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Comparative Failure Analysis of Components Exposed to Multi-Axis & Single-Axis Vibration Testing

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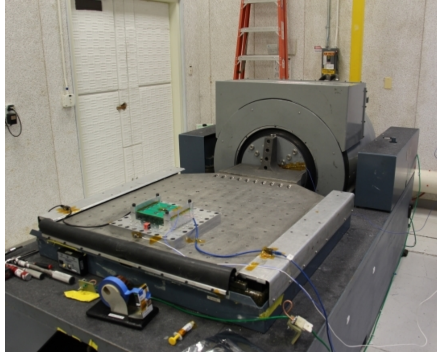
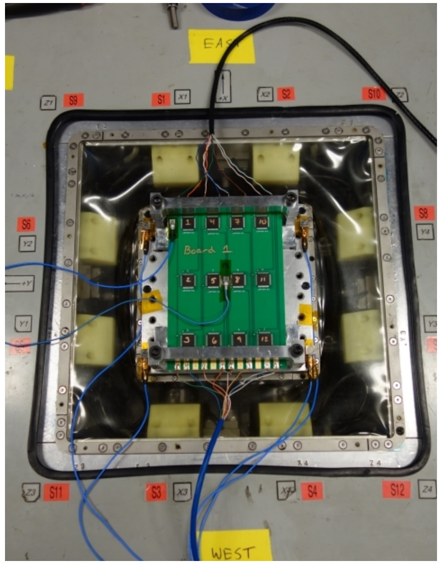
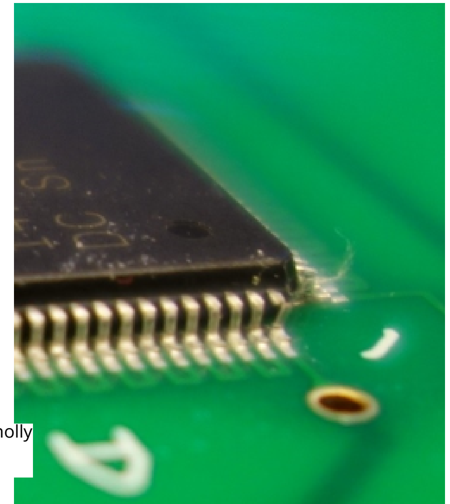
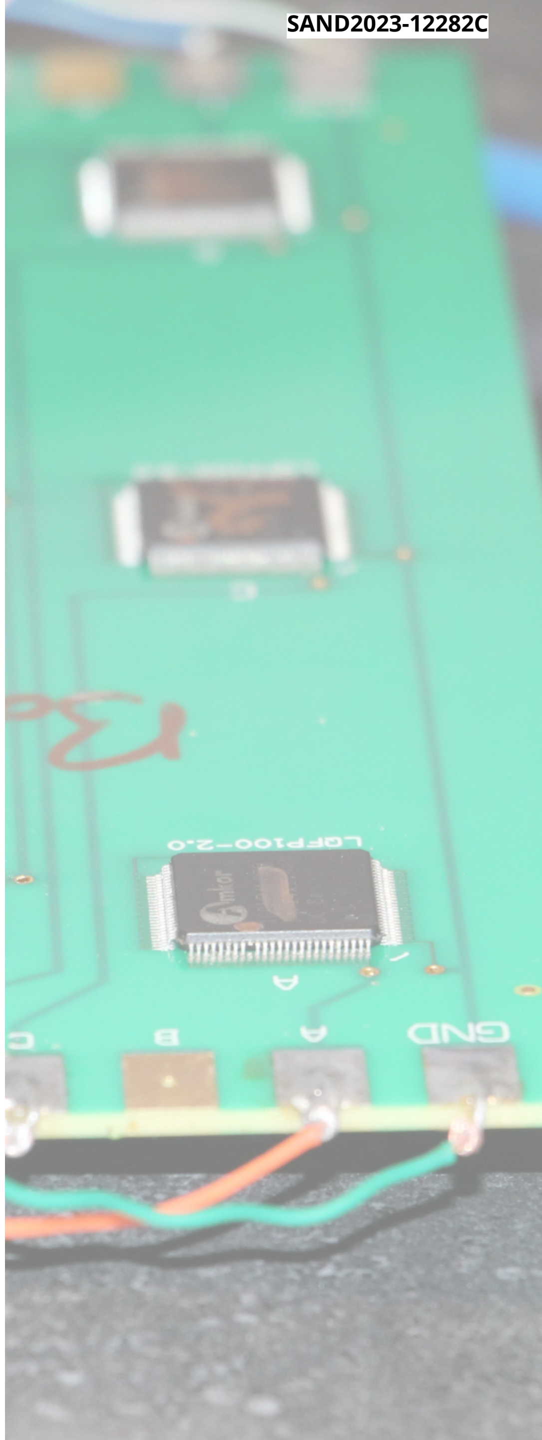
IMAC 2023









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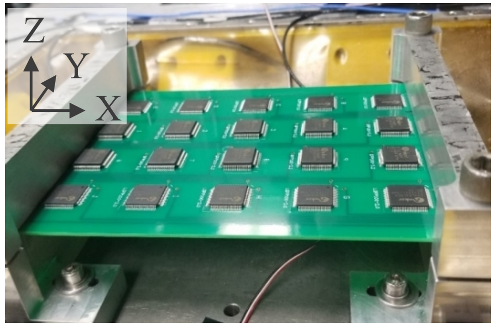
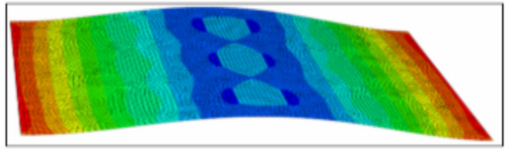
Motivation & Background

- Dynamic field environment may not be represented well by a single-axis shaker test
  - System component boundary conditions and impedances are ignored
  - Laboratory testing may contain different boundary conditions
- Evidence of difference in fatigue life and failure modes when comparing multiple-degree-of-freedom (MDOF) and single-degree-of-freedom (SDOF) testing *(Gregory, D., Bitsie, F., Smallwood, D.O.)*
- Aim to understand how MDOF and SDOF testing affect component time to failure (TTF)
- Different internal boundary conditions of a SDOF shaker and MDOF shaker
  - SDOF: other five degrees of freedom are constrained
  - MDOF: allows the armature to move unconstrained in the other degrees of freedom

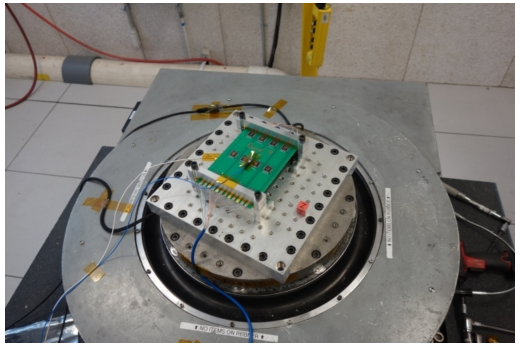
Testing Approach

- Initial testing began at KCNSC and the University of Maryland
  - TE6-900 shaker with X and Z excitation
  - Similar printed wiring assembly (PWA) board in a clamped-clamped fixture
- Testing on both **UD T1000 (1DoF)** shakers and **TE6-900 (6DoF)** shaker
  - Single-axis excitation on T1000 *(1DoF)*
  - Single-axis excitation on TE6-900 *(6DoF, unconstrained translation/rotation)*
  - Tri-axis excitation on TE6-900 *(6DoF, unconstrained rotation)*
- Frequency ranges:
  - 100-400 Hz
  - 100-2000 Hz
- 5 g_{RMS} per axis

