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

Part 5: HIGHLIGHT OF ADDITIONAL MEASUREMENT METHODS FOR SHOCK AND VIBRATION
REVISION A

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Figure 1.

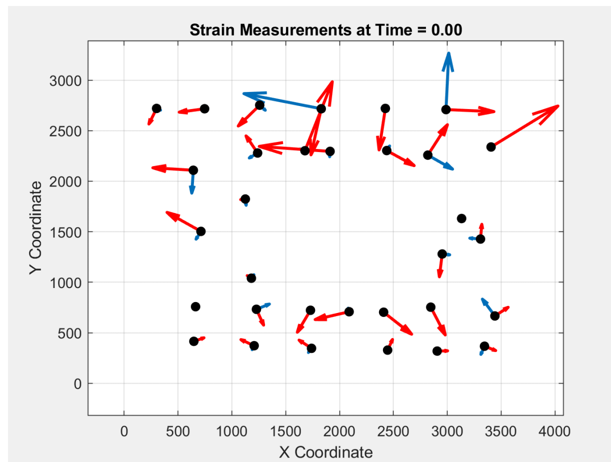


Figure 2.

Additional measurement methods for Component Specific Behavior

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

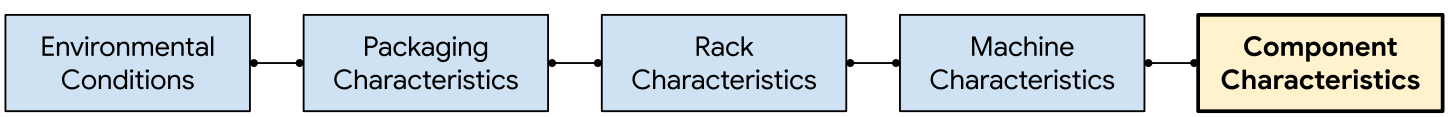


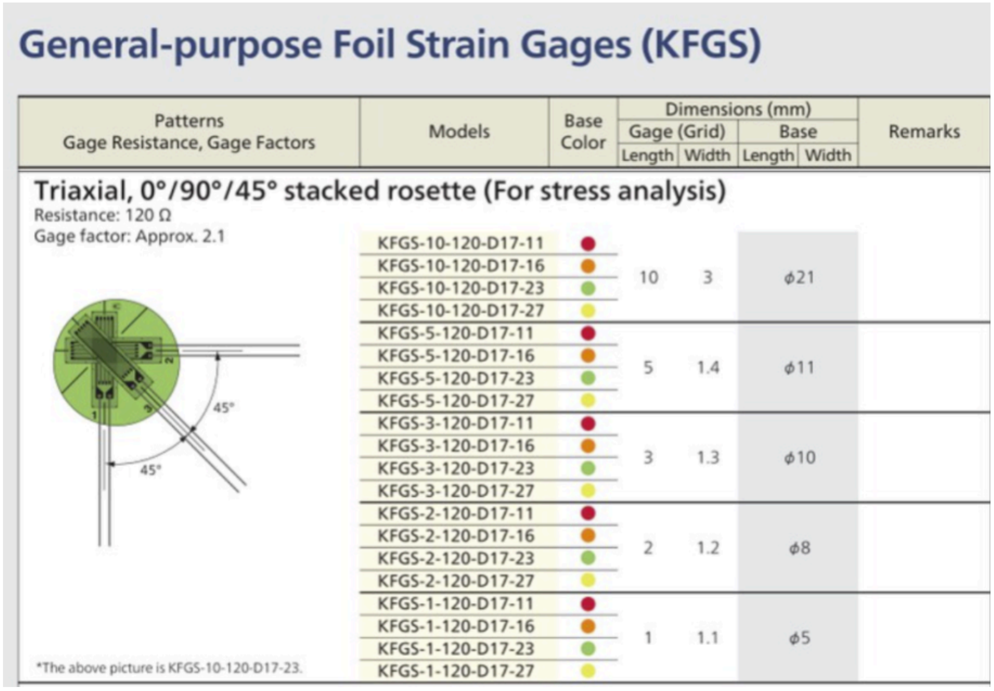
Figure 3.

In Part 4, we discussed how chip packages and BGA solder joints were tested, and how strain gauges were used to measure local strain. That was a specific measurement for a specific workflow. Other components may require other forms of measurement that are better correlated to damages, so we need to continue building up our capabilities.

Strain is generally useful for many kinds of mechanical deformation, so we will spend some time on it. In this paper, we will also cover **High Speed Resistance Measurement** and **High Speed Pressure Measurement**.

