An Examination of Random Vibration Data from Google's US Supply Chain (July 2022)

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***Abstract*—At a time when electronic components are smaller, denser, and more complicated structurally, it is crucial that data center hardware are properly designed against shock and vibration. Striking a balance is important - too much structural and packaging material leads to tremendous amounts of waste at the global scale, while too little leads to unreliable hardware that causes downtime and waste in the RMA process.**

There are 5 elements in structural analysis and testing of DC hardware: Environment, Packaging, Component, Chassis, and Rack. This paper focuses on "Environment", and describes how random vibration data were captured and analyzed from Google's US supply chain. (*Abstract*)

Keywords—Shock and Vibration, Data Analysis, Hardware Testing, Test Standards, Supply Chain (key words)

I. Introduction

Current Shock and Vibration specifications of data center hardware (OCP, Dell) [1] give the impression that products only need to be subjected to a shock and vibration test to meet global supply chain and data center robustness requirements. To be sure, when everything is well understood about the system - from environment to component to chassis to rack to packaging, these tests can be very useful as screening tools.

What the specifications don't talk about is the tremendous amount of engineering involved in structural design, analysis, and testing, and the industry trends that affect us all: 1. Products became much more complicated structurally in the last five years due to the end of Moore's Law; 2. components are smaller, denser, run with lower power, and potentially more fragile; 3. HALT and HASS (which allow products to be designed to an arbitrary level of robustness) are gaining popularity over traditional shock and vibration testing; and 4. the global supply chain is infinitely more complex than ever before.

Electronic components, the tiny building blocks that create the data centers, are susceptible to fatigue damage resulting from thermal and shock & vibration events. To fully characterize fatigue, you need to track stress cycles [2], which correlate with natural phenomenons in the global supply chain and data center environment.

This paper focuses on the measurement and understanding of such environments, and outlines the workflow around the measurement and analysis of random vibration data from trucks in Google's US Supply Chain.

Good data accurately reflects real world environmental conditions. They allow us to set product requirements properly and design lab experiments correctly. With this paper, we hope to share good data with the OCP community, the methodology behind obtaining them, and a foundation for future papers on structural analysis of DC hardware.

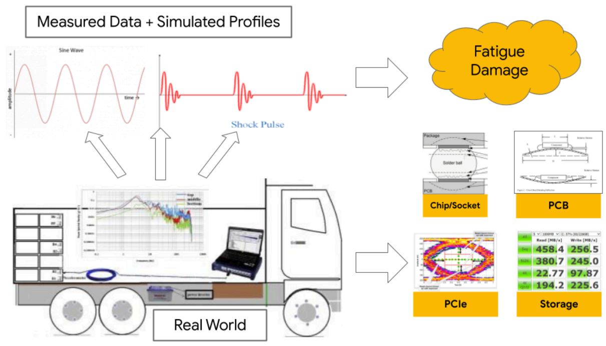
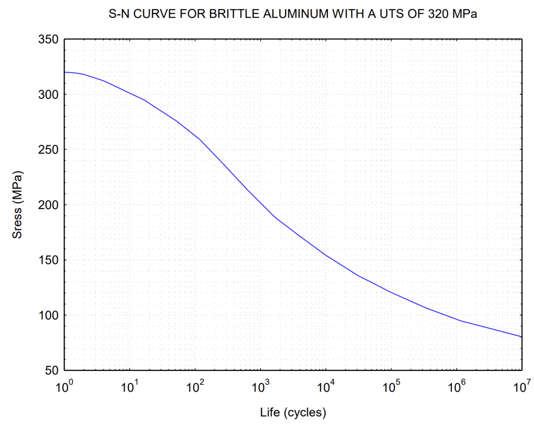


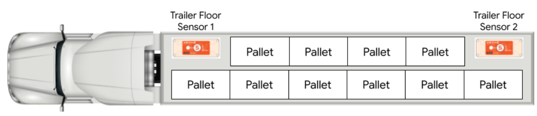
Figure from [3].