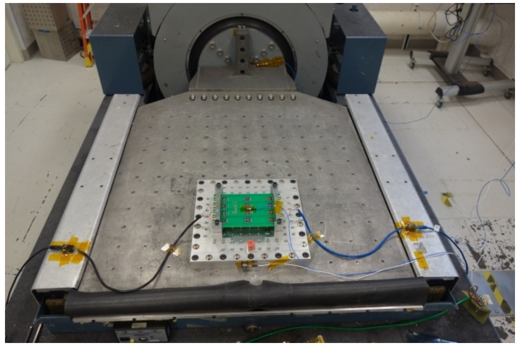




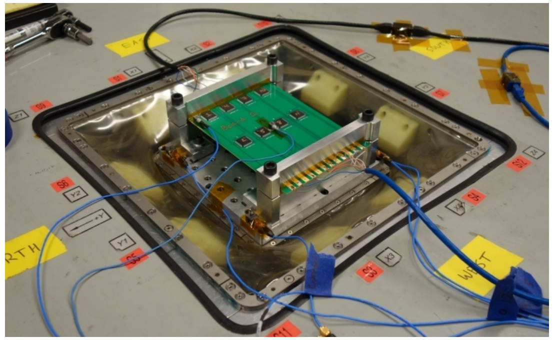
FEA model and PWA board from KCNSC



UD T1000 (Z-axis excitation tests)



UD T1000 (slip table, X and Y-axis excitation tests)



Team Tensor TE6-900

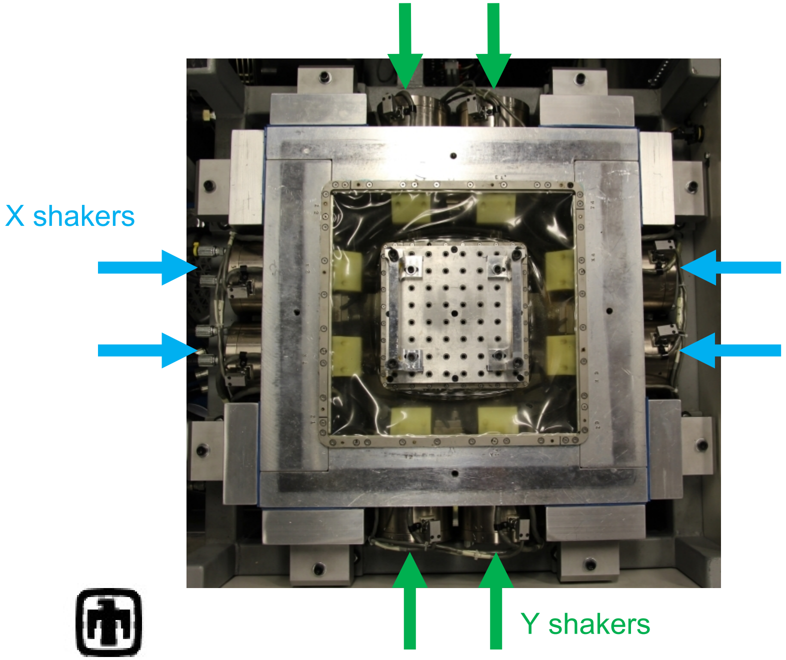
6DoF TE6-900 Shaker Setup

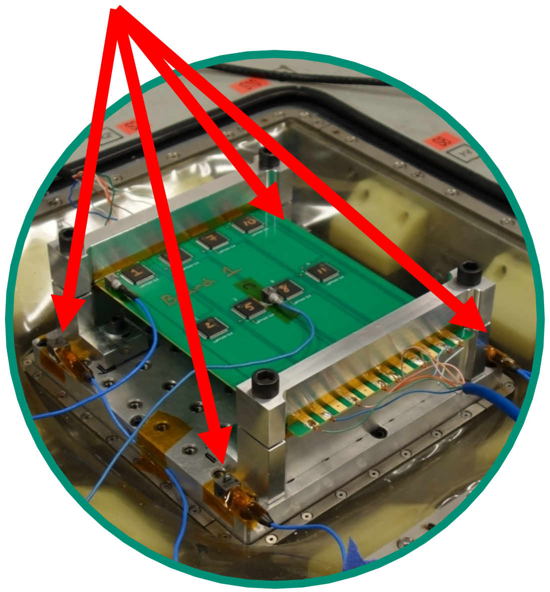
Hardware

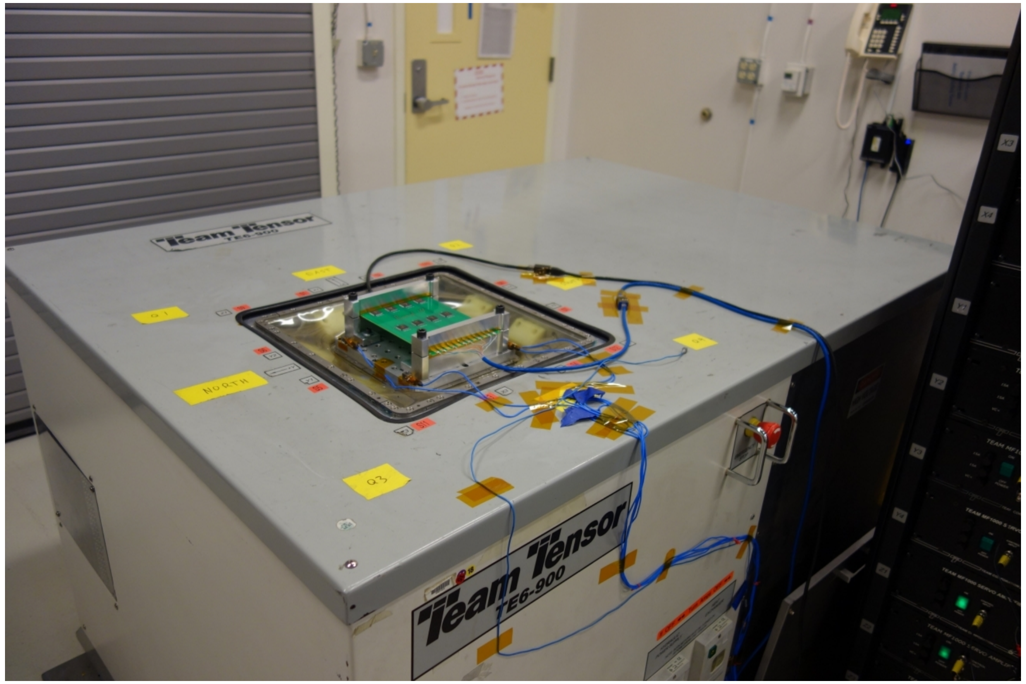
- Team Tensor TE6-900
- National Instruments PXIe Chassis
  - Accelerometer input
  - Drive voltage output
- Tri-axis base control accelerometers on corners of table

