GOOGLE'S RANDOM VIBRATION TESTING METHODOLOGY, A HIGH LEVEL OVERVIEW

Part 3: IMPACT OF RANDOM VIBRATION ON MACHINES AND PCB
REVISION A

By Ken K.H. Leung
Email: openrandomvibe@ocproject.net

Rainflow Counting of Heatsink Z Axis Relative Displacement (mm) Time History during Random Vibration Transportation Profile, CPU1

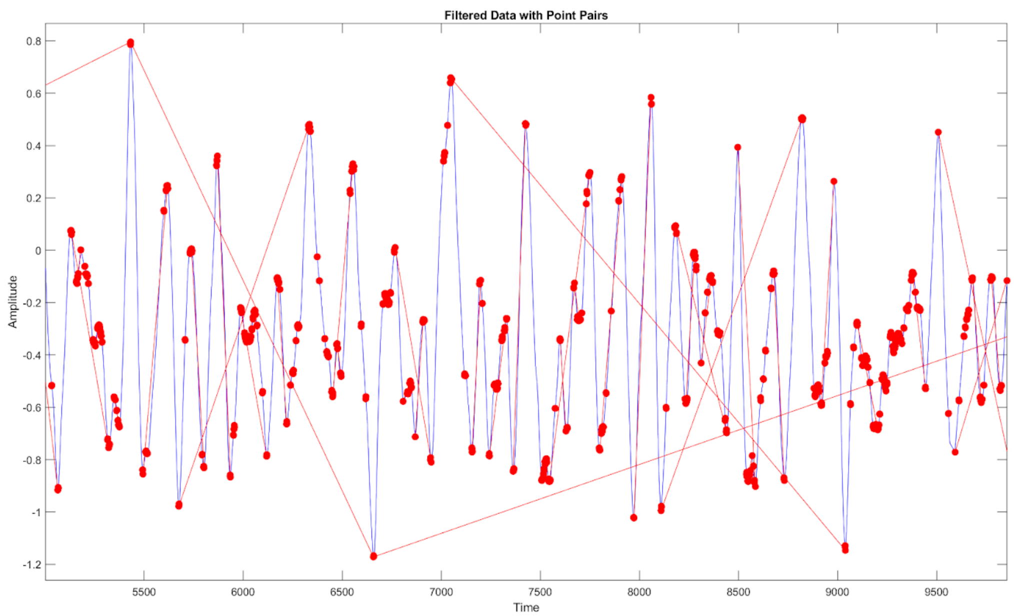


Figure 1.

<u>What happens to the machine and PCB when it is subjected to random vibration?</u>

Tom Irvine's Vibrationdata has a great series of papers discussing random vibration and how they are analyzed. The most interesting paper is the calculation of "POWER SPECTRAL DENSITY UNITS: [G^2 / Hz]" [1], which describes how a random vibration signal can be filtered into specific frequency bands to calculate GRMS values, and used to calculate the Power Spectral Density (PSD) plot of the signal.

PSD plots make it easier to program shaker tables and summarize a huge amount of random vibration data, but we lose the insights hidden within the time history data that precisely describe what happened when the signal was first recorded. PSD profiles are also quite unintuitive to the average user - it takes understanding of the original calculation to know what the plots actually represent.

Lenovo ThinkSystem SR650 V2 mounted on shaker table

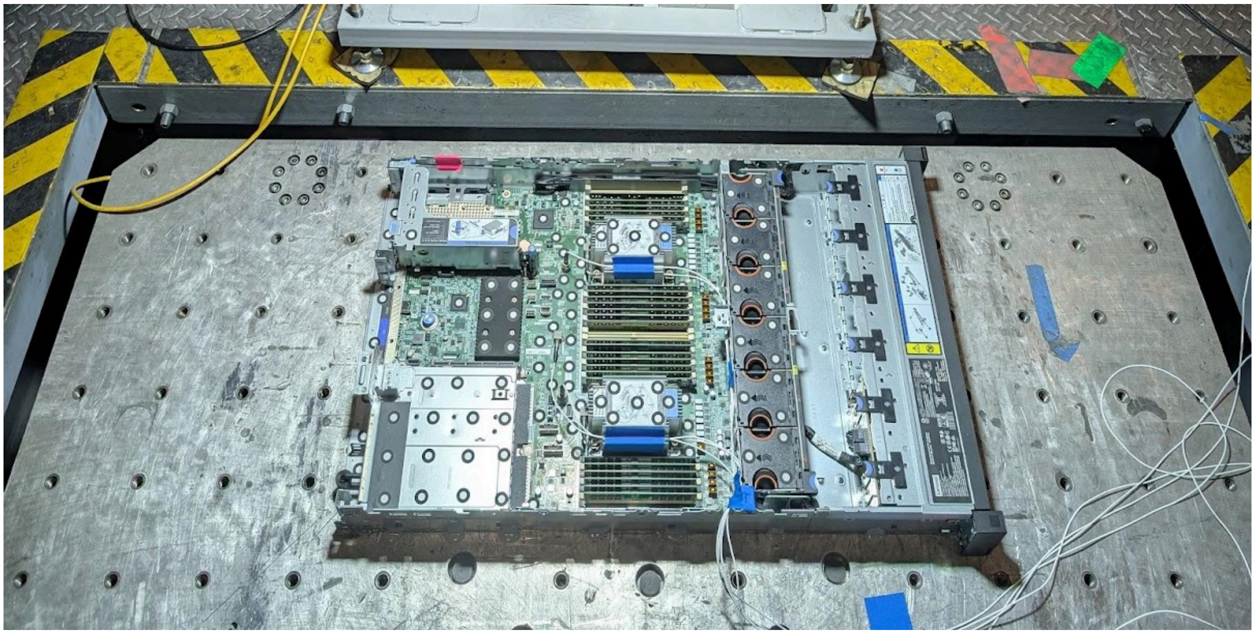


Figure 2.