High Speed Strain Measurement

Kyowa KFGS series Rosette Strain Gauges [1]



General-purpose Foil Strain Gages (KFGS)

Patterns Gage Resistance, Gage Factors	Models	Base Color	Dimensions (mm) Gage (Grid) Length	Gage (Grid) Width	Base Length	Base Width	Remarks
Triaxial, 0°/90°/45° stacked rosette (For stress analysis) Resistance: 120 Ω Gage factor: Approx. 2.1	KFGS-10-120-D17-11		10	3	φ21		
	KFGS-10-120-D17-16						
	KFGS-10-120-D17-23						
	KFGS-10-120-D17-27						
	KFGS-5-120-D17-11		5	1.4	φ11		
	KFGS-5-120-D17-16						
	KFGS-5-120-D17-23						
	KFGS-5-120-D17-27						
	KFGS-3-120-D17-11		3	1.3	φ10		
	KFGS-3-120-D17-16						
	KFGS-3-120-D17-23						
	KFGS-3-120-D17-27						
	KFGS-2-120-D17-11		2	1.2	φ8		
	KFGS-2-120-D17-16						
	KFGS-2-120-D17-23						
	KFGS-2-120-D17-27						
	KFGS-1-120-D17-11		1	1.1	φ5		
	KFGS-1-120-D17-16						
	KFGS-1-120-D17-23						
*The above picture is KFGS-10-120-D17-23.	KFGS-1-120-D17-27						

Figure 4.

Test Scenario	Sample Speed
Static Deflection, Installation, DIMM Insertion, etc.	Up to 10,000 Hz
Sine Vibration and Random Vibration up to 1000 Hz	10,000 Hz to 100,000 Hz
High Acceleration Shock (2ms or less)	100,000 Hz or Higher

Table 1.

At the time of publication, Intel [2] and JEDEC/IPC guidelines [3] specified up to 2,000 Hz sample rate for strain measurements. Nowadays, it is common to sample at 10 kHz since most strain data acquisition units are capable of such speed at a reasonable price range. When performing high acceleration narrow pulse width shock tests, that number gets raised to 100 kHz due to the sharpness of deformation and high natural frequencies of the critical components (up to thousands of Hz).

We will have a paper in the future that talks about how fast is enough - we are hitting a very real speed limit particularly when 3D DIC is concerned. For strain, it gets difficult to measure much higher than 100 kHz. 1

mHz is available, but the choice of equipment becomes highly limited, which creates challenges for test labs and test teams who have to balance capability with cost considerations.

Sample Principal Strain Data During Sine Vibration, Sampled at 100 kHz

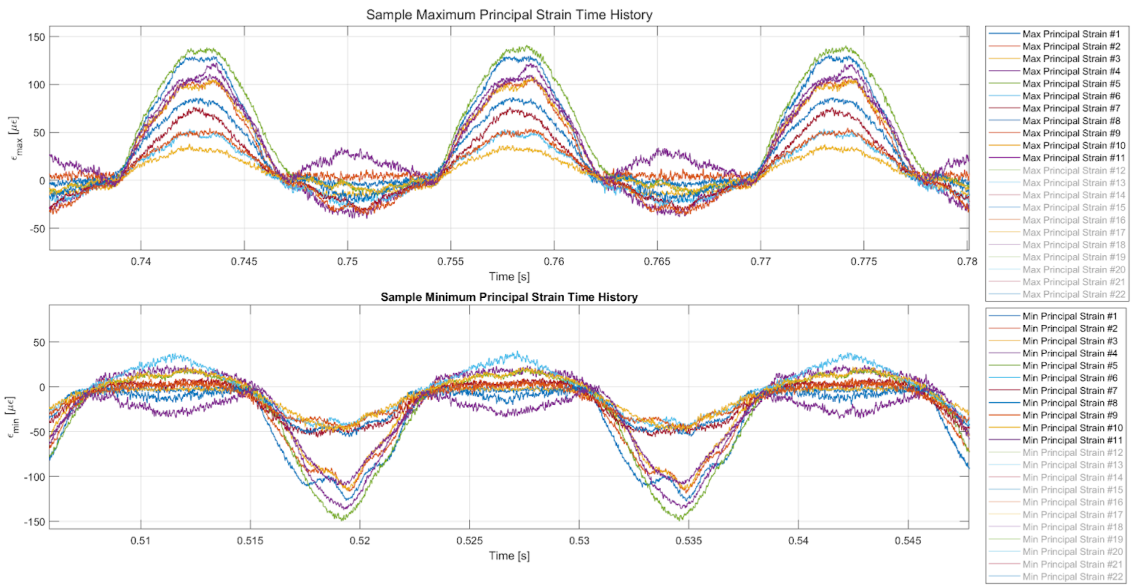


Figure 5.

Once the component behaviors are well established, we can then recommend more cost effective minimal sample rates. For now, 100 kHz provides sufficient smoothness with plenty of room in case shock events occur during random vibration.   Strain data analyzers like Kyowa's EDX-5000A [4] and CDV-40B-F conditioner cards [5] allow up to 32 strain or voltage channels to be recorded simultaneously, with a maximum of 200 kHz sample rate. That rate is reduced to 100 kHz when the number of channels increases to 64.

Kyowa EDX-5000A Data Analyzer and CDV-40B-F Conditioner Card

Figure 6.

