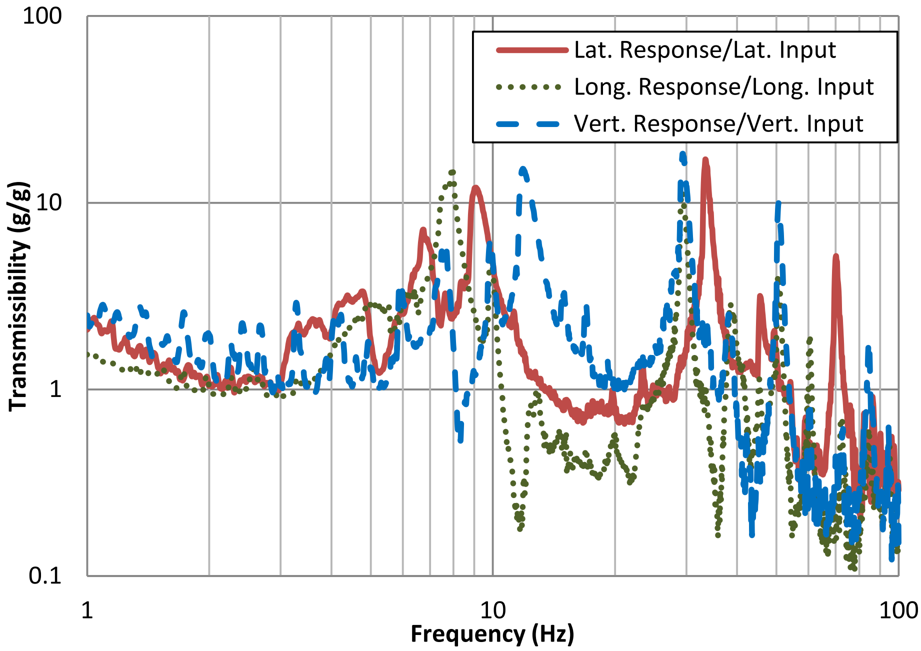


(9b)

Figure 9: a. *Compressor response to vertical motion only,* ***b.*** *Compressor response to sequential lateral, longitudinal, and vertical motion*



(10a)



(10b)

Figure 10: *a. Condenser response to vertical motion only, b. Condenser response to sequential lateral, longitudinal, and vertical motion*

An alternative way to compare the frequency response of a component when subjected to single versus multi-translational-axis motion is to look at the difference in shape of the frequency response plot in one axis when excited in different axes. Per ASTM D3580 [11], response of a component to motion in the vertical axis is recorded. However, by comparing the first response to that obtained by exciting the system in the two horizontal axes results in a different response, particularly at low frequency where frequency response is of greatest concern.

Figure 11 illustrates the difference in the longitudinal response of the condenser when excited in the lateral, longitudinal, and vertical axes sequentially. Similarly, Figure 12 illustrates the difference in the lateral response of the condenser when excited in the lateral, longitudinal, and vertical axes, and Figure 13 illustrates the difference in the vertical response of the condenser when excited in the lateral, longitudinal, and vertical axes. If the three curves in each of these figures had the same shape, then input axis would not affect the frequency response of a component. Clearly this is not the case at frequencies below 20 Hz, highlighting the importance of multi-translational-axis testing of critical components in determining response to vibration.