Consider the same test unit in Part 1, mounted directly on the shaker table. This time, we subject the unit to a random vibration profile (shown below):

Equipment	Specifications
Electrodynamic Shaker: Unholtz-Dickie, K170 series	48" by 48" head expander, up to 15g (sine and shock), up to 2000hz, up to 2500lbs test unit load
Vibration Controller: Vibration Research VR10500	16 channels, up to 256khz sample rate
Accelerometers: Dytran Uniaxial IEPE accelerometer	Ch 1: Shaker table as reference control Ch 2: Area of the PCB in front of CPU0 Ch 3: Area of PCB between CPU0 and CPU1 Ch 4: Area of PCB in front of CPU1 Ch 5: On top of Heatsink of CPU0 Ch 6: On top of Heatsink of CPU1
Software: Vibrationview 2022 for shaker control, data acquisition, and data analysis	Profile: Random Vibration, 5hz to 300hz, 1.074 Grms
Setup Time: 30 mins	

Table 1.

Lenovo SR650 V2 Machine Level Power Spectral Density Plot

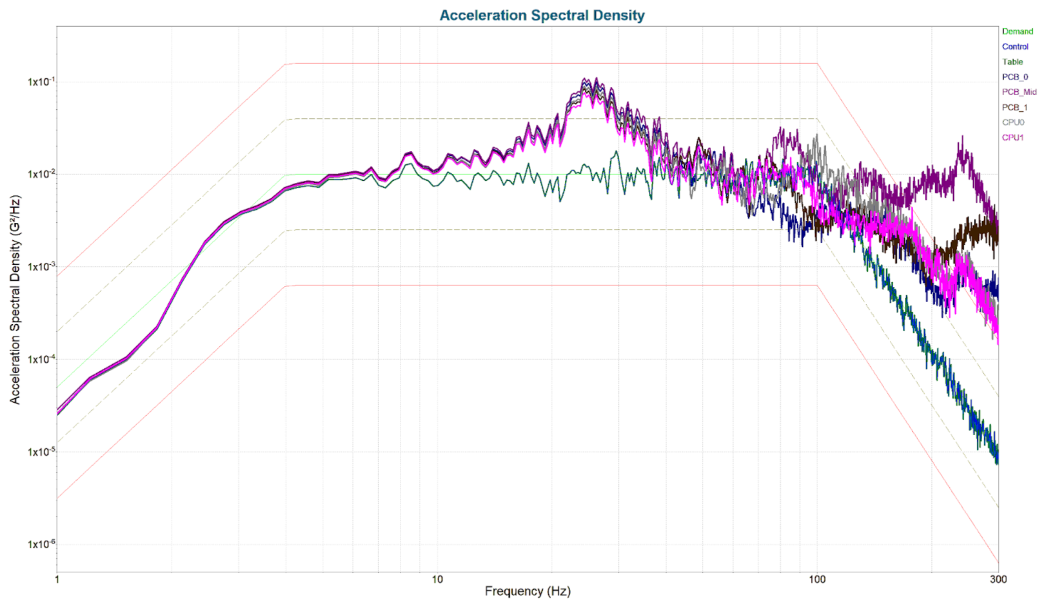


Figure 3.

If you compare the results carefully with the sine sweep results in Part 1, you will find the first natural frequency shifted from 28.53hz to 24.72hz. One possible explanation has to do with amplitude-dependent damping - the unit under test experiences a higher level of acceleration during random vibration, which can change the unit's dynamic properties and resonance peaks frequencies. 0.2G does not always do the same thing as levels as high as 0.6G. This makes it more important to look within the original acceleration time history.

We recorded the control channel (sensor mounted on the shaker table as control) during testing:

Acceleration Time History during Random Vibration Profile, Control Channel

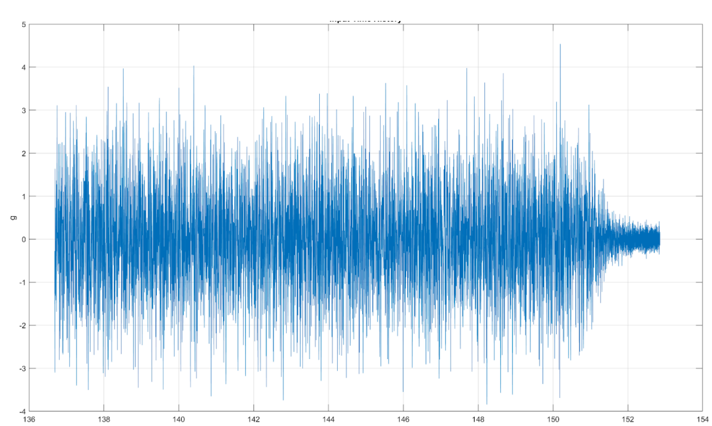


Figure 4.