NI Chassis

Amplifier rack

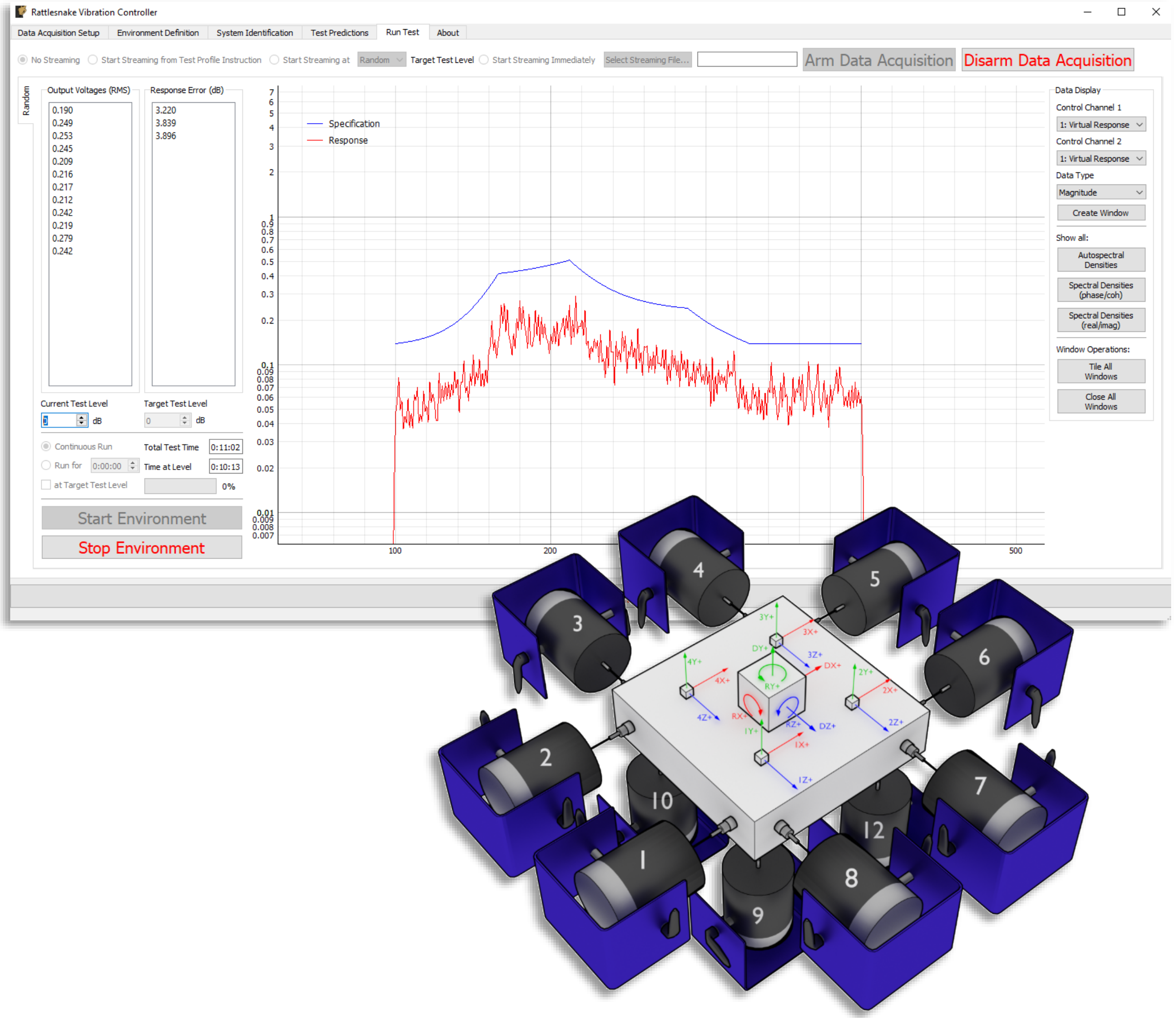






Team Tensor TE6-900

Shaker Software Setup



Rattlesnake Vibration Controller

- Python based multi-input-multi-output (MIMO) controller
- Interfaces with NI DAQmx (also LAN-XI)
- Developed at SNL-NM by D. Rohe, et al.
- Source code available on GitHub
  - https://github.com/sandialabs/rattlesnake-vibration-controller

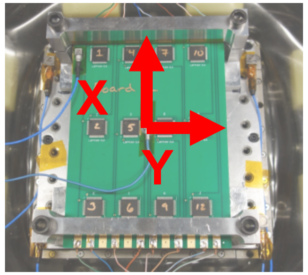
Usage

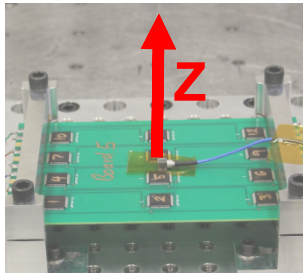
- MIMO Random Environment
- 12 accelerometer input channels
  - 3 additional channels from board-mounted accelerometer (used for pre and post-test workmanship)
- 12 drive voltage output channels

T1000 tests run using Spectral Dynamics

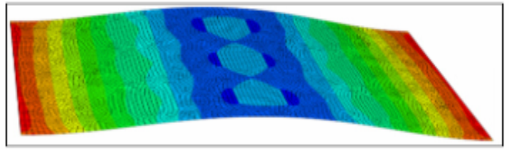
Determining Test Specifications

- Aiming to achieve failure with a reasonable test duration
- Ran a series of buzz tests
  - Operational modal analysis
  - X, Y, Z, and XYZ
  - 100-2000 Hz, 1.4 g_{RMS} per axis
- Used buzz test response to identify modal frequencies
- Constructed an envelope to target those modes
  - Two specs, 100-400 Hz and 100-2000 Hz
  - Each spec scaled to 5 g_{RMS}