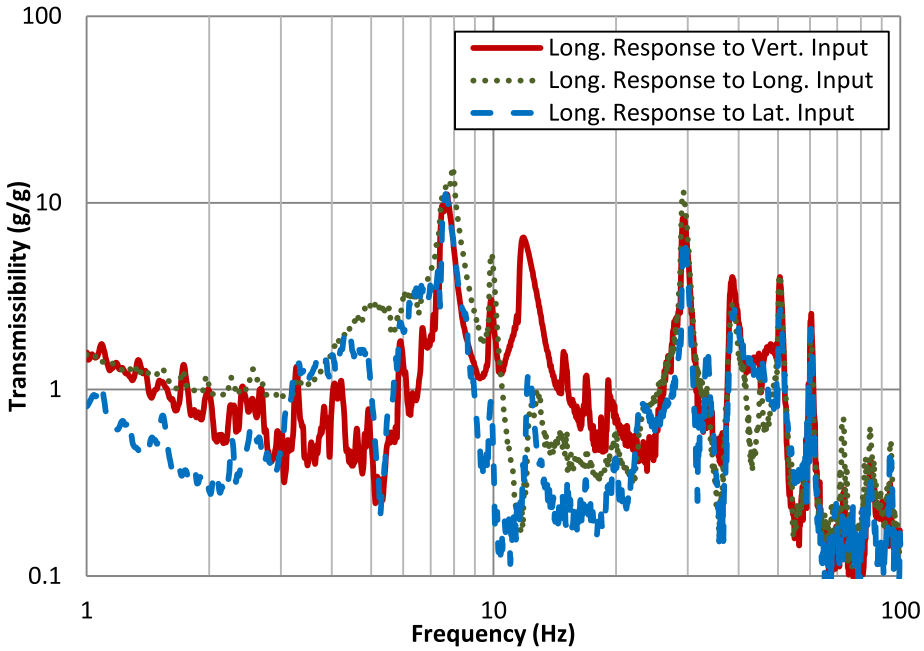


Figure 11: *Lateral response of the condenser with sequential lateral, longitudinal, and vertical input*

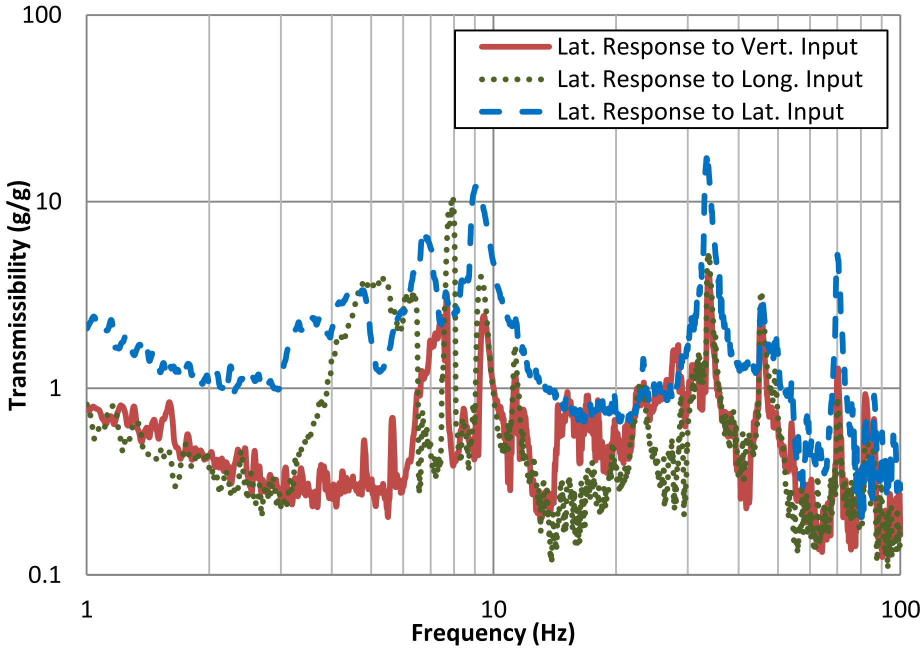


Figure 12: *Longitudinal response of the condenser with sequential lateral, longitudinal, and vertical input*