Equipment	Specifications
Strain Acquisition: x1 Kyowa EDX-5000A (analyzer), x8 Kyowa CDV-40B-F (conditioner cards)	Up to 200 kHz / 32 channels, 100 kHz / 64 channels, 10 ohm to 1000 ohm, 3 channels per gauge
Strain Gauge: Kyowa KFGS-1-120-D17 Rosette Strain Gauges with RJ45 connectors, Kyowa 33AX5 Adhesive	KFGS model Gage length: 1mm D17: Triaxial gage pattern Resistance: 120ohm Cable length: 3m, 3-wire type + N30C3 Cable end: RJ-45 connector plug
Software: Kyowa DCS-100A [6] and PCAS-200A [7]	Profiles: Shock profiles up to 340G 2ms, and most vibration profiles between 1hz to 1500hz.
Setup Time: 2 hours for application of 32 strain gauges on sample PCB, 2 hours for connection to data acquisition system and software configurations	

Table 2.

When using a high number of channels, strain workflows are more labor intensive than most other measurement workflows. It takes time to prepare, attach, and connect 32 rosette strain gauges. It takes even more time to perform principal strain analysis, export the data, analyze the results, which makes this workflow difficult to scale (for example, compared to accelerometer measurements).

Test Sample with 32 Rosette Strain Gauges

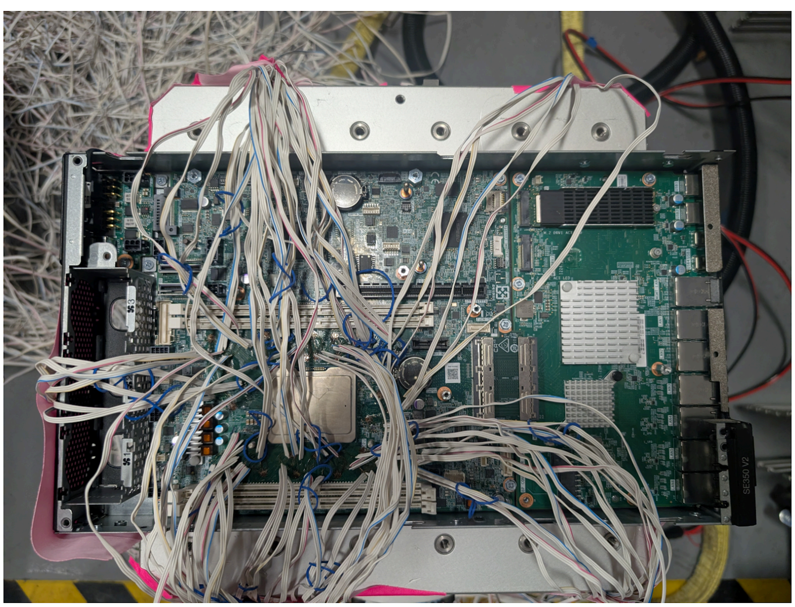


Figure 7.

There are a few additional down sides:

1. Strain measurement is 2D, which means calibration is needed to visualize 3D deformation of the material. Location of the gauge also needs to be exact to compare different samples.
2. Cable management is a real issue in tight spaces when large amounts of sensors are needed (4 rosette strain gauge per chip package or critical component means 12 wires to secure).
3. The sensor is not reusable, which adds to the cost of testing.
4. Post processing takes time due to the large amount of data captured.

The data, when measured properly, is very good. The scale, precision, and accuracy of strain gauges is exactly what's needed for electronics components in shock and vibration scenarios. (Imagine how much work and resources it took to zero in on the exact type and size of strain gauges needed for PCB measurements).

There are a few other positive aspects as well:

1. The data is relative to board deflection, so there is no need to worry about translation or rotational movement of the whole unit.
2. Strain gauges can be attached inside the unit, so data can be captured during scenarios where the instrumented location is not easily visible.
3. Strain can be correlated directly with stress and damage.
4. Robust workflow has already been developed for the correlation of strain with FEA models.

Sample Principal Strain Plotted With Sensor Coordinates and Direction of Sample Unit in Figure 7.

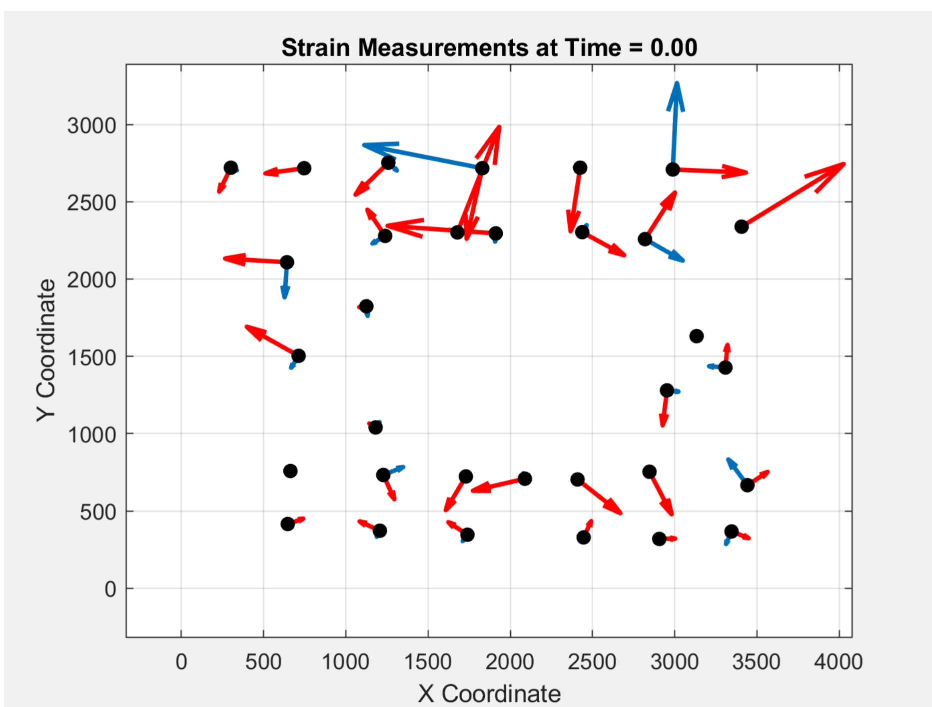


Figure 8.