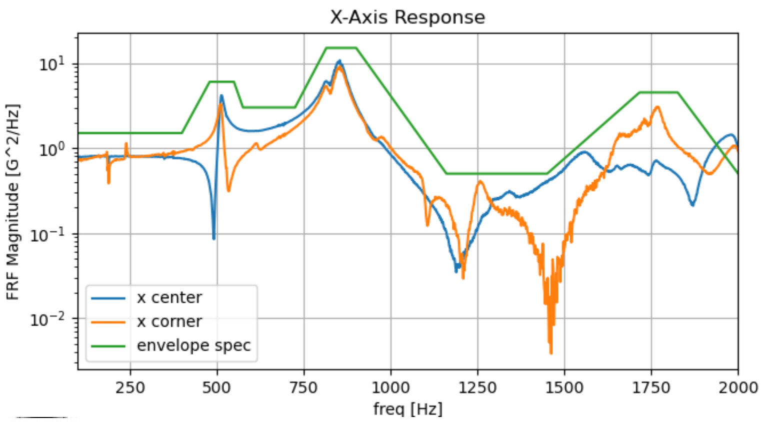


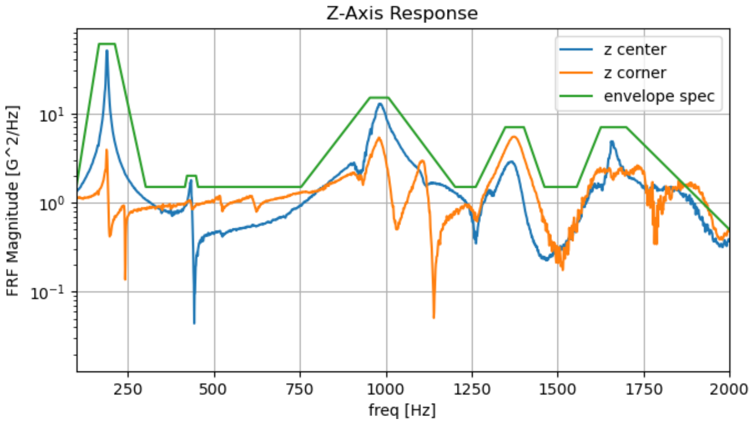


Mode Frequencies		
X	Y	Z
500 Hz	240 Hz	190 Hz
850 Hz	1100 Hz	980 Hz
1760 Hz	1780 Hz	1370 Hz



190 Hz bending mode





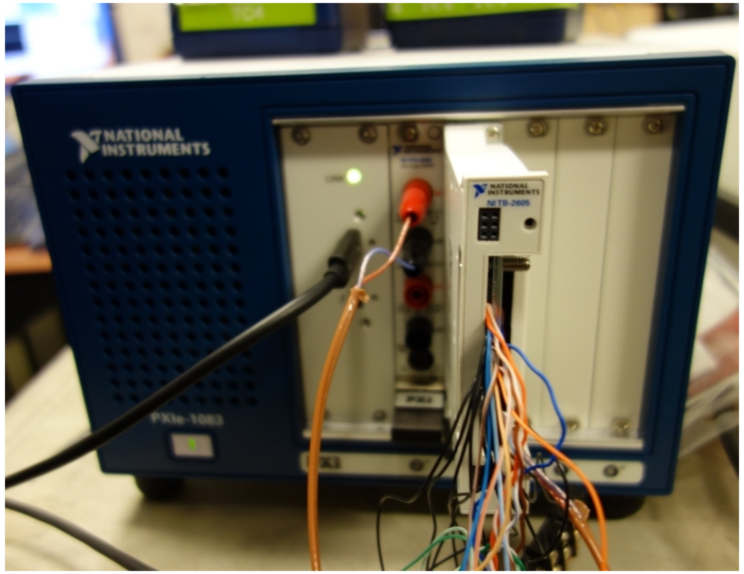
PWA Board Data Acquisition

Software

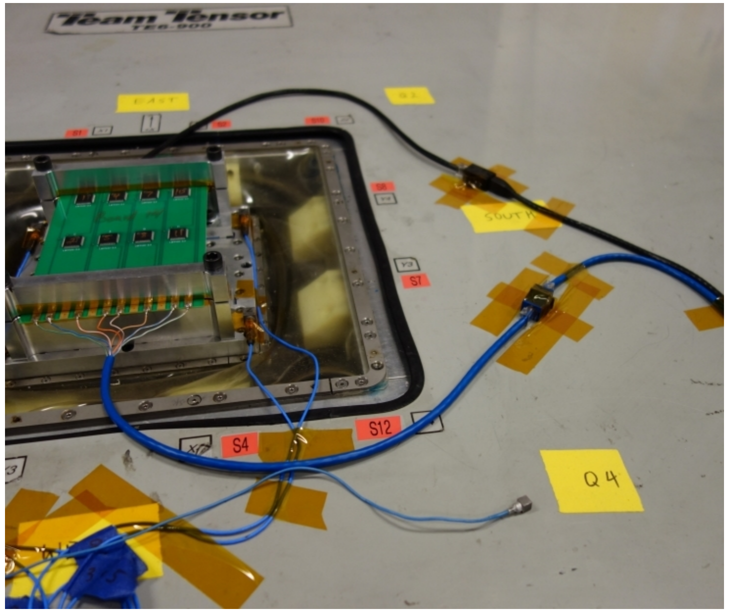
- MATLAB control script
- Measures resistance of each chip to determine failure
- Switches sequentially between 12 chips on PWA board

Hardware

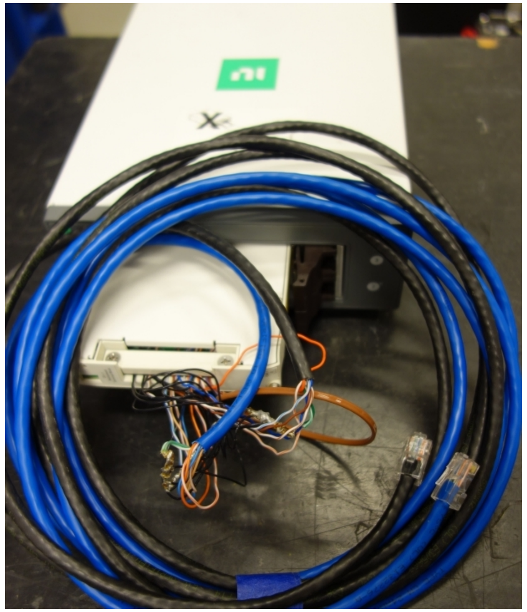
- Ethernet cabling from switch to PWA boards
- Ethernet strands soldered to contact pads
- National Instruments chassis
  - Switch – mechanical relay array
  - DMM – 2-wire resistance measurements
- Chips numbered 1-12