This is a huge amount of information at first glance. To make the data more digestible, we apply a 15hz to 20hz bandpass filter, put the results through one of our peak detection algorithms, then create a histogram of the peaks afterward:

Acceleration Time History during Random Vibration Profile, Control Channel
Bandpass Filtered, 15hz to 20hz

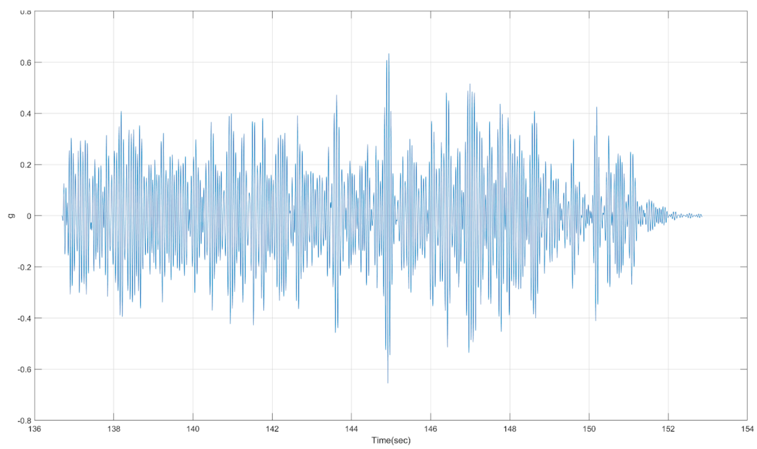


Figure 5

Acceleration Time History during Random Vibration Profile, Control Channel
Bandpass Filtered, 15hz to 20hz
With Peak Detection

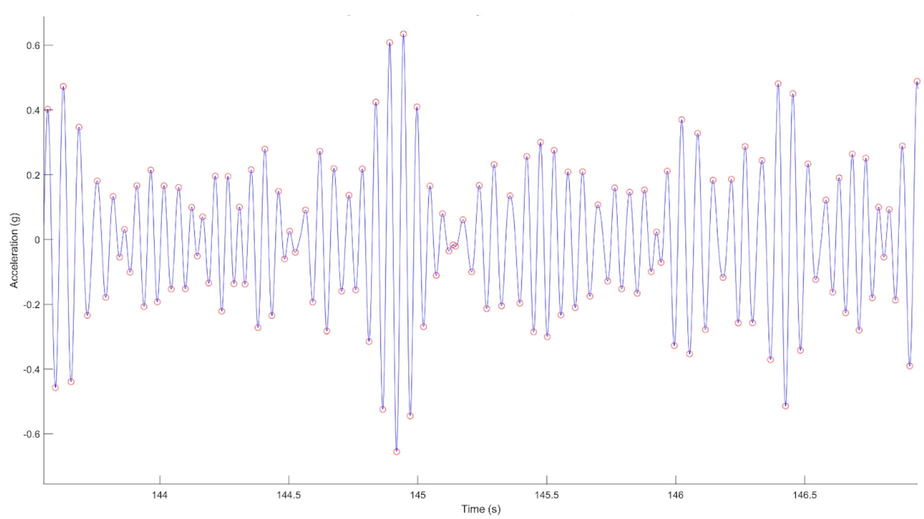


Figure 6.

Acceleration Time History during Random Vibration Profile, Control Channel
Bandpass Filtered, 15hz to 20hz

Acceleration Cycle Histogram

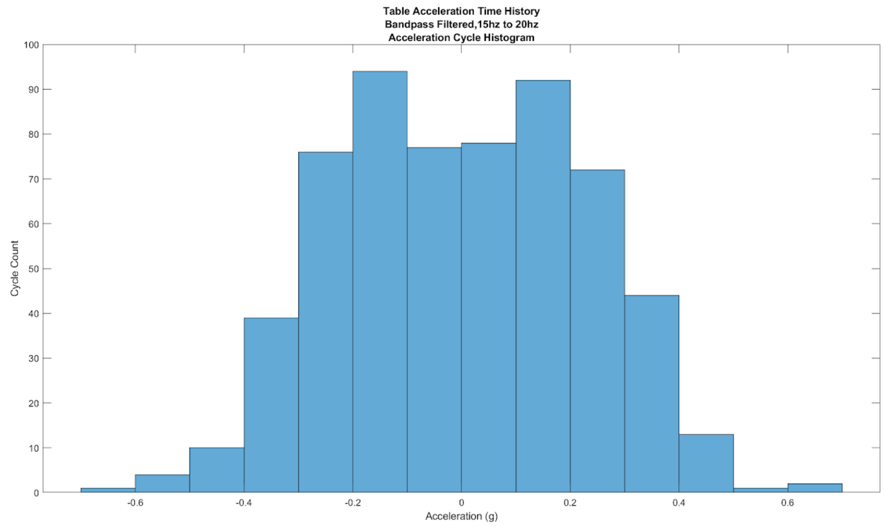


Figure 7.

This distribution of amplitude vs. acceleration cycle is typical of the shaker table controller we used, Vibration Research's VR10500 (and ones widely available commercially). The peaks are designed to approximate a gaussian distribution and fall within 3 times the standard deviation of the signal. No two random vibration signals are identical, but they do satisfy the input PSD profile and parameters surrounding its execution, including this one. This applies to the entire range of frequencies of the PSD profile, generating a shaker table control signal in real time.

We repeat the same procedure to 90hz to 100hz, shown below in Figure 7. Notice the higher cycle counts. This is an intentional feature of modern shaker controllers. In fact, when we look at the same histograms for a wide range of frequencies of the ASTM d4169-14 Truck Profile, we can see a clear pattern of this phenomena, shown in figure 8. Random vibration conditions, particularly ones found in transportation and handling, do not share the same characteristics in the real world. In fact, field data looks quite different in figure 9.

