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

PART 1: SINE VIBRATION OF A SINGLE MACHINE
REVISION A

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Introduction

The history of shock and vibration testing of electronic components is a fascinating topic, one we won't have time to cover in this first white paper of our project: Open Source Random Vibration Testing of Fully Populated Racks with Off-The-Shelf Data Center Hardware

Nevertheless, this project would not exist without the foundations that guided this body of work. Among the many, these made the most impact throughout my career:

1. Dave S. Steinberg's textbook on Vibration Analysis for Electronic Equipment [1]
2. Tom Irvine's Vibrationdata Shock and Vibration Testing Webinar and Signal Analysis Package [2]
3. RDI Technologies's Motion Amplification software [3]
4. The IPC/JEDEC-9703 standard: MECHANICAL SHOCK TEST GUIDELINE FOR SOLDER JOINT RELIABILITY [4]
5. Intel's Strain Measurement Methodology for Circuit Board Assembly - Board Flexure Initiative (BFI) [5]
6. "Effect of Elevated Testing Temperature on Sn-Ag-Cu Interconnect, High and Low G Board Level Mechanical Shock Performance", by Cisco Systems [6]

There were many reasons why this project was conceived. The demand for velocity and standardization in the era of AI is high on the list as record number data centers are built around the world, but I've always just wanted to know what happens when things are subjected to shock and vibration. That curiosity deepened as I entered the field of microelectronics.

From a testing perspective, products are often sent to testing with very little information about them. We could only rely on the tools available to us to figure things out - a shaker table, a shock tower, various instruments for measurements and equipment for failure analysis. After a while, we form a unique perspective based on lab observations. Our idea is simple: It's always worth it to look inside the black box.

These initial papers will be written from that perspective, always asking: "What can we measure during testing to tell us more about the design, its internal structure, and potential point of failure?". I will release materials as quickly as possible so that the industry as a whole can collaborate through this open source platform.

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.

Should anyone have any topic or questions they want answered, I will be happy to add them to the regular release schedule. And of course, feedback is always welcomed on how to make this project more useful.

One last note: these are written with the assumption that readers already have some experience with shock and vibration testing. For those of you who don't, Tom Irvine's Vibrationdata Webinar is an invaluable resource in building a strong understanding of this work. Should the need arise, I will be happy to put together a comprehensive beginner's guide. In the meantime, I will do my best to make the materials easy to follow.

Let's begin with an example.

What happens to electronics when subjected to Shock and Vibration?

Factors that contribute toward localized component level stress
and failure modes in a fully populated rack

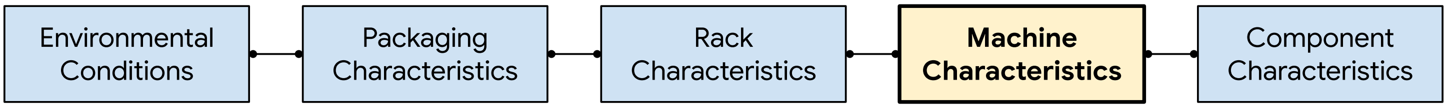

Figure 1.

We begin with a standard off the shelf Lenovo ThinkSystem SR650 V2 rack server. It has two two sockets, and a number of optional drive bays and expansion slots. This particular unit has the basic components - two Intel CPUs and 32GB of DDR4 memory [7]. It is mounted directly on our shaker table with the cover removed, glued down along the two long edges to allow the sheet metal to flex. There will be future papers on Pros and Cons of various test setup. For now, this was done because it allows the best view inside the unit, and because the input vibration is relatively low.