NI Chassis w/ switch & DMM

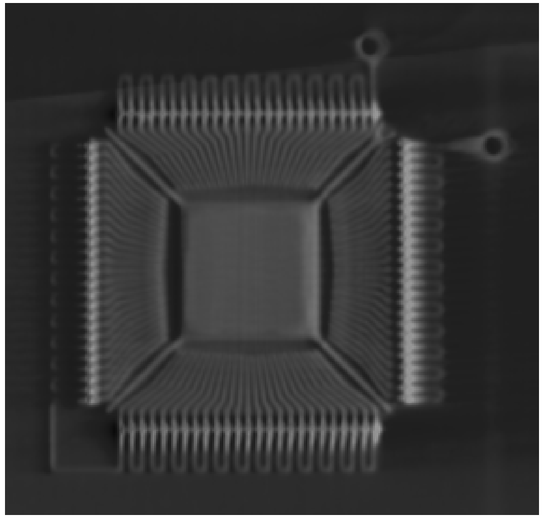


Ethernet connections from board to chassis

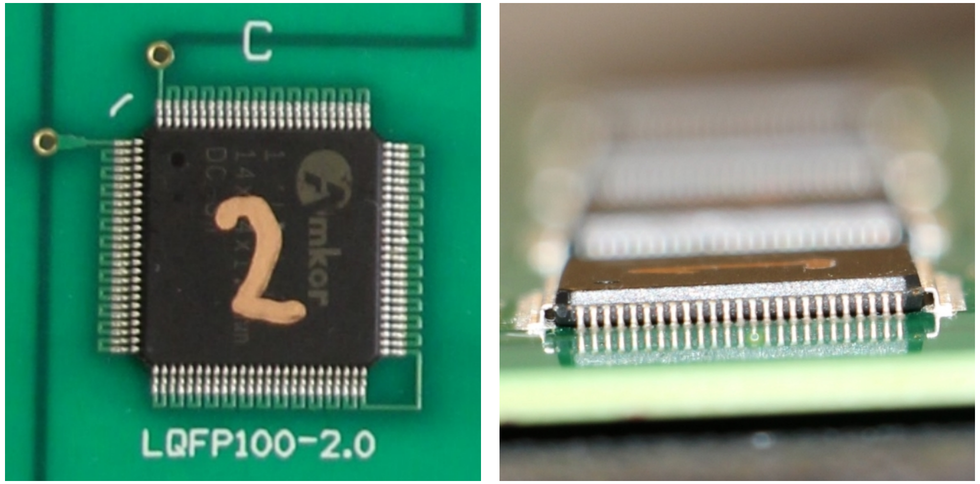

2nd NI Chassis w/ switch & DMM

Failure Criteria

- Observations during initial testing
  - Resistances fluctuate as chips begin to fail
    - Often return to nominal resistance even after failed readings begin to show
  - Resistance trends upward until stabilizing at a much higher reading or breaking continuity
- Resistance readings captured by data recorder dependent on length of ethernet cable
- Resistance increase indicative of chip failure
  - 100% change in nominal resistance (≈ 2.2 Ω) constitutes a failed reading
  - 20 consecutive failed readings constitutes a chip failure



CT scan of a single chip



top and side profile

Completed Tests

- Certain test series abandoned following early testing
  - SDOF X-axis and Y-axis tests produced no failures
  - 100-2000 Hz tests ran upward of 6 hours
  - *Neither test series was used in further analysis due to limited data*
- Three specifications were prioritized for further testing
  - Z-axis, 100-400 Hz, T1000
  - Z-axis, 100-400 Hz, TE6-900
  - XYZ-axes, 100-400 Hz, TE6-900
- Workmanship test conducted before and after each test
  - Accelerometer in the center of the board*
  - Check for changes in frequency response

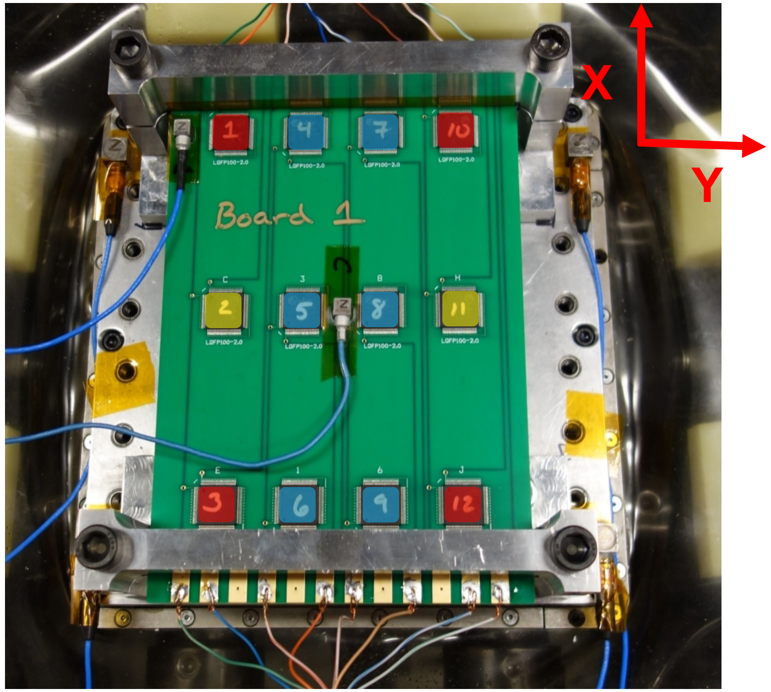
  *removed during time-to-failure test

Axes	Levels	Frequency	Shaker	Duration (minutes)
Z	5 g_{RMS}	100-400 Hz	T1000	31
Z	5 g_{RMS}	100-400 Hz	T1000	27
Z	5 g_{RMS}	100-400 Hz	T1000	24
Z	5 g_{RMS}	100-400 Hz	TE6-900	26
Z	5 g_{RMS}	100-400 Hz	TE6-900	39
Z	5 g_{RMS}	100-400 Hz	TE6-900	31
Z	5 g_{RMS}	100-400 Hz	TE6-900	28
Z	5 g_{RMS}	100-400 Hz	TE6-900	25
Z	5 g_{RMS}	100-400 Hz	TE6-900	28
Z	5 g_{RMS}	100-400 Hz	TE6-900	33
XYZ	5 g_{RMS}	100-400 Hz	TE6-900	52
XYZ	5 g_{RMS}	100-400 Hz	TE6-900	32
XYZ	5 g_{RMS}	100-400 Hz	TE6-900	52
XYZ	5 g_{RMS}	100-400 Hz	TE6-900	47
XYZ	5 g_{RMS}	100-400 Hz	TE6-900	31
XYZ	5 g_{RMS}	100-400 Hz	TE6-900	26
XYZ	5 g_{RMS}	100-400 Hz	TE6-900	29
XYZ	5 g_{RMS}	100-400 Hz	TE6-900	33
XYZ	5 g_{RMS}	100-400 Hz	TE6-900	32

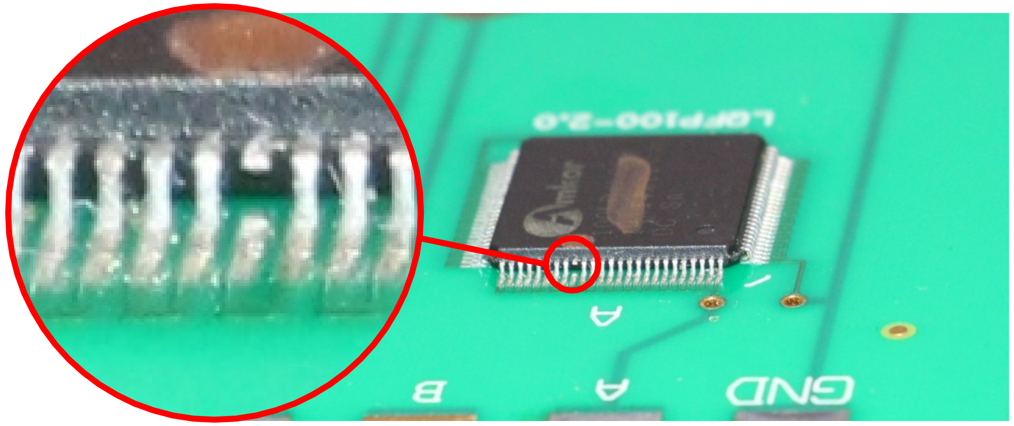
Showing only tests included in analysis, duration refers to the time of the last chip failure