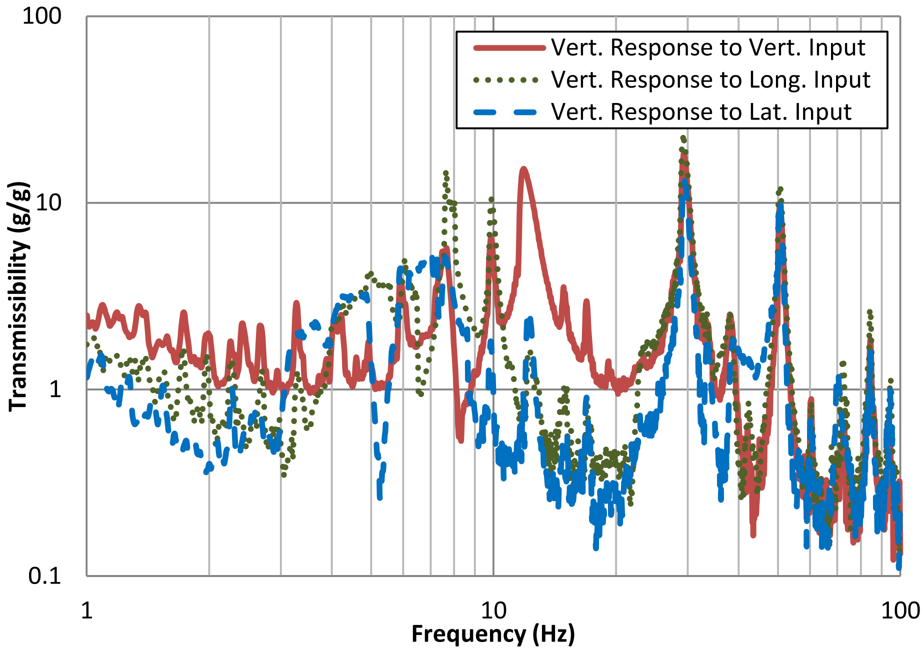


Figure 13: *Vertical response of the condenser with sequential lateral, longitudinal, and vertical input*

3.2.2. *Unit Load Stability*

The railcar vibration PSD from Melbourne to Perth [17], Figure 6, was used as the driving PSD for the unit load stability comparison. A clear visual difference in unit load stability was observed between the single-axis vertical input and the simultaneous multi-translational-axis input. When vibrated in the vertical axis only, no instability was observed. The strapping and machine stretch wrapped load had no observable box shifting or box-pallet misalignment. Contrastingly, within three minutes of simultaneous multi-translational-axis vibration, boxes in the same pallet load shifted as much as two inches, Figure 14. Similar results were found when testing the single stack of packaged printers.

The single stack of packaged printers included boxes that were not strapped or wrapped, and were subjected to only vertical and then multi-translational-axis simultaneous motion. There was no observed shifting of the load when vibrated vertically, however the simultaneous multi-translational-axis vibration caused immediate instability and eventual tip over, Figure 15. Although the overall grms of the lateral and longitudinal motion was less than that of the vertical motion (0.11 and 0.07 versus 0.20), their contribution to affecting the performance of the unit load and single stack packaged product systems was significant.

Figure 14: *Unit load instability as a result of three minutes of simultaneous multi-axis vibration*

Figure 15: *Single stack instability as a result of simultaneous multi-axis vibration*

4. Conclusions

The results from this study led to several conclusions:

- Previous work in the aerospace, nuclear power facilities, and automotive industries has demonstrated clear differences in the dynamic response of components and structures when exposed to multi-axis vibration as compared to single-axis vibration.
- Analysis of various three axis vibration power spectrum density profiles from rail, truck, and air transport indicate that within particular frequency ranges, lateral and longitudinal vibration levels can equal or exceed those in the vertical axis.
- Overall grms, while useful for comparing PSD profiles, can average out or hide large variations in the average intensity of vibration over narrow frequency ranges thereby making true frequency specific comparison inconclusive.

- The frequency responses of components in a refrigerator vary significantly at frequencies below 20 Hz when comparing vertical to lateral to longitudinal input. Similarly, the frequency responses in the vertical, lateral, and longitudinal axes of components in a refrigerator vary significantly depending on the axis of input vibration.
- The stability of a unit load and a single stack of printers when exposed to simultaneous three-translational-axis railcar vibration inputs was clearly less than when exposed to only the vertical axis motion. These results for multi-translational-axis vibration reinforce the value of using simultaneous three-translational-axis vibration in the laboratory simulation of the vehicle motion for the evaluation of packaged product systems.

Acknowledgements

This research work was made possible through test sample donations by HP and Electrolux Home Products Inc. and through the access granted to the multi-translational-axis vibration table and support by Kokusai Inc.

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