Acceleration Time History during Random Vibration Profile, Control Channel
Bandpass Filtered, 90hz to 100hz
Acceleration Cycle Histogram

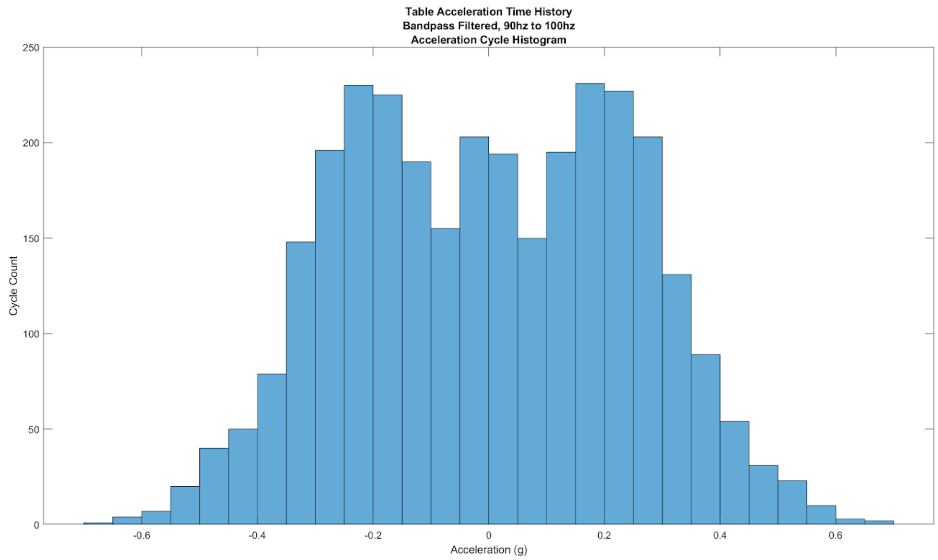


Figure 8.

Example of a 3D bar plot of amplitude vs. frequency vs. cycle
ASTM d4169-14 Truck Profile, Level 2

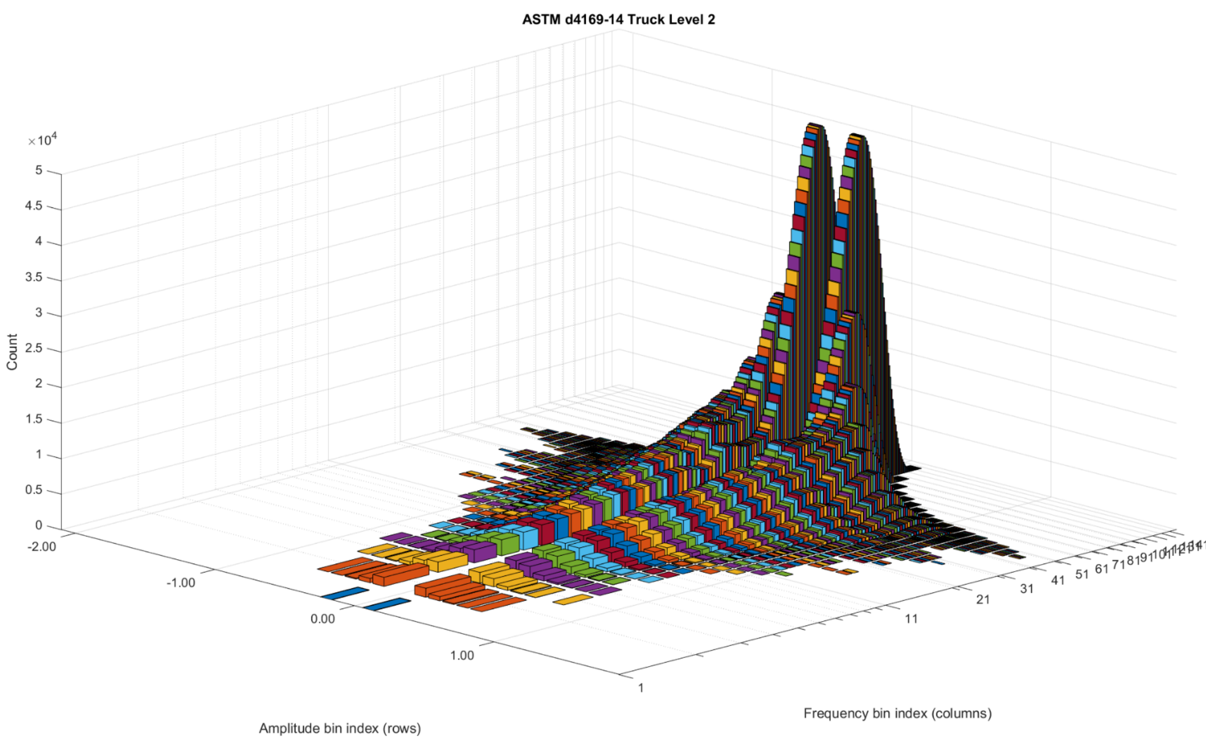


Figure 9.

Example of a 3D bar plot of amplitude vs. frequency vs. cycle
Google US Field Measurement, 2019