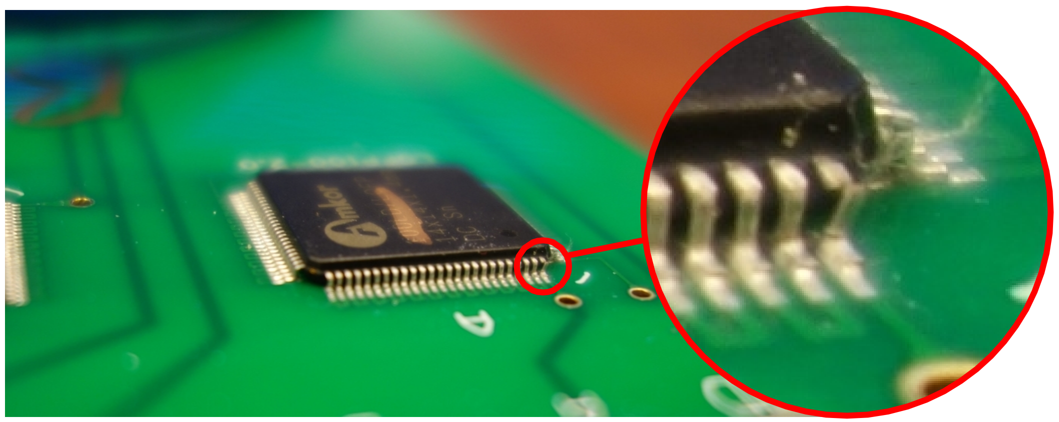
Chip Failure Observations

- Chip leads fatigue over the course of a few minutes
- Resistance readings fluctuate and trend upward
  - Some stabilize in the kΩ or MΩ range
  - Many lose continuity entirely
- Leads fail along edges parallel to clamps
- X-axis and Y-axis tests produce no failures

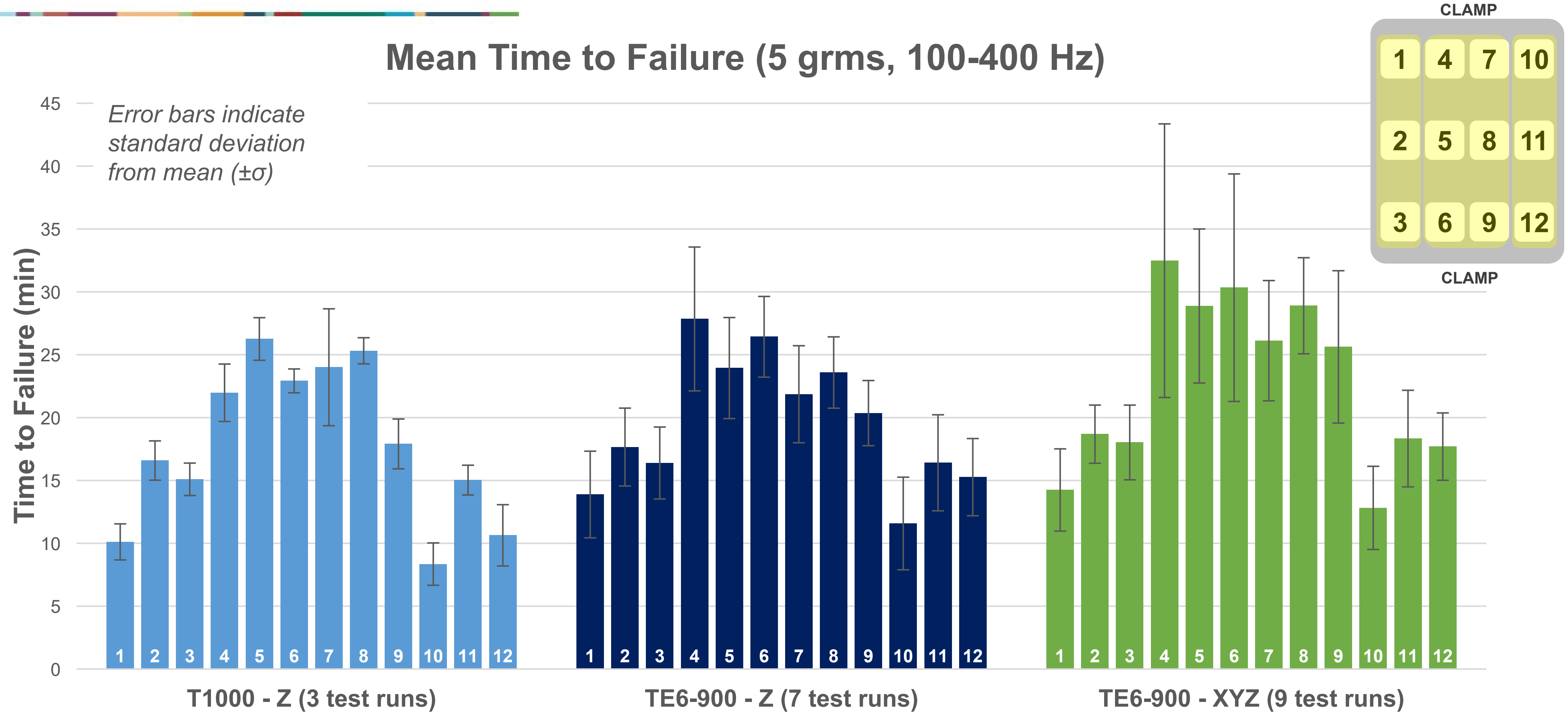


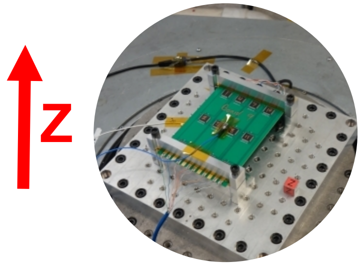
First group to fail
Second group to fail
Third group to fail