High Speed Resistance Measurement

Left: Example PCB and PBGA Detachment After Drop Impact
Right: Dynamic Strain and Resistance Measurement During Shock Testing

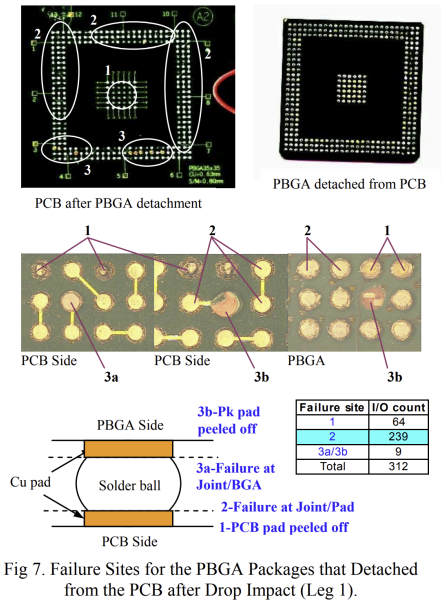


Figure 9.

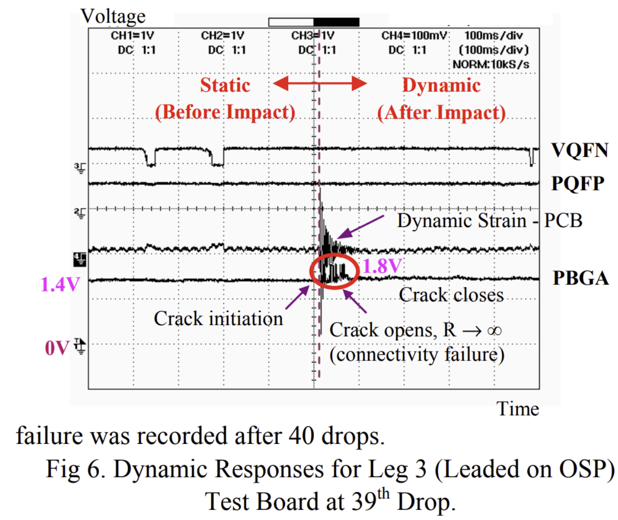
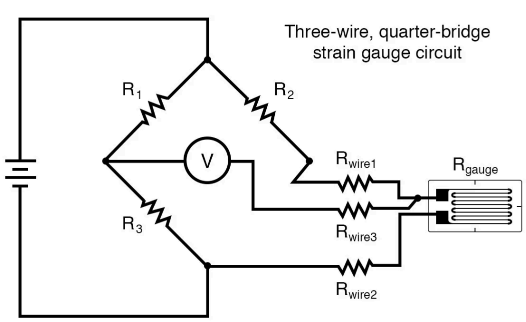


Figure 10.

Many papers are written on the reliability of BGA solder joints against thermal and mechanical shock. Many describe resistant measurement as a means to detect solder joint fracture during testing. An example paper [8] described putting a DC voltage supply and a resistor in series with the circuit so that voltage drop across the circuit can be measured to calculate dynamic resistance. We built a similar setup by taking advantage of capabilities already built into Kyowa's Strain Data Analyzer.

Left: Sample Quarter-Bridge Strain Gauge Circuit
Right: Google's Shock and Vibration 4-wire Resistance Measurement Circuit



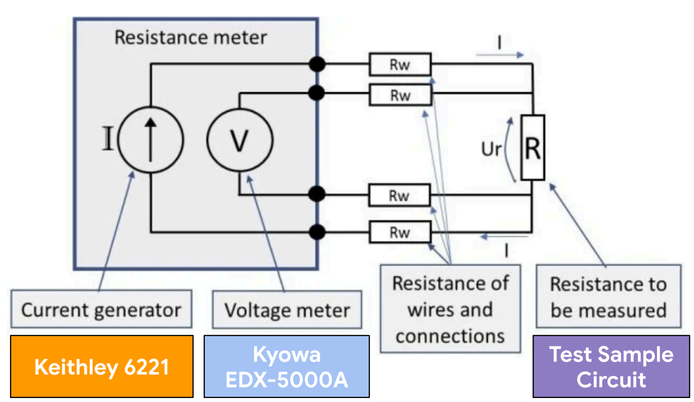


Figure 11.

Figure 12.

Strain gauges are measured using a quarter-bridge circuit like ones shown in figure 9. When materials deform, strain gauges' resistance change, which causes an imbalance in the Wheatstone bridge. This imbalance creates a small output voltage that is proportional to the applied strain. With correct calibration, this output voltage can be amplified and measured to determine the amount of strain experienced by the test sample.