Fatigue S-N Curves



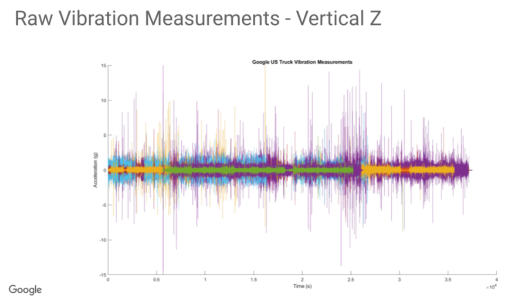
II. Capturing Random Vibration Data

Current portable vibration data acquisition units have amazing sensor, battery, and storage capabilities integrated into the size of a USB drive. The ones used in our experiments have sufficient capacity for 30 hours of continuous recording at 3000 samples per second. [4]



We conducted multiple field experiments in the US between 2018 and 2020. Portable acquisition units were attached to trailer floors of many cargo trucks before they began their journey to data centers. Trailer floors provide the best data, but other locations such as the outside of a cardboard box or internally inside the products can be informative as well.

More than 100 hours of data at 5000 samples per second were captured by the end of the experiments in 2020, giving us more than 1.8 x 10^9 data points to analyze.

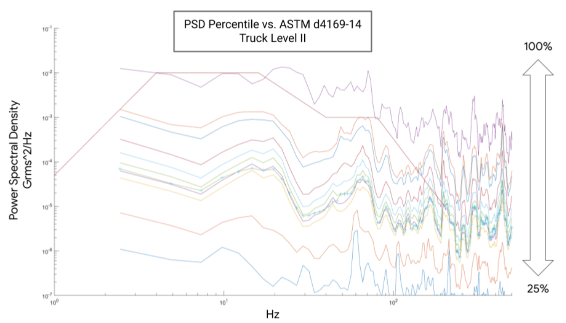


III. Random Vibration Analysis

Power Spectral Density plots are commonly used to summarize random vibration data. Fundamentally, random vibration is the sum of many sine waves made up of various distributions of amplitude and frequency. Each sine wave reflects the motions of a particular part of the vehicle over time, such as tires, suspension, and truck trailer, and their sum contributes toward fatigue in every product shipped.

Tom Irvine describes two standard PSD generation techniques in his papers: Bandpass Filtering [5] and Fast Fourier Transformation [6]. Most vibration software uses the second method for speed and efficiency. Irvine uses Matlab's FFT function [7] in his Matlab version of Vibrationdata GUI, with additional features to customize the calculations further.

A large data set such as the ones collected in these experiments are divided into smaller segments to calculate individual FFTs and PSDs, which are then averaged or maximized to display a final result. It is useful to display all PSDs in one graph to show how the data is distributed. It looks something like the following figure.



In the plot above, data captured from short haul trucks with leaf spring suspension show close resemblance to ASTM d4169-14's Truck Random Vibration profile, which means the 2014 standard was probably measured in such a vehicle. The 2016 standards represent trucks with air ride suspension.

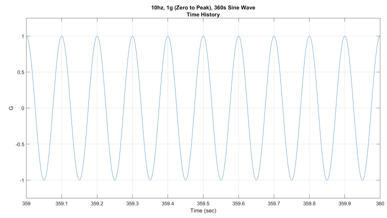
IV. Known Issues Of Standard Techniques

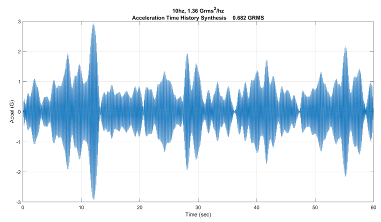
Decades of research are available on how FFT and PSD can be best utilized to describe real world random vibration environments. It was clear to our team early on there are some fundamental shortcomings in techniques involving Grms, FFT, and PSD:

1. Time history information is lost during the calculations for PSD.
2. The distribution of data among the frequency bands are also lost, giving the false impression that it can be predetermined.

All of these rely on the assumption that the random vibration environment can be approximated with normal distribution. But reality is much more complicated and may not reflect such distribution.

Here is an example Sine Wave (1g Zero to Peak, 10hz, 360 seconds). It was transformed into a PSD plot, then transformed again to generate a shaker table time history.