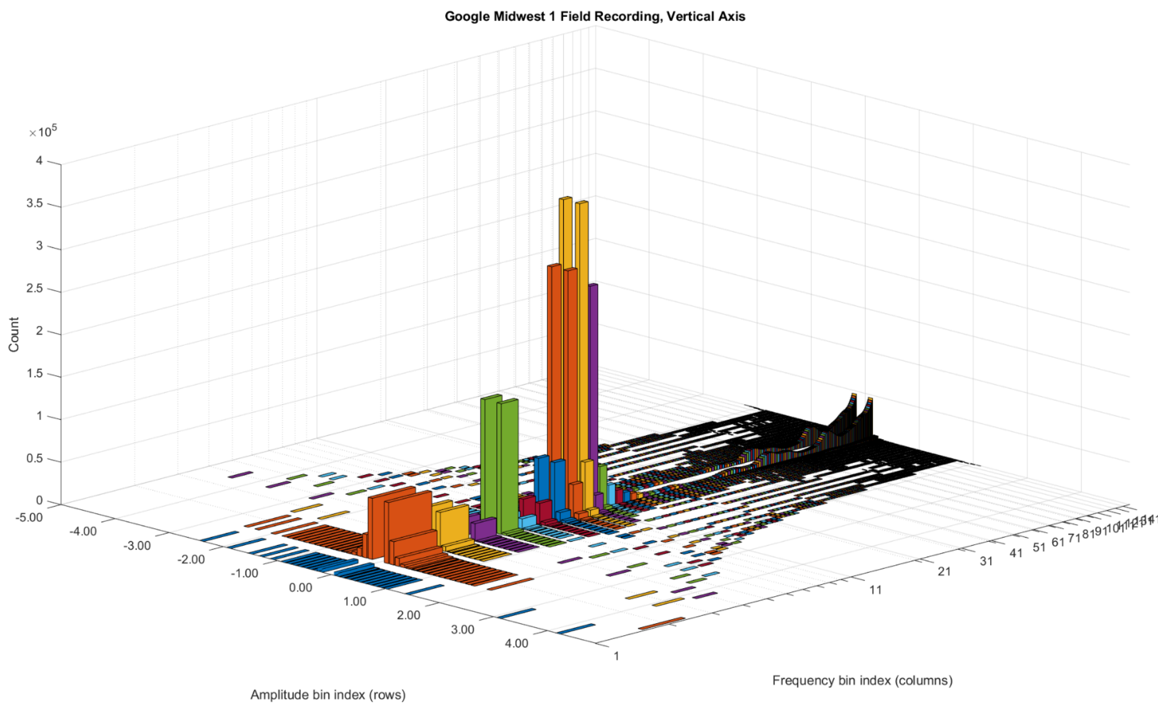


Figure 10.

The question is: Does the unit under test experience the same quantity and amplitude of board deflection, when comparing a shaker table profile to the original field data time history? And in the back of our head, we should also wonder, assuming we keep the same PSD profile, if different shaker tables and shaker controllers lead to the same amount of board deflection and cycles on the same unit under test every single time.
Measuring displacement and board deflection during random vibration

Tom Irvine's Vibrationdata webinars described one way to compare two shaker table profiles by looking at the amount of fatigue damage that accumulates in the test sample [2]. A random vibration test and a sinesweep test can be "equivalent" if they both lead to the same amount of fatigue damage. To do that, we have to measure displacement during a random vibration profile, which directly correlate with mechanical stress and fatigue damage:

Equipment	Specifications
High Speed Camera: Duo Phantom v2640	4000 frames per second, 7.5 seconds duration, 2048 x 1536 resolution
Calibration Target: Zeiss Calibration Object	CP20 Panel / CP20/350, 20.5" x 18.5"
Software: Zeiss Inspect Correlate	Profile: Random Vibration, 5hz to 300hz, 1.074 Grms

Setup Time: 3 hours

Table 2.

The following displacement measurement is captured during the random vibration profile using a high speed 3D DIC setup:

Z Axis Relative Displacement Time History during Random Vibration Profile, CPU1

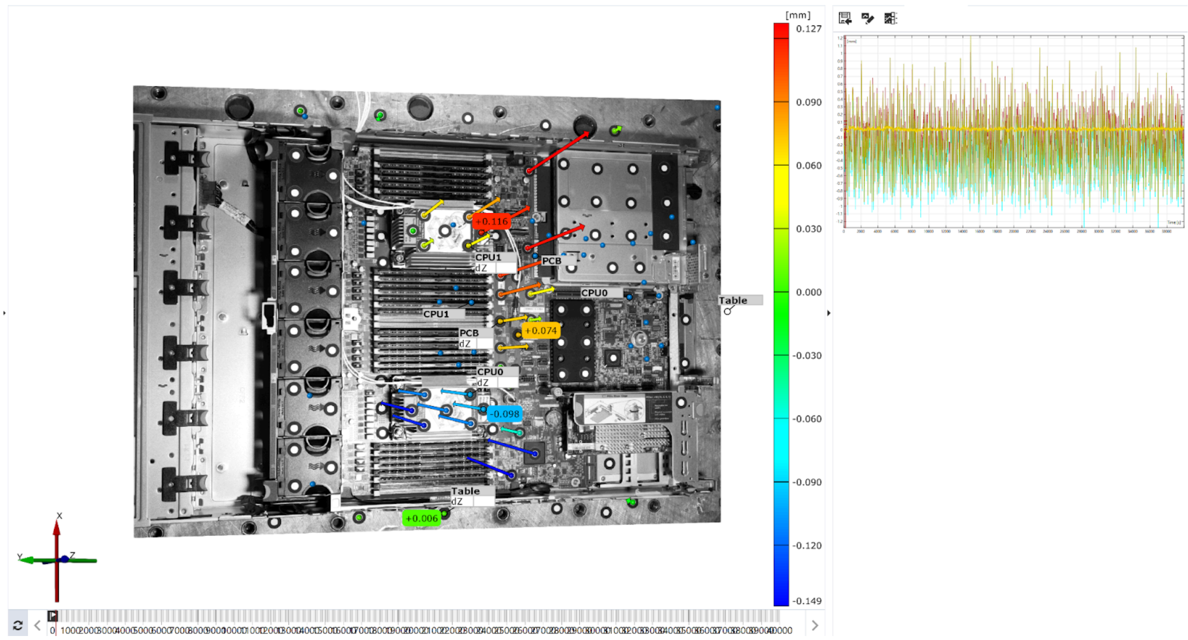


Figure 11.