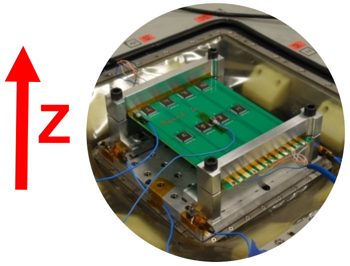


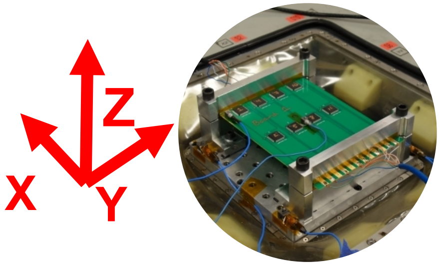


Test Results – Mean Time to Failure



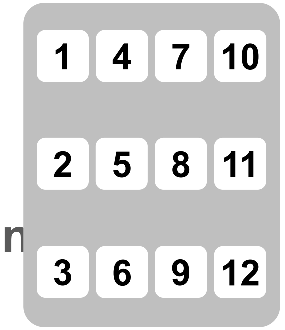




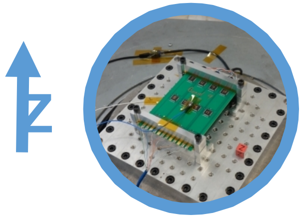


Red axis labels indicate excitation axes for each test series

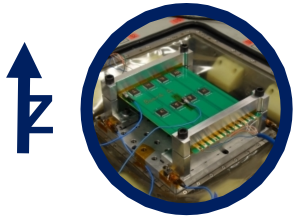
Test Results – T1000 vs TE6-900



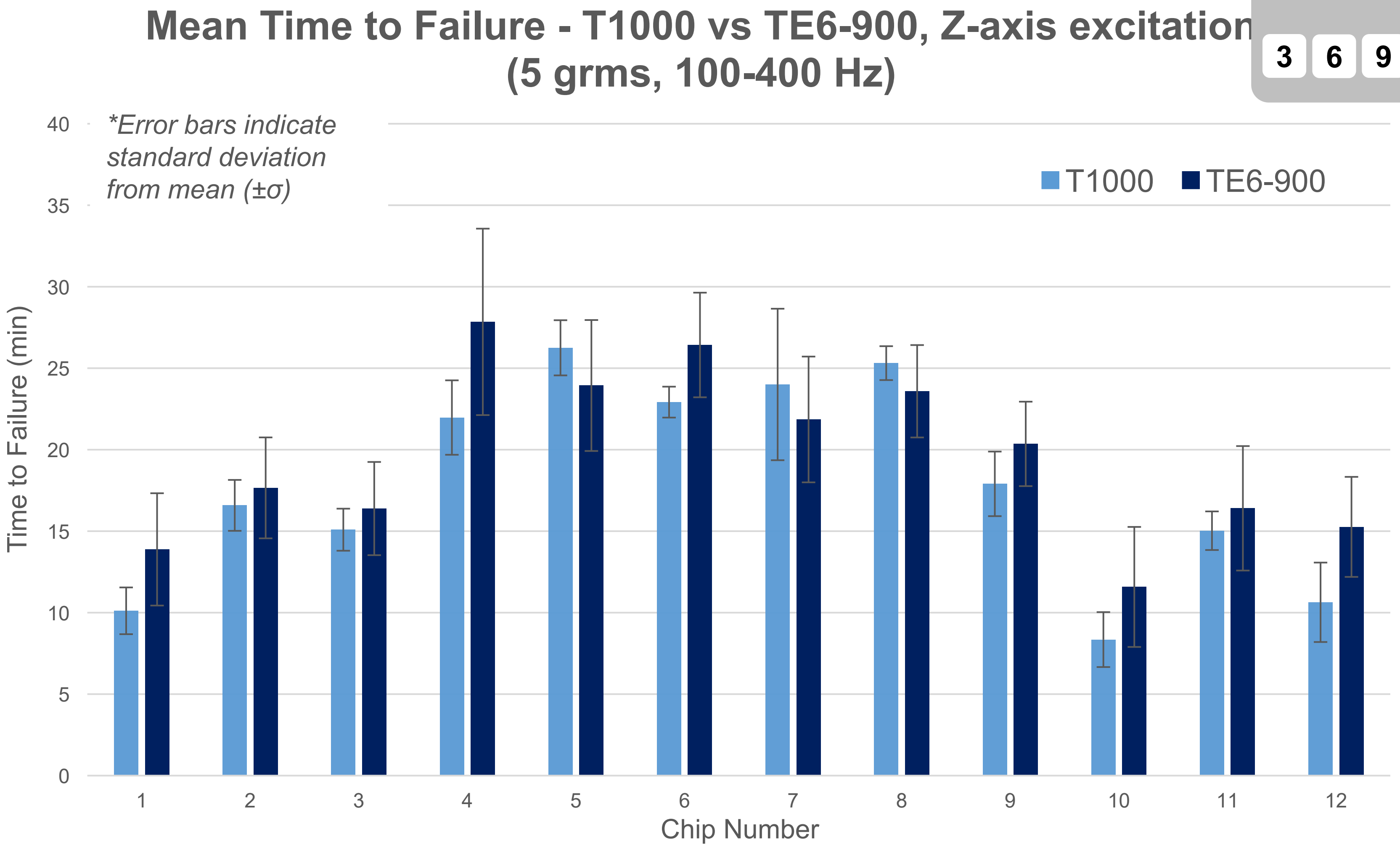
- Comparable results from SDOF and MDOF shakers
- Additional 5 degrees of freedom do not appear to substantially raise or lower the average TTF
- Larger deviation between tests on TE6-900