Lenovo ThinkSystem SR650 V2 mounted on shaker table

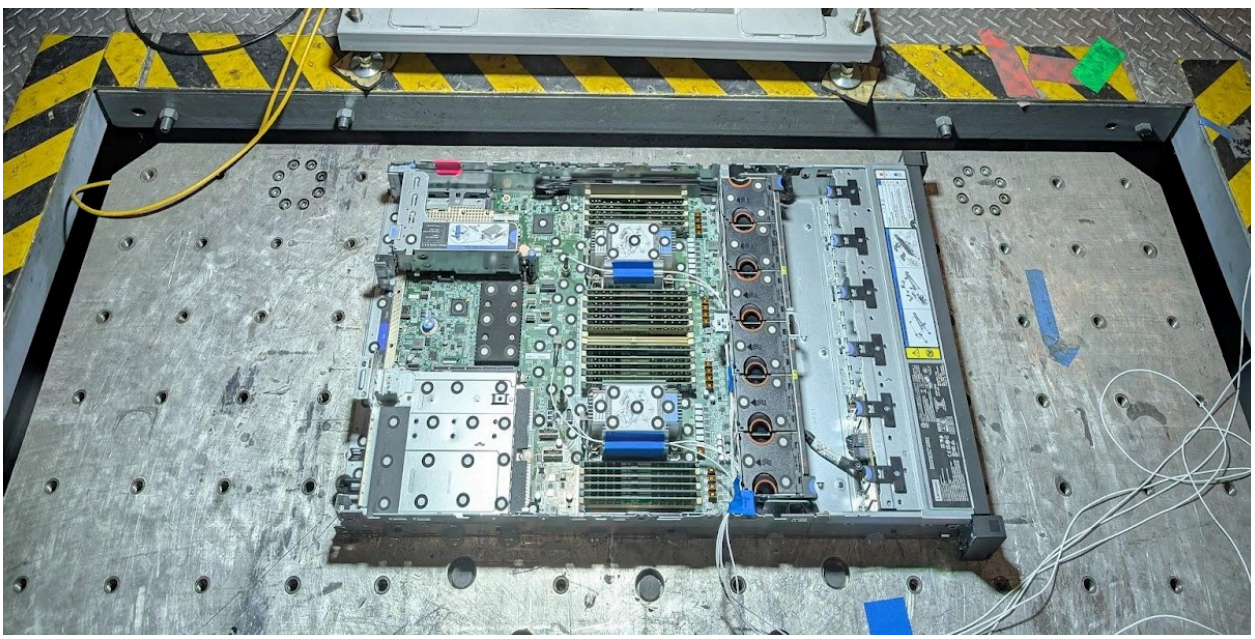

Figure 2.

Here are some details of our test setup:

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: Sinesweep, 0.2G (zero to peak), 5hz to 500hz, 1 oct/min
Setup Time: 30 mins	

Table 1.

The very first measurement is a sinesweep, which is often used to identify natural frequencies of test samples. This sample is subjected to a 0.2G (zero to peak), 5hz to 500hz, 1 oct/min sinesweep. The results are shown below:

Lenovo SR650 V2 Acceleration Profile

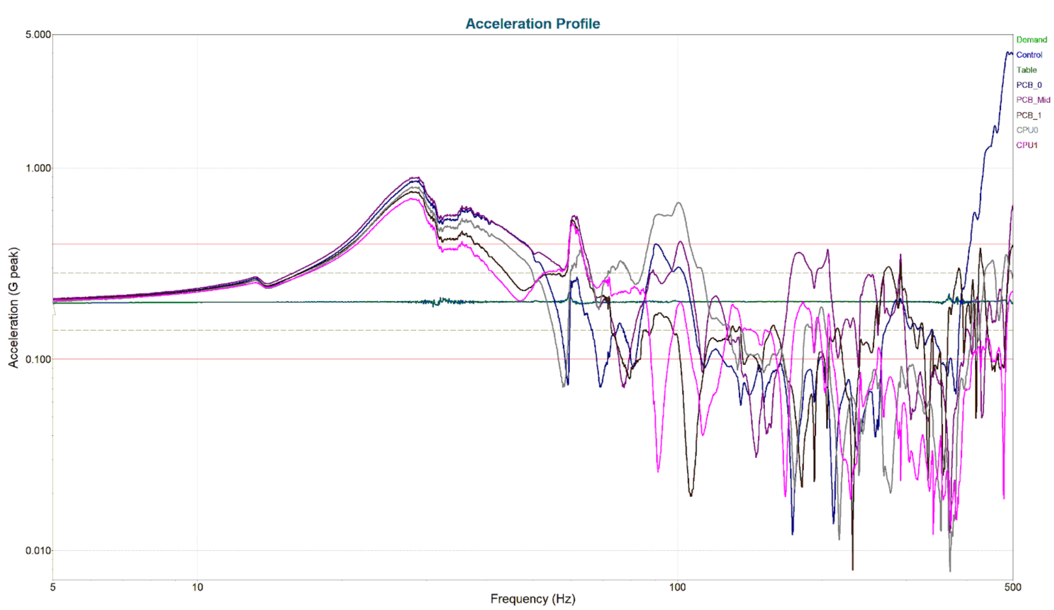

Figure 3.