We took advantage of Kyowa EDX-5000A's high channel count, accuracy, and sample rate, and turned additional channels into individual high speed resistance measurement setups. Here is how it works. A DC current generator is put in series with the test circuit. The EDX-5000A voltage acts as a volt meter, which allows us to calculate dynamic resistance through the circuit using the following formula:

Dynamic Resistance (ohm) = Measured Voltage (volt) / Input Current (amp)

Everything is recorded using the same data analyzer, all the data (strain and voltage) are saved into the same file, and that makes the test setup and post processing a lot easier.

The sample rate is not as high as an oscilloscope, but the channel count and ease of use far outweighs the cost and effort needed to integrate a large number of oscilloscopes into the test setup. 100 kHz is also plenty for the type of fracture circuit boards typically experienced during transportation and handling shock and vibration conditions.

BGA Solder Joint Fracture During Shock Testing,
and Dynamic Resistance Measurement Sampled at 100 kHz

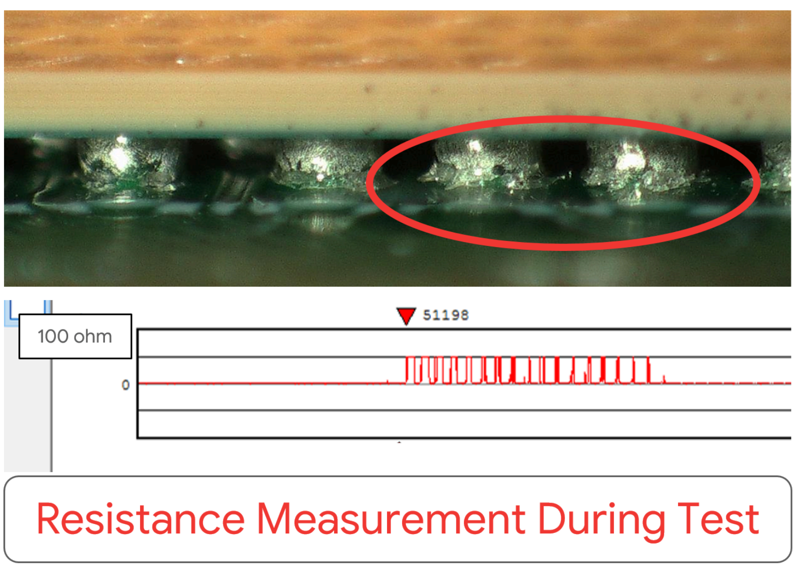


Figure 13.

Kyowa CDV-40B-F Conditioner Card Specifications

●Standard conditioner cards specifications

■Strain/Voltage Measurement Card CDV-40B*, CDV-40B-F

For measuring both strain (Strain gages and strain-gage transducers) and voltage (Model with antialiasing LPF is the CDV-40B-F.)
*Models with output are available, inquires are welcome.

Items	Strain	Voltage
Measuring Targets	Strain gages, strain-gage transducers	Voltage
Channels	8	
Input Modes	Balanced differential	Unbalanced
Input Resistance	Within (10 MΩ + 10 MΩ) ±10%	Within 1 MΩ±10%
Coupling	DC/AC	
Frequency Response	DC coupling: DC to 50 kHz, deviation: 1 to -3 dB AC coupling (DC cut): 0.2, 1 Hz to 50 kHz (See the HPF)	
Gage Factor	2.00 fixed	—
Bridge Excitation	2 VDC ±2%	—
Compatible Bridge Resistance	120 to 1k Ω	—
Balance Adjustment Range	±2.4% or more (±12000 ×10⁻⁶ strain)	—
Balance Adjustment Method	Auto balance Accuracy: Within ±(0.1%FS +2×10⁻⁶ strain)	—
Measuring Range	500, 1 k, 2 k, 5 k, 10 k, 20 k, 50 k [×10⁻⁶ strain], OFF	0.1, 0.2, 0.5, 1, 2, 5, 10 V, OFF
Range Accuracy	±0.2% FS, each range ±100%, ±50%, each range	
Calibration	Accuracy: Within ±0.3%FS	
Nonlinearity	Within ±0.1% FS	
LPF	Transfer characteristics: 2nd order Butterworth Cutoff frequencies: 8 steps of 10, 30, 100, 300, 1 k, 3 k, 10 k [Hz] and FLAT Amplitude ratio at cutoff point: -3±1dB Attenuation: (-12±1) dB/oct.	
HPF (DC cut)	Cutoff frequencies: 0.2, 1 Hz Attenuation: -6 dB/oct.	
Antialiasing LFP (CDV-40B-F only)	The LPF setting on the DCS-100A:AUTO Transfer characteristics: 8th order Butterworth Cutoff frequencies: Automatically set at sampling frequencies × 0.25 Attenuation: -48 dB±5 dB (At sampling frequency ×0.5) Note: Enabled when the sampling frequency 100 HZ or more	
AD Converter	16 bits	
Sampling Frequency	200kHz (MAX)	
Compliance	Directive 2014/30/EU (EMC) Directive 2011/65/EU, (EU)2015/863 (10 restricted substances) (RoHS)	

Figure 14.