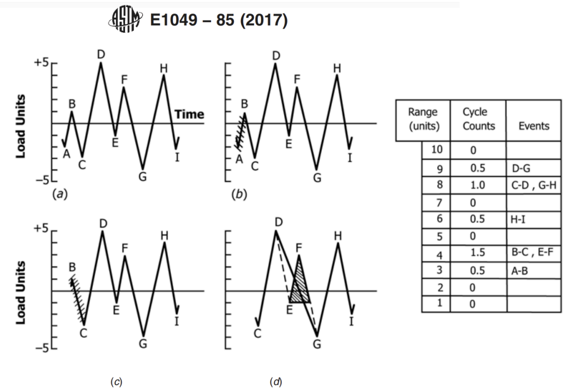


The result looks nothing like the original signal. We would not be testing our products correctly if we created a shaker table profile by simply following the standard techniques. Again, the actual environment may very well be perfectly described by normal distribution; but they may not. We need tools that help us perform quick sanity checks that can be quickly and easily followed by everyone in the industry.

V. Applying Bandpass Filtering and Rainflow Count To Raw Data

At the end of the day, many design choices will be made depending on the environment, component, chassis, rack, and packaging. But we need something beyond Grms and PSD to quantify random vibration data sets. Rainflow Counting is one such tool.

ASTM E1049 describes various techniques of counting cycles [8]. For our team, we settled on Rainflow Counting because it is easily accessible in Irvine's software and easy to understand[9]. After using Bandpass Filtering to isolate the data into specific frequencies, Rainflow Counting can be used to track each peak and valley of the data, and that information will help us make better design and testing decisions throughout product development and structural testing.



Range (units)	Cycle Counts	Events
10	0	
9	0.5	D-G
8	1.0	C-D , G-H
7	0	
6	0.5	H-I
5	0	
4	1.5	B-C , E-F
3	0.5	A-B
2	0	
1	0	

VI. Results and Discussion

Our team has wondered since the beginning what happens if our products have to stay on the road for one more day, or if some roads in some countries are extra bumpy. We've had to answer questions such as: "Why can't we lower the requirements just a little bit so that products can be developed faster?"

These questions are the result of the industry's practice to reduce product structural requirements into simple standards and tests. How can we justify a handful of test profiles, measured in minutes or hours, when millions of different components and products are shipped around the world in days to weeks? The simple answer is, "We can't."

When we measure actual environmental data from the real world, look deeper into **billions of data points**, and try to evaluate them against complex physical phenomena in the real world, we shift our perspective from that of writing and executing simple test plans to looking at the problem holistically, which is: **How does modern data center electronics hold up in the modern global supply chain?**

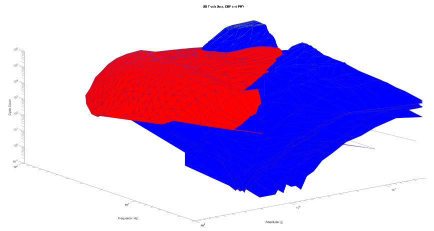
In this proposed method, Bandpass Filtering and Rainflow Counting reduce billions of data points into pages and pages of spreadsheets. They create charts like the one below, which provide useful insights into real world environments. Product designers and structural test engineers can then take these, and devise the best testing methodology for the product being evaluated.