Lenovo Lenovo SR650 V2 Acceleration Transmissibility Plot

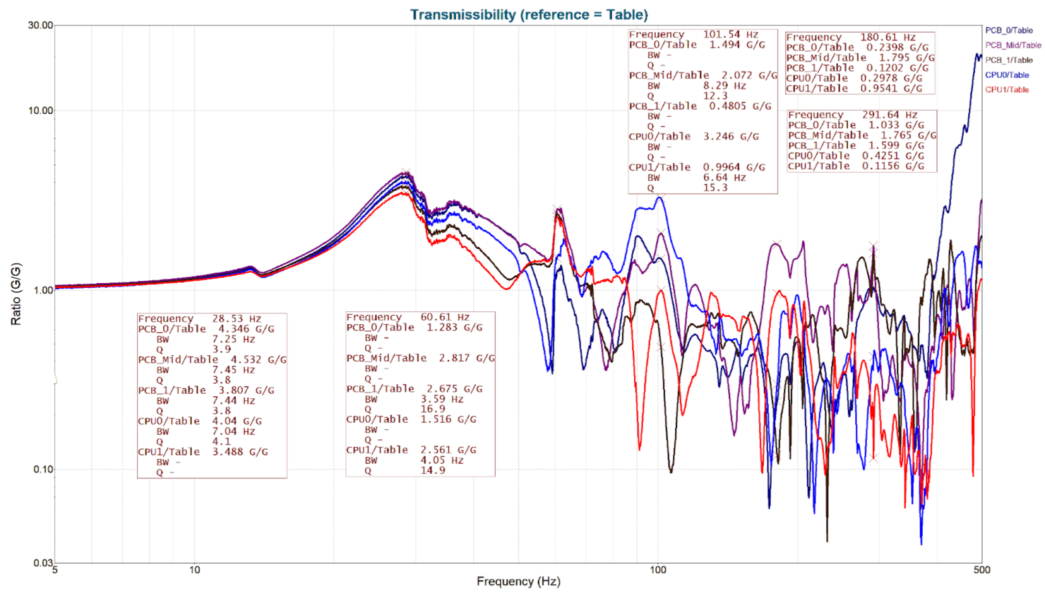

Figure 4.

Lenovo Lenovo SR650 V2's Natural Frequencies and Amplification Factor

First Natural Frequency	28.53hz, between 3 to 4.5 G/G amplification factor
Second Natural Frequency	60.61hz, between 1.2 to 2.8 G/G amplification factor
Additional Natural Frequencies	101.54 hz, 180hz, 291hz, etc.

Table 2.

We can gather a lot of critical information from these plots, such as the exact natural frequencies and amplification factors (most stopped looking after this). But sine sweeps only provide a limited view of what actually happens during testing. Without years of experiences in this field working with this particular style of servers, it is often difficult to answer the following questions:

- How do the unit and internal components move during natural frequencies?
- What are the most common failure modes?
- What component is most likely to break, at what specific frequency and what amplitude?
- Where are the locations of local stress concentrations?

We need more skills and capabilities to help us answer these questions - which is one of the main goals for this open source project. Ultimately, the risk for damaging this particular product might be low, particularly when shipped in traditional packaging, but the skills and capabilities will serve us through all variations of hardware products, for any object where reliability of microelectronics in real world conditions is important.

<u>Visualizing dynamic behavior during shock and vibration</u>

Lenovo Lenovo SR650 V2, snapshot from RDI Motion Amplification with displacement cursors
Test Profile: Sine Dwell @ 28hz & 1.0G