One important part of the setup is the DC current source, which has to be fast enough to respond to changes of resistance during shock and vibration. High amplitude shock testing could subject a test sample to shock pulse width as short as 2.0 to 0.5 milliseconds. If the current supply's internal circuitry doesn't adapt quickly, it is possible for the shock event to be missed entirely (in terms of resistance measurement).

I once built a test setup using more conventional current sources, and was not able to measure any resistance change even though solder joints were ripped apart during high G shock testing (fractures were visible in the cross sectioning results afterward). I was able to improve the setup and capture the data correctly by using Keithley's 6221 Ultra-sensitive Current Source [9], which has a settling time as low as 2 microsecond.

Keithley Ultra-sensitive Current Sources Series 6200

Figure 15.

Keithley 6220 & 6221 DC Current Source Specifications

Source Specifications

					6221 Only		Settling Time [1, 2] (1% of Final Value)	
Range (+5% over range)	Accuracy (1 Year) 23°C ±5°C ±(% rdg. + amps)	Programming Resolution	Temperature Coefficient/°C 0°–18°C & 28°–50°C	Typical Noise (peak-peak)/RMS [3] 0.1Hz–10Hz	Typical Noise (peak-peak)/RMS [3] 10Hz–(Bw)	Output Response Bandwidth (BW) Into Short	Output Response Fast (Typical[3]) (6221 Only)	6220, 6221 with Output Response Slow (Max.)
2 nA	0.4 % + 2 pA	100 fA	0.02 % + 200 fA	400 / 80 fA	250 / 50 pA	10kHz	90 µs	100 µs
20 nA	0.3 % + 10 pA	1 pA	0.02 % + 200 fA	4 / 0.8 pA	250 / 50 pA	10kHz	90 µs	100 µs
200 nA	0.3 % + 100 pA	10 pA	0.02 % + 2 pA	20 / 4 pA	2.5 / 0.5 nA	100kHz	30 µs	100 µs
2 µA	0.1 % + 1 nA	100 pA	0.01 % + 20 pA	200 / 40 pA	25 / 5.0 nA	1MHz	4 µs	100 µs
20 µA	0.05% + 10 nA	1 nA	0.005% + 200 pA	2 / 0.4 nA	500 / 100 nA	1MHz	2 µs	100 µs
200 µA	0.05% + 100 nA	10 nA	0.005% + 2 nA	20 / 4 nA	1.0 / 0.2 µA	1MHz	2 µs	100 µs
2 mA	0.05% + 1 µA	100 nA	0.005% + 20 nA	200 / 40 nA	5.0 / 1 µA	1MHz	2 µs	100 µs
20 mA	0.05% + 10 µA	1 µA	0.005% + 200 nA	2 / 0.4 µA	20 / 4.0 µA	1MHz	2 µs	100 µs
100 mA	0.1 % + 50 µA	10 µA	0.01 % + 2 µA	10 / 2 µA	100 / 20 µA	1MHz	3 µs	100 µs

Figure 16.

With the EDX-5000A and 8 CDV-40B-F conditioner cards, I was able to use 48 strain channels to measure 16 rosette strain gauges in a test unit, and 16 voltage channels to measure resistance through the unit's test circuits. The number of voltage channels allow me to monitor smaller segments within the test circuit and pin point the precise locations of damages during testing. Without them, repeated testing is needed to determine the exact location of failure.

High Speed Pressure Measurement

Test Sample with Thin Film Pressure Mapping Sensor Between CPU and Heatsink

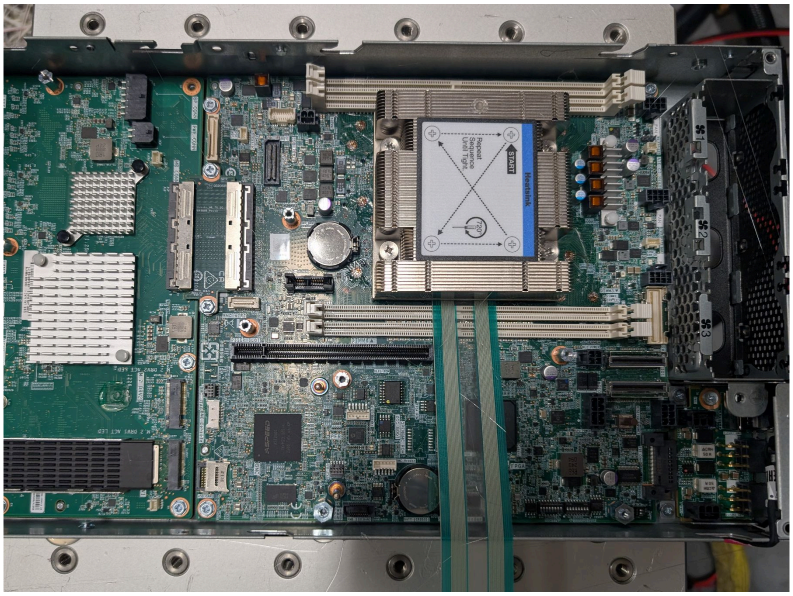


Figure 17.