Z Axis Relative Displacement (mm) Time History during Random Vibration Profile, CPU1

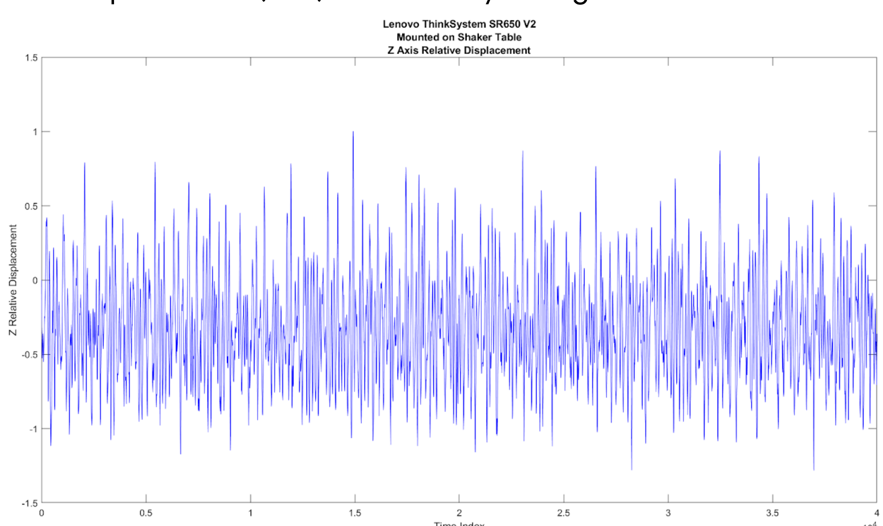
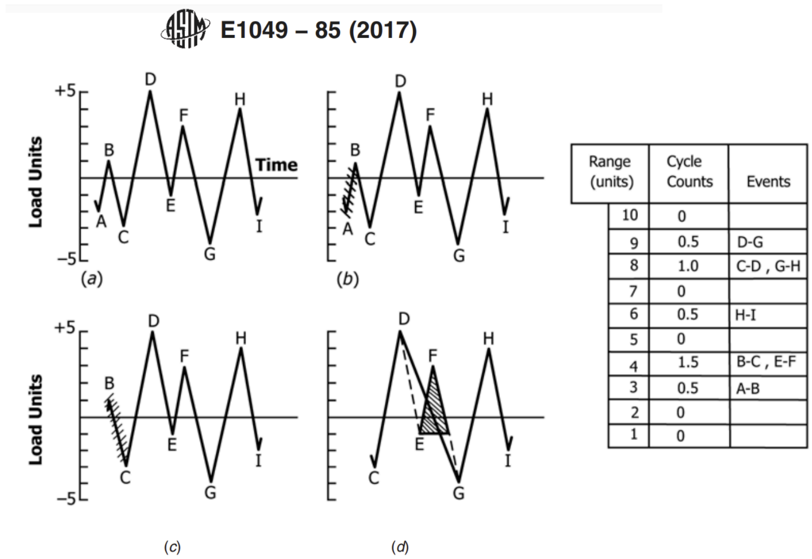


Figure 12.

Again, the data has a huge amount of information in it, so we need tools to help us break it down in a manageable way. One way is with rainflow counting (described in Vibrationdata's webinar [3] and ASTM E1049 [4]), which quantifies amplitude and cycle count of a cyclical stress over time. Rainflow counting has the ability to distinguish temporary stress reversals over long term ones and keep track of them. We apply it to our relative displacement time history using Vibrationdata's Signal Analysis Package [5]:

Explanation of Rainflow Counting in ASTM E1049



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	

Figure 13.

Rainflow Counting Applied to Z Axis Relative Displacement (mm) Time History during Random Vibration Profile, CPU1

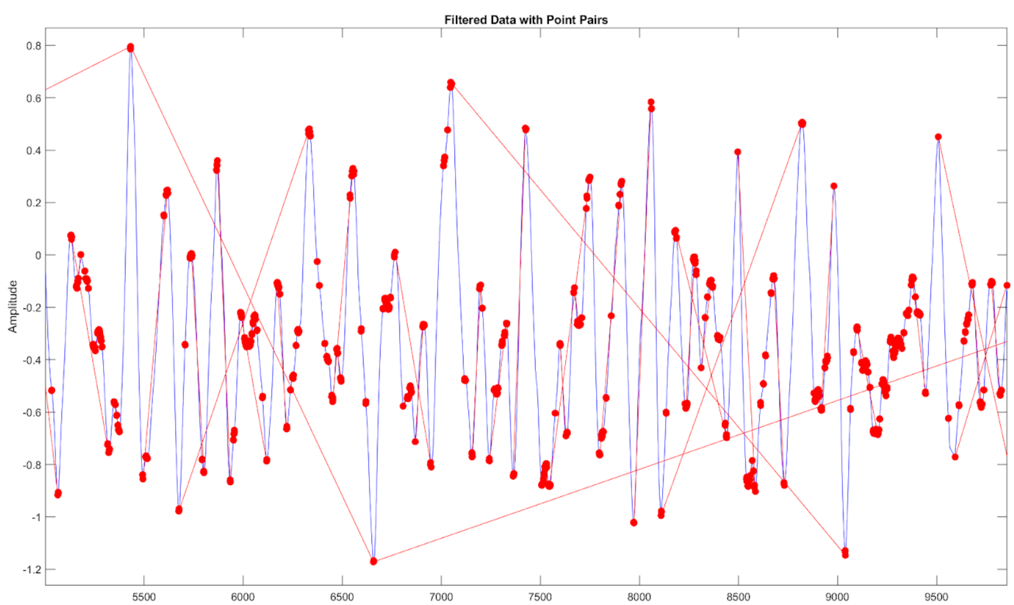


Figure 14.