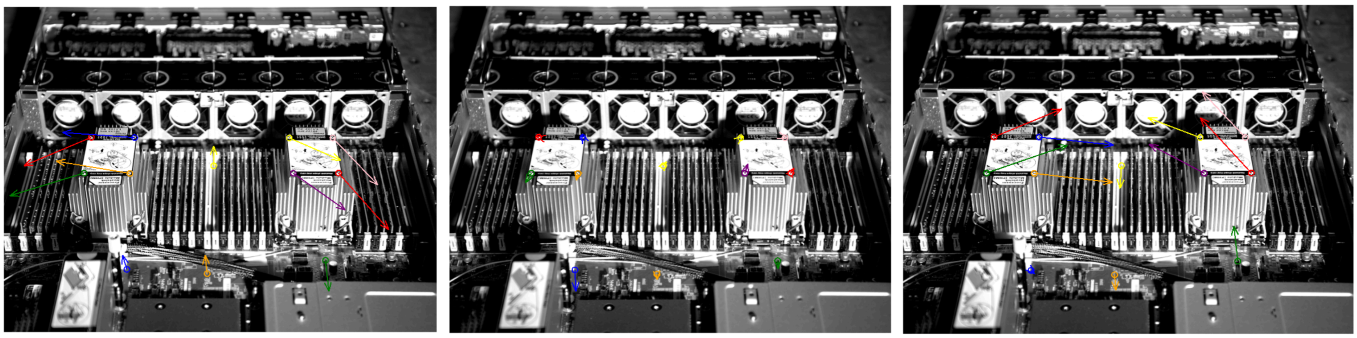

Figure 5, 6, and 7.

One of the most important discoveries of my career happened accidentally when a colleague and I, while attending a conference in Florida in 2017, ran into RDI Technologies and their booth. The idea of their motion amplification solution is simple - using a high speed camera and computer vision algorithms, vibration motion of an object can be captured, filtered, amplified, and made visible to the human eye. RDI videos are captured in this example.

Equipment	Specifications
High Speed Camera: Phantom v2640, 1920 x 1280	6000 frames per second, 0.2 second duration, 1920 x 1080 resolution
Software: RDI Iris MX, Motion Acquisition and Motion Amplification	Profile: Sine Dwell @ 28hz & 1.0G
Setup Time: 45 mins	

Table 3.

RDI’s Motion Amplification software allows us to visualize dynamic behavior of a test sample directly. That is important because motions and deformations of the test sample, specifically, the deflection of the printed circuit board due to input excitation and structural characteristics, is what leads to localized strain and localized stress at the critical components. The molecules are pushed and pulled apart as strain energy is stored and released [8], and this cyclical phenomena, with sufficient amplitude and cycle count, leads ultimately to mechanical fracture [9]. For microelectronics and PCB, this behavior manifests itself in the form of circuit board deflection [10].

Classical model of interatomic bonds and dynamic deflection mode of a circuit board

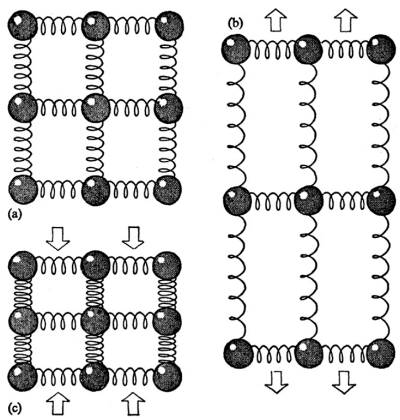

Figure 6. Simplified model of distortion of interatomic bonds under mechanical strain.

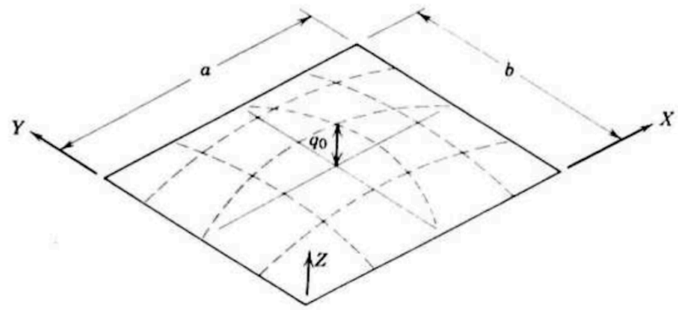

FIGURE 6.17. Dynamic deflection mode of a circuit board.

Figure 9 & 10.

Figure 5, 6, and 7 demonstrate RDI software's ability to display 2D movement of selected regions of interest, but the most valuable feature of the software is its ability to amplify captured video. Sample videos are available at the project's Github repository, in the same folder as each paper under "RDI and Zeiss Videos".

Vibration motion analysis solutions like RDI's goes a long way toward understanding cause and effect, and quantifying the strain and stress at the area of interest. Intuitively, RDI videos just make sense. The amplified motion allows users to grasp the interaction between various parts of the sample's structure, and come up with potential failure root causes quickly.