Heatsinks, particular ones in large GPU servers, drive the dynamic behavior of the machine's PCB. When the unit is subjected to shock and vibration, stress concentrations are often found at the chip package, chip socket, BGA solder joints, and thermal interface material underneath the heatsink. Heatsinks are critical to the performance of the machine, and are critical points of failure themselves.

Example Pressure Measurement of Test Sample Showing Slight
Change of Shape During 64 Hz Sine Dwell, 375 Frames Per Second

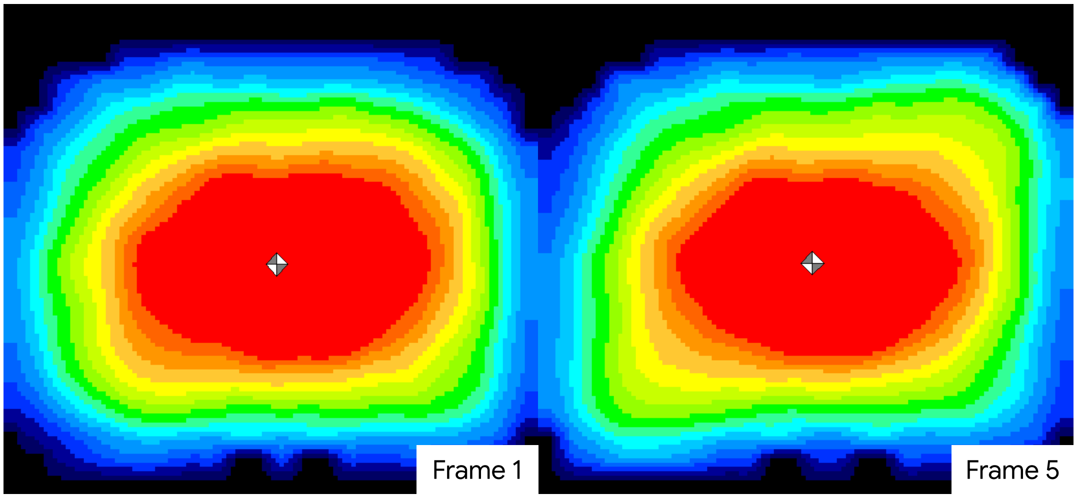


Figure 18.

One way to evaluate stress underneath a heatsink is by using thin film pressure mapping sensors such as ones provided by Tekscan. When inserted between the heatsink and the CPU, these pressure sensors provide data that quantify the quality of contact between the two mating surfaces. During shock and vibration testing, these sensors show exactly how the heatsink moves relative to the CPU underneath.

Left: Tekscan I-Scan Specifications, Right: Tekscan 4205 Sensor

Model Option	**Evolution (Standard USB)**	**VersaTek (High Speed USB)**
Data Acquisition Electronics	Evolution Handle »	VersaTek Handle » VersaTek Hub »
I-Scan Software Compatibility	I-Scan 9 and below	I-Scan 9 and below
Maximum Scanning Speed	100 Hz	20,000 Hz
Cross Handle Scanning	No	Up to 8
Pulse-Per-Frame Synchronization	No	in & out
Adjustable Sensitivity	x 3 to 1/7 of Sensor Pressure Rating	x 7 to 1/3 of Sensor Pressure Rating

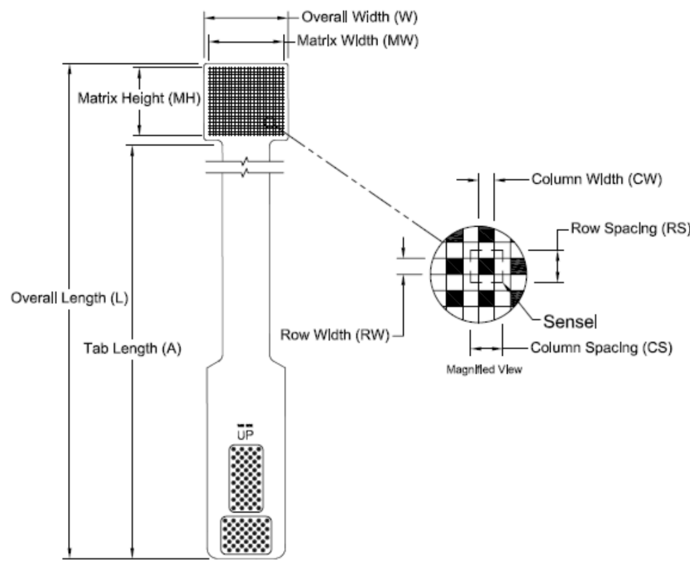


Figure 19.

Figure 20.

Tekscan's I-Scan system [10] samples up to 20,000 Hz depending on the size and density of the sensor being used. Ones able to cover the full size of CPU or GPU, such as Tekscan's 4205 thin film pressure mapping sensor [11], typically sample between 300 Hz to 500 Hz, unless you find ways around it (using smaller sensors or multiple sensors at the same time).

500 Hz is good enough for random vibration since large PCB movement occurs under 100 Hz, but it is slow for shock impacts (strain gauges around chip packages are typically sampled with at least 2,000 Hz). Still, the measurement provides some useful information if you consider the fact that most heatsinks are spring loaded and do not typically experience the sudden movement that occurs at the component and solder joint level.