Rainflow Counting Histogram of Z Axis Relative Displacement (mm) Time History, CPU1

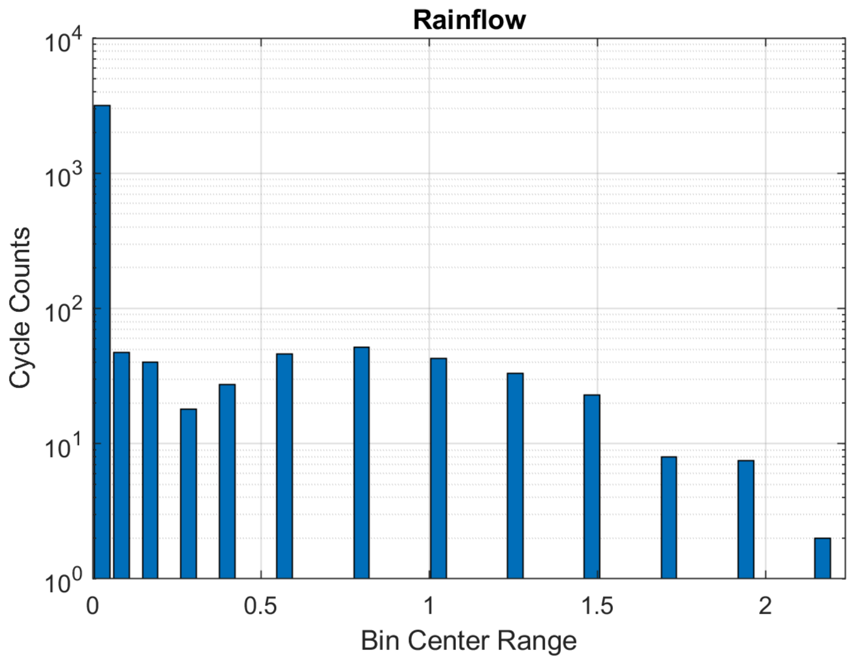


Figure 15.

Table of Rainflow Counting Results of Z Axis Relative Displacement (mm) Time History, CPU1

Lower Range	Upper Range	Cycles	Ave Amp	Max Amp	Min Mean	Ave Mean	Max Mean	Min Valley	Max Peak
2.06	2.28	2.0	1.1	1.14	-0.204	-0.158	-0.085	-1.28	1
1.83	2.06	7.5	0.953	1.01	-0.347	-0.167	-0.13	-1.28	0.871
1.6	1.83	8.0	0.855	0.912	-0.291	-0.218	-0.123	-1.15	0.73
1.37	1.6	23.0	0.742	0.798	-0.375	-0.242	-0.11	-1.12	0.629
1.14	1.37	33.0	0.629	0.684	-0.407	-0.291	-0.179	-1.08	0.484
0.914	1.14	42.5	0.512	0.571	-0.498	-0.318	-0.0648	-1.01	0.421
0.685	0.914	51.5	0.403	0.457	-0.526	-0.332	-0.0457	-0.965	0.368
0.457	0.685	46.0	0.29	0.342	-0.567	-0.37	-0.189	-0.833	0.121
0.343	0.457	27.5	0.203	0.228	-0.534	-0.35	-0.0979	-0.727	0.0854
0.228	0.343	18.0	0.139	0.167	-0.614	-0.325	-0.0207	-0.758	0.131
0.114	0.228	40.0	0.0797	0.114	-0.655	-0.368	-0.00158	-0.728	0.0762
0.0571	0.114	47.0	0.0418	0.057	-0.985	-0.43	-0.0152	-1.04	0.0211
0	0.0571	3186.0	0.00225	0.0281	-1.17	-0.347	0.994	-1.17	0.995

Figure 16.

The result is the histogram and table shown above, breaking the data down by range and cycles. We observed a lot of cycles centered around 0.5mm to 1.5mm, with a small amount of peaks reaching up to 2.28mm.

So what does that mean? At the moment, these results still read like a bunch of meaningless numbers (they are at least quantifiable). What we need to do is find meaning, to see the forest for the trees. I've always been a very visual person, so one way to make sense of this is to plot the relative displacement over time in three dimensional space, creating something known as "Orbit Plot" in RDI's software [6]. This provides an intuitive way for us to visualize the data.

3D Relative Displacement Orbit Plot of CPU1 during Random Vibration Profile

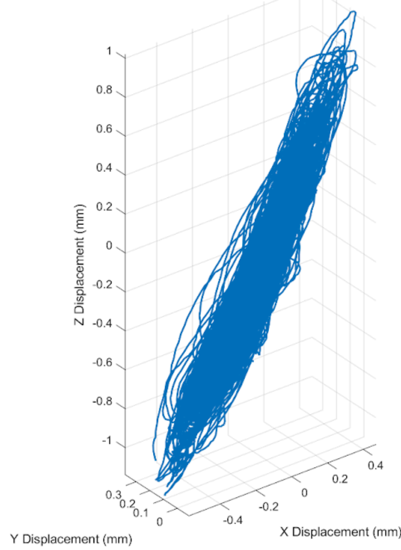


Figure 17.