Measuring 3D Deflection and Deformation

Lenovo Lenovo SR650 V2, snapshot from Zeiss Inspect Correlate with Z Axis Relative Displacement Measurements

Test Profile: Sine Dwell @ 28hz & 2.0G, 375 frames duration

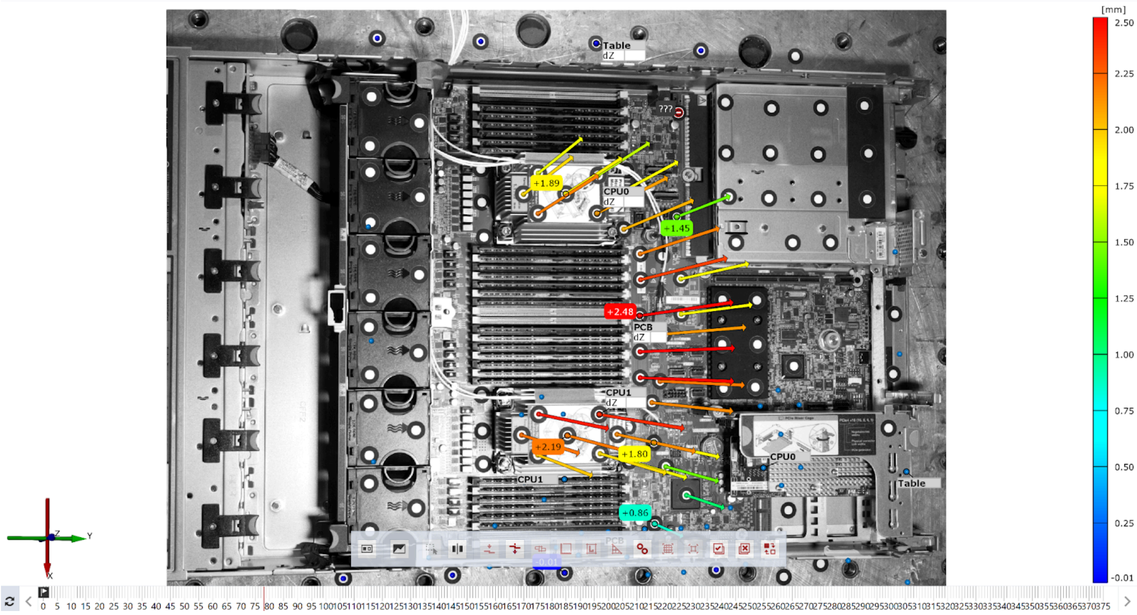

Figure 10.