	3 Hz		7 Hz		11 Hz		15 Hz	
	Amplitude	Count	Amplitude	Count	Amplitude	Count	Amplitude	Count
Field Experiment #1, 6000 seconds	1.49E+00	1.50	6.66E-01	1.00	3.81E-01	4.00	4.69E-01	4.00
	1.33E+00	5.50	5.96E-01	0.50	3.41E-01	5.50	4.20E-01	10.00
	1.18E+00	9.50	5.26E-01	1.00	3.01E-01	11.00	3.71E-01	19.00
	1.02E+00	19.00	4.56E-01	8.50	2.61E-01	13.50	3.21E-01	34.00
	8.62E-01	34.50	3.86E-01	23.00	2.20E-01	39.00	2.72E-01	100.50
	7.05E-01	56.50	3.15E-01	90.00	1.80E-01	150.50	2.22E-01	220.00
	5.49E-01	205.50	2.45E-01	484.00	1.40E-01	2,285.00	1.73E-01	545.00
	3.92E-01	1,054.50	1.75E-01	1,520.00	1.00E-01	17,953.00	1.24E-01	2,057.00
	2.74E-01	1,895.00	1.23E-01	2,432.50	7.02E-02	14,857.00	8.65E-02	3,639.50
	1.96E-01	4,779.50	8.76E-02	6,899.50	5.01E-02	13,304.50	6.18E-02	12,199.50
	1.18E-01	9,618.00	5.26E-02	16,704.50	3.01E-02	8,636.50	3.71E-02	39,144.50
	5.88E-02	5,159.50	2.63E-02	7,949.00	1.50E-02	2,663.50	1.85E-02	29,773.50
	1.96E-02	2,898.00	8.76E-03	10,810.00	5.01E-03	2,035.00	6.18E-03	18,076.00
ASTM Truck and Air Combined, Level 2, 6000 seconds	6.32E-02	68.18	1.10E-01	159.08	1.78E-01	68.18	6.17E-01	113.63
	5.65E-02	113.63	9.87E-02	181.80	1.60E-01	318.15	5.52E-01	318.15
	4.99E-02	454.50	8.71E-02	454.50	1.41E-01	886.28	4.87E-01	1,136.25
	4.32E-02	749.93	7.55E-02	1,249.88	1.22E-01	2,227.05	4.22E-01	2,908.80
	3.66E-02	1,204.43	6.39E-02	3,226.95	1.03E-01	4,272.30	3.57E-01	5,431.28
	2.99E-02	2,499.75	5.23E-02	4,794.98	8.45E-02	7,294.73	2.92E-01	11,476.13
	2.33E-02	4,090.50	4.07E-02	7,090.20	6.57E-02	11,385.23	2.27E-01	15,566.63
	1.66E-02	4,704.08	2.90E-02	7,862.85	4.70E-02	13,566.83	1.62E-01	17,452.80
	1.16E-02	1,954.35	2.03E-02	3,885.98	3.29E-02	6,703.88	1.14E-01	7,749.23
	8.31E-03	1,727.10	1.45E-02	2,590.65	2.35E-02	3,908.70	8.12E-02	6,749.33
	4.99E-03	1,727.10	8.71E-03	2,863.35	1.41E-02	3,863.25	4.87E-02	6,203.93
	2.49E-03	1,068.08	4.36E-03	1,886.18	7.04E-03	2,136.15	2.44E-02	2,317.95
	8.31E-04	2,522.48	1.45E-03	3,522.38	2.35E-03	3,795.08	8.12E-03	4,817.70

This sample table shows a portion of random vibration data sets organized in terms of amplitudes, cycle counts, and frequency. The top in blue represents numbers captured during one of Google's field experiments, while the other represents numbers measured during a lab experiment using ASTM d4169-14 standards.

Using this data, a design engineer or structural test engineer can quickly determine whether the lab environment accurately reflects the real world environment.

A 3D representation of the same table can also be plotted to help user quickly visualize the difference between two data sets:



With these data, we can begin to answer the following questions:

1. Q: What happens if a product stays on the road for a few more days? A: Product will be subjected to additional <insert number> stress cycle per unit time (second, hour, day, etc).
2. Q: Can we lower the test profile by 1% to pass the test? A: If we do so, we would've missed <insert number> stress cycles, which account for <insert number>% of the product's fatigue life.
3. Q: How well will this product hold up in the global supply chain? A: This product can endure 100 hundred days (for example) of truck shipment in the US, Europe, and Asia without significant fatigue damage to the internal components, so it shouldn't be a problem as long as it is properly packaged.
4. Q: How can we optimize our packaging design? A: We should examine the field data, conduct lab experiments to determine a product's fatigue life, and estimate at a high level of how much packaging material is really needed for the amount of shipping we expect this product to experience. Alternatively, we can also determine whether it makes sense to make the product a little more robust, so that cost and waste can be optimized from a packaging standpoint.

Reference

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