Equipment	Specifications
Pressure Measurement Equipment: Tekscan I-Scan VersaTek Handles and Hub, up to 8 handles total	Sample Rate: Typically between 300 Hz to 700 Hz sample rate for sensors large enough for CPUs and GPUs Duration: Data can be recorded for a very long time so it is typically not an issue

Thin Film Pressure Mapping Sensor: Tekscan 4205 Sensor, up to 8 sensors total	Matrix Height: 1.65 inch Matrix Width: 1.80 inch Thickness: 0.007 inch Row Quantity: 22 Column Quantity: 24 Number of Points: 528 Max Pressure: 300 PSI

Table 3.

Example Pressure Measurements of Test Sample, Free Fall Drop, 3 Inches

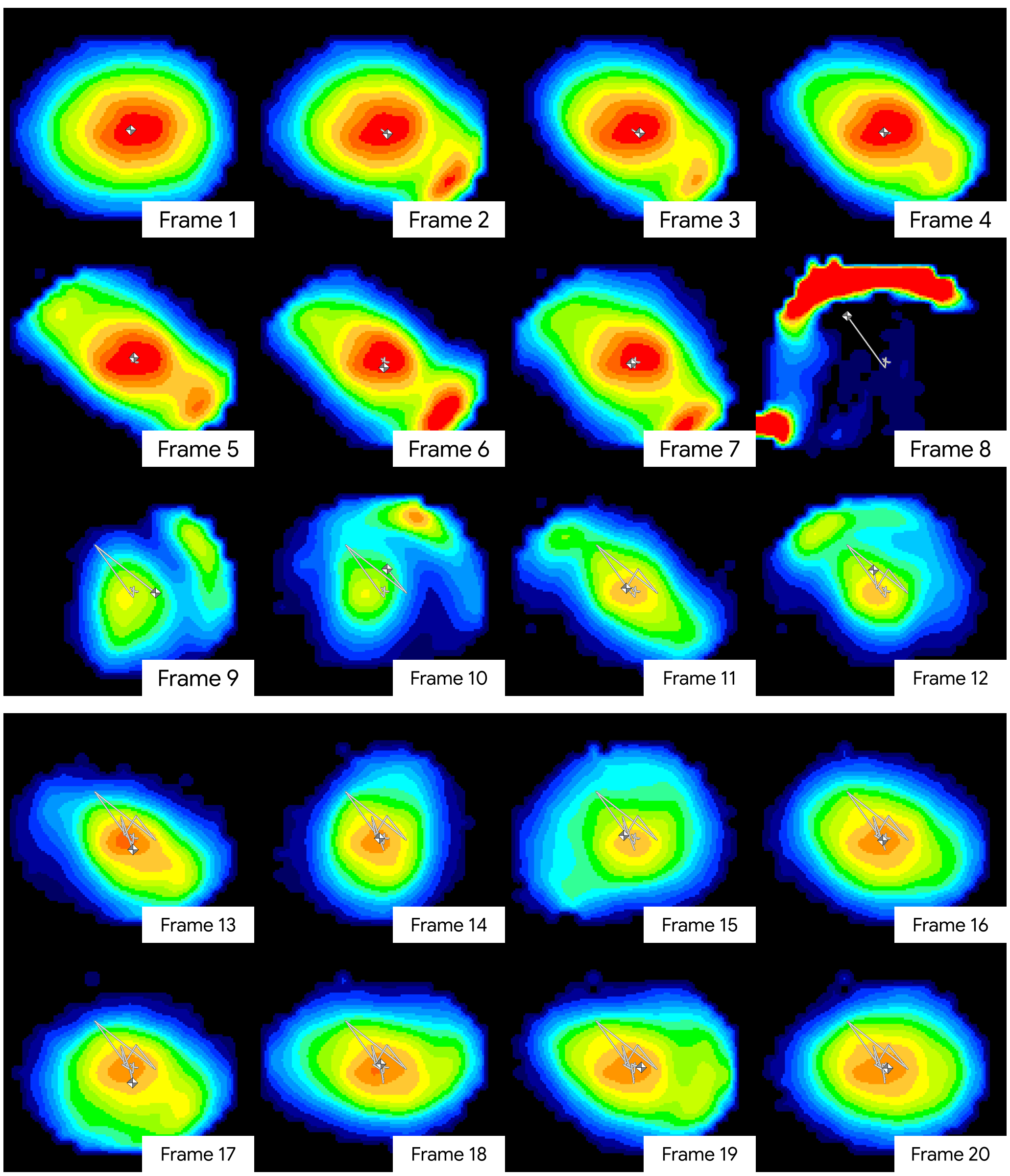


Figure 21.

In the above example, it is easy to see change of contact pressure from frame #1 to 7. Contact pressure becomes very different suddenly in frame #8 - the heatsink likely got tilted to one side where the pressure is concentrated, then slowly recovers by frame #20. We didn't get the complete story, but this is enough to tell, for this level of shock impact, the spring force wasn't enough to keep the heatsink in contact with the CPU.

<u>Reference</u>

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