3D Relative Displacement Measurements, XZ plane view

Test Profile: Sine Dwell @ 28hz & 2.0G

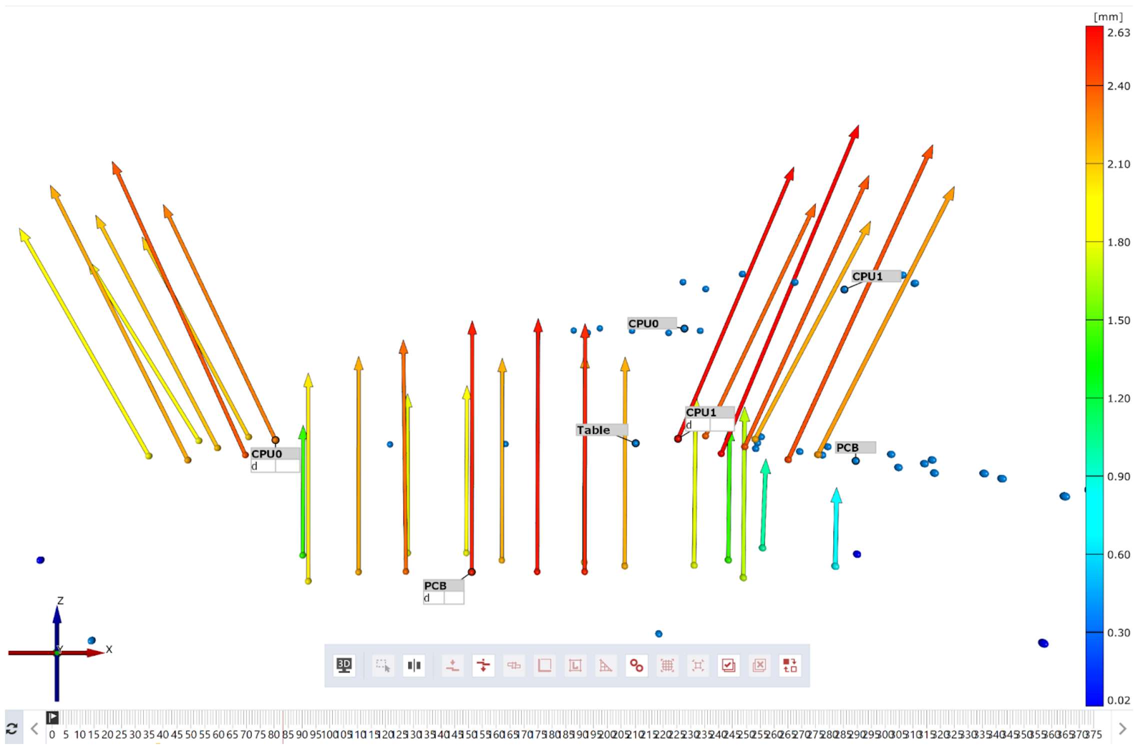

Figure 11.

PCB Relative Displacement Measurement Time History
Test Profile: Sine Dwell @ 28hz & 2.0g, 375 frames duration

Figure 12.

A single camera can capture movement in the X and Y axis of the camera's sensor plane, but it cannot capture depth. Stereo vision can overcome this challenge by using a pair of cameras, stereo calibration, and triangulation to measure the movement of objects in three dimensional space. Recent advances in computer vision led to 3D Motion Tracking solutions such as 3D Digital Image Correlation, which are now widespread across many industries. 3D Displacement measurements are captured for this example.

Equipment	Specifications
High Speed Camera: Duo Phantom v2640	4000 frames per second, 0.2 second duration, 2048 x 1536 resolution
Calibration Target: Zeiss Calibration Object	CP20 Panel / CP20/350, 20.5" x 18.5"
Software: Zeiss Inspect Correlate	Profile: Sine Dwell @ 28hz & 2.0G
Setup Time: 3 hours	

Table 5.

Inside the Zeiss Inspect Correlate, tracking markers allow the software to measure and display 3D displacement over time. Markers are placed at both the shaker table and inside the machine to zero out the shaker table's movement, generating relative displacement measurements between the two (deformation of an object is difficult to analyze without overall translations removed).

At the moment of peak displacement, PCB shows an upward relative movement of 2.63mm in the Z direction, while the heatsinks showed an angled relative movement of similar amplitude away from the center (shown in figure 11). This aligns with RDI videos captured earlier.

We now have a basic description of the relative deformation/movement of a two socket server, in its first natural frequency, mounted directly on a shaker table, measured during testing.

The Bigger Picture

Google's Chassis Level Sine Vibration Analysis

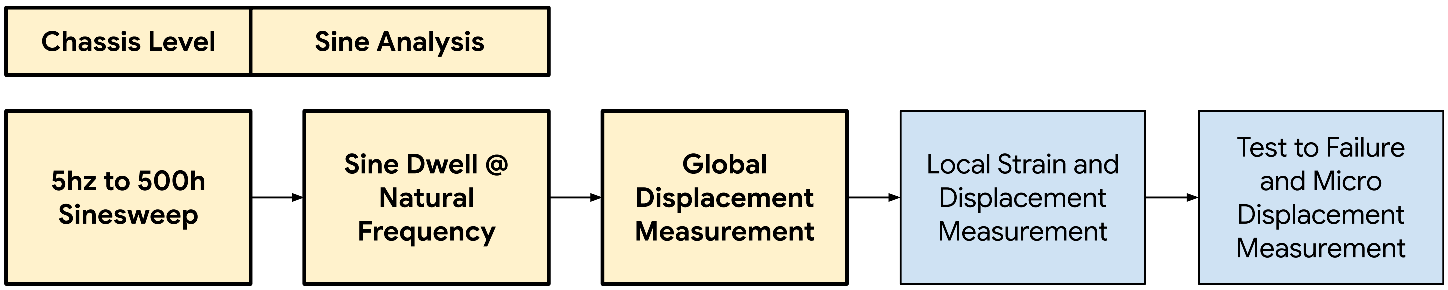

Figure 13.

Sine vibration of the first natural frequency is only the first step toward understanding how a unit behaves in shock and vibration. In the real world, the field conditions and the structures around the unit (such as a fully populated rack) are a lot more complex.

We are still a few steps away from behaviors inside a rack. That will be covered in part 2. We are a few more steps away from understanding behaviors in random vibration (part 3), visualizing critical component's local stress and strain (part 4), and identifying specific failure modes. These will be covered in our regular release schedule of papers.