3D Relative Displacement Measurements, XZ plane view
Unit Attached Directly To Shaker Table
Test Profile: Sine Dwell @ 28hz & 2.0G

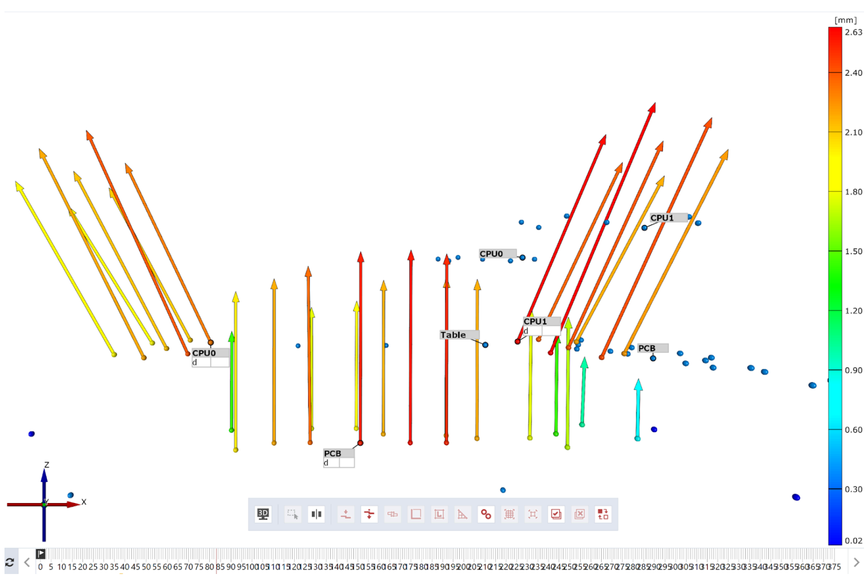


Figure 18.

In figure 17, we trace the displacement of one of the points on a heatsink over time. What we see is the heatsink is moving up and down with the PCB, and as it is doing so, flexing outward and inward. This makes sense because we've already seen the same behavior in part 1, except now it is observed during random vibration.

This is encouraging because natural frequencies still appear to be driving the motion of the PCB and heatsink. Still, it is hard to tell at the moment whether other modes are hidden within this orbit plot, which spanned 7.5 seconds (that is a long time considering the frequency of the modes). Without data from all major natural frequencies and breaking this data down into pieces, we won't know for certain.

The Bigger Picture

Google's Chassis Level Random Vibration Analysis

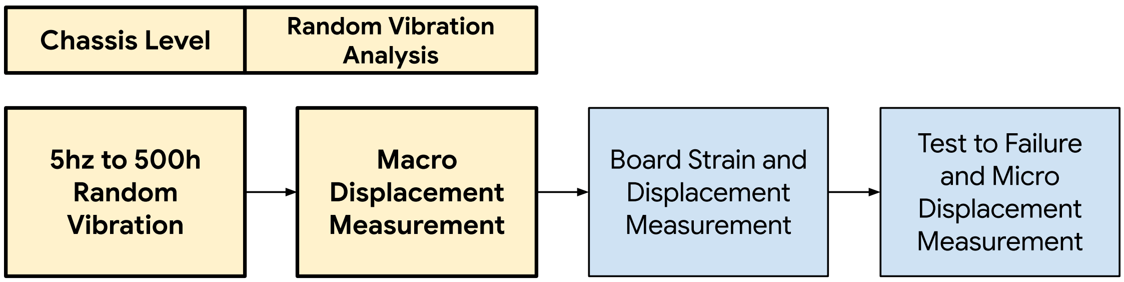


Figure 19.

We are still at the beginning of this work. We introduced a few measurement methods and identified a couple of natural frequencies in Part 1 and 2. We just attempted to observe the test sample in random vibration, by looking at acceleration time history and relative displacement time history in detail. We are beginning to make sense of things, but there is still so much to unpack.

Taking a step back, we have to remember that for a majority of the history of this work (shock and vibe testing of electronics and printed circuit boards), most results are explained in terms of hand calculations and accelerometer and strain gauge data. FEA became popular in the past 20 years, but it's not typical for companies to share FEA results in full details, open for all to see.

Now, we can easily apply robust, commercially available computer vision solutions to testing. What I hope to do with these papers is to use these new tools to improve our collective understanding one layer at a time. It takes time to perform the experiments, gather the data, analyze the results, and turn them into papers that can be understood by anyone interested.

One of the end goals, or the north star of this project, if we can get there, is to have similar results published for most common critical components, in masses, sizes, and form factors of common data center hardware, for typical shock and vibration conditions present in the global supply chain. I think that will go a long way toward standardization and speeding the work of everyone. But that is an ambitious task, all the more so as I begin to write these papers.

We will do what we can with the time and resources available to this project. Again, the papers are not meant to be perfect - they are meant to be revised and evolve as the work moves forward. They are meant to be quick and straightforward (though I find that hard to achieve in this first batch), but with all the necessary details so that anyone can replicate the experiments themselves. Most importantly, they are meant to be useful, and grow with the readers.

References

1. T. Irvine, "POWER SPECTRAL DENSITY UNITS: [G^2 / Hz], Revision B," Vibrationdata, 2007.
2. T. Irvine, "SINE AND RANDOM VIBRATION EQUIVALENCE, Revision B," Vibrationdata, 2012.
3. T. Irvine, “RAINFLOW CYCLE COUNTING IN FATIGUE ANALYSIS, Revision B,” Vibrationdata, 2018.
4. ASTM E1049-85(2017): “Standard Practices for Cycle Counting in Fatigue Analysis,” ASTM International, West Conshohocken, PA, 2017.
5. T. Irvine, “Vibrationdata, Shock & Vibration Software & Tutorials,” Jan. 19, 2017. [Online]. Available: https://vibrationdata.wordpress.com/2017/01/19/webinar-index/. [Accessed Mar. 18, 2025].
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