These analyses are meant to be performed as needed for any scenario applicable to the product's shipping environment (rack transportation, FRU packaging, etc). Performing them one layer at a time allows us to build our understanding in small, manageable blocks. We would be lost if we go straight to a populated rack test and complex shock and random vibration conditions without any understanding of the subsets of the system.

Google's Shock and Vibration Analysis, By Example Levels and Types

Chassis Level	Sine Analysis
Chassis Level	Vibration Analysis
Chassis Level	Shock Analysis
Risks identified?	

Rack Level	Sine Analysis
Rack Level	Vibration Analysis
Rack Level	Shock Analysis
Risks identified?	

Packaging Level	Sine Analysis
Packaging Level	Vibration Analysis
Packaging Level	Shock Analysis
Risks identified?	

Figure 14.

Google's Open Source Random Vibration Testing of Fully Populated Racks with Off-The-Shelf Data Center Hardware

At the end of the day, the risk for damage might be low, particularly when foam and cardboard packaging is involved. But there are a number of benefits from having a comprehensive set of results, done once per release of a major architecture:

1. Theories and models often assume ideal situations. Testing measures real life behaviors.
2. All models should be correlated with test results.
3. The number of tests in future developments of the same architecture can be greatly reduced once risks are properly identified.
4. The findings should feed directly into product design so that product reliability is baked in at the beginning, when the design is still open to changes.
5. Having potential failure modes identified will significantly shorten time for root causing when issues arise in production.
6. Having test methodology and capability in place short any ramp up time when future needs arise (troubleshooting field failures, feasibility evaluation for a future product, etc).
7. Having standardized methodologies and capabilities allow the work to scale across the whole industry.

From a testing standpoint, the act of testing is relatively easy. Once a sample unit is fully instrumented, it can go through different setups quickly to gather the necessary data for the characterization and determination of critical displacement/strain/acceleration. The amount of time spent in such activities (days) are small compared to the round and round of traditional test methods, where little information is gained (weeks to months).

It is often too late to develop any specific measurement methods, test setup, or fixturing when issues suddenly appear during product development or product release. Each specific product has unique dynamic and failure modes, and requires different methods and solutions. It is also not feasible to scale the work when everyone has their own unique methods and solutions. And in the Era of AI, standardization and scalability is going to be key to a product's success.

References

1. D. S. Steinberg, *Vibration Analysis for Electronic Equipment*, 3rd ed. New York, NY, USA: John Wiley & Sons, 2000.
2. 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].
3. RDI Technologies, *Motion Amplification* [Software]. [Online]. Available: https://rditechnologies.com/models/. [Accessed Mar. 18, 2025].
4. IPC/JEDEC, *IPC/JEDEC-9703: Mechanical Shock Test Guideline for Solder Joint Reliability*. Bannockburn, IL, USA: IPC, 2007.
5. Intel Corporation, Strain Measurement Methodology for Circuit Board Assembly - Board Flexure Initiative (BFI). Santa Clara, CA, USA: Intel, 2016.

6. Cisco Systems, "Effect of Elevated Testing Temperature on Sn-Ag-Cu Interconnect, High and Low G Board Level Mechanical Shock Performance". San Jose, CA, USA: Cisco, 2015.
7. Lenovo, *ThinkSystem SR650 V2*. [Online]. Available: https://www.lenovo.com/us/en/p/servers-storage/servers/racks/thinksystem-sr650-v2/77xx7sr65v2?orgRef=https%253A%252F%252Fwww.google.com%252F&srsltid=AfmBOopwC0-Gw4VbZ2P9WroAlrHBfMljHsZlv0m6qXTlXbf7Y6G39aEX. [Accessed Date: Mar. 18, 2025].
8. J. E. Gordon, *Structures: Or Why Things Don't Fall Down*. Cambridge, MA, USA: Da Capo Press, 2003. Fig. 3.2, p. 150.
9. Wikipedia, "*Stress–strain curve*," [Online]. Available: https://en.wikipedia.org/wiki/Stress%E2%80%93strain_curve. [Accessed Date: Mar. 18, 2025]. (Figure 1)
10. D. S. Steinberg, *Vibration Analysis for Electronic Equipment*, 3rd ed. New York, NY, USA: John Wiley & Sons, 2000. Fig. 4.3, p. 185.