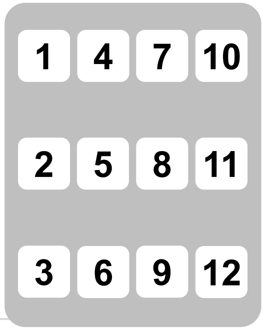
3 test runs



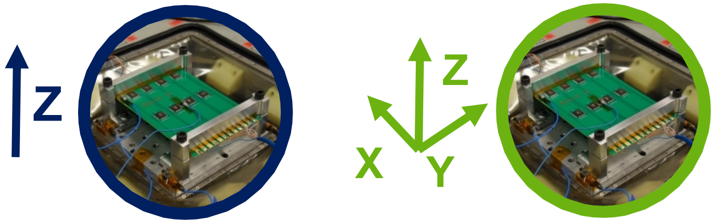
7 test runs

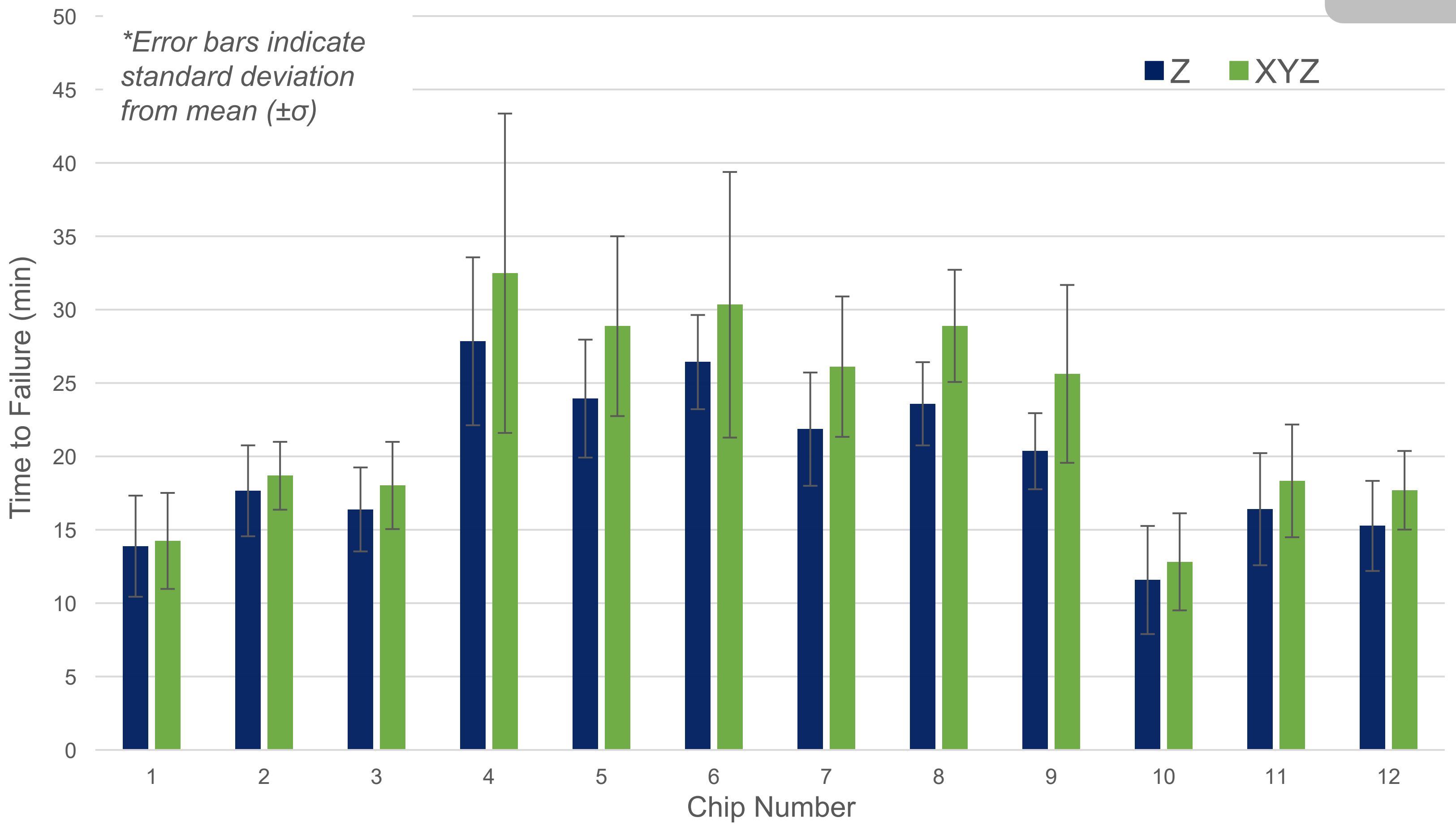


Test Results – Z vs XYZ *(TE6-900)*

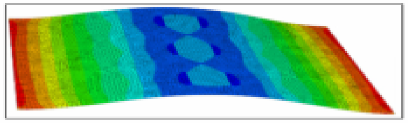


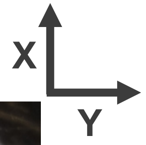
- Average TTF increased for every chip during 3-axis excitation compared to Z-axis excitation
- Standard deviation increase indicates less consistency among MDOF tests (particularly for chips 4-9)

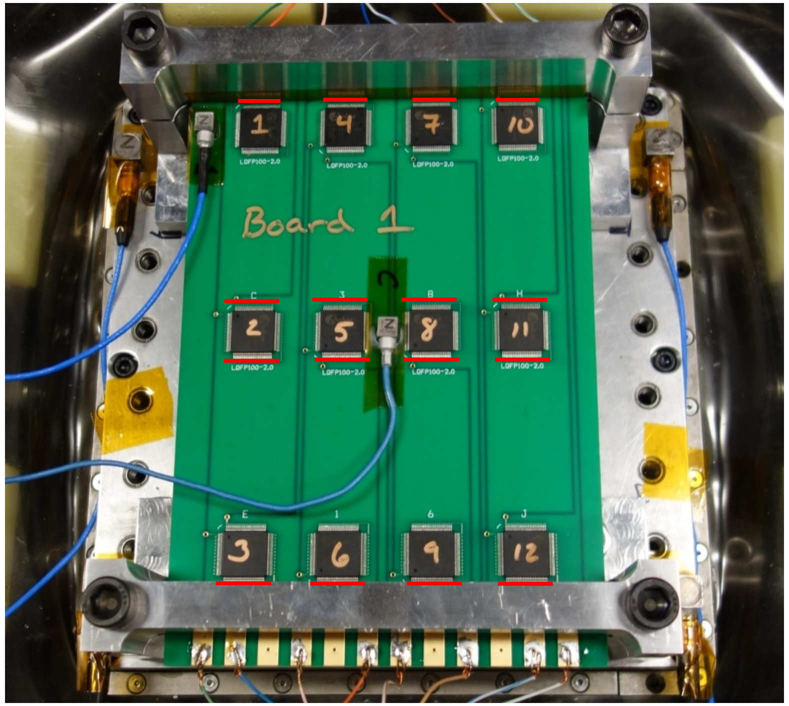




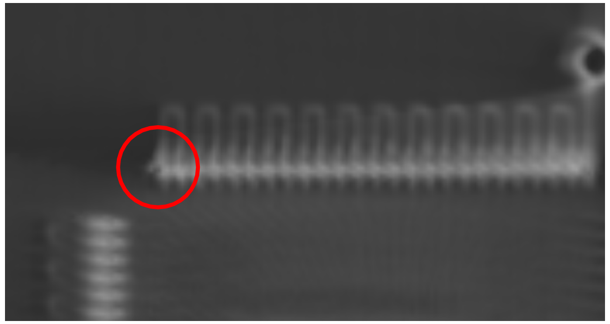
Test Results



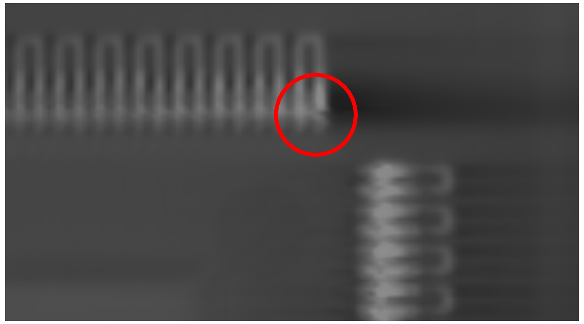




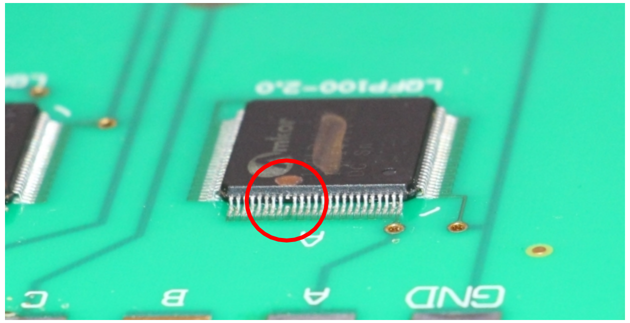
- The bending mode at 190 Hz results in maximum stress near the center and outer edges of the board where it is clamped.
- Leads fail from fatigue due to displacement from the 190 Hz Z-axis bending mode
- From inspection of boards with visible damage (bottom right) as well a CT scan of a single failed board, failures have been localized to the zones marked in red.



Broken lead along top edge of chip 10



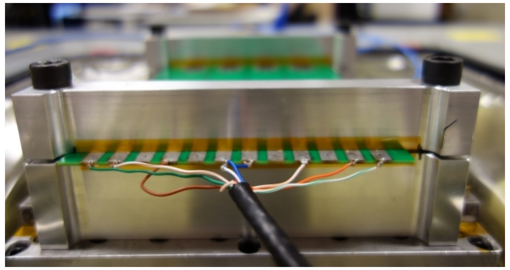
Top left corner of chip 8



Top of chip 1

Conclusions and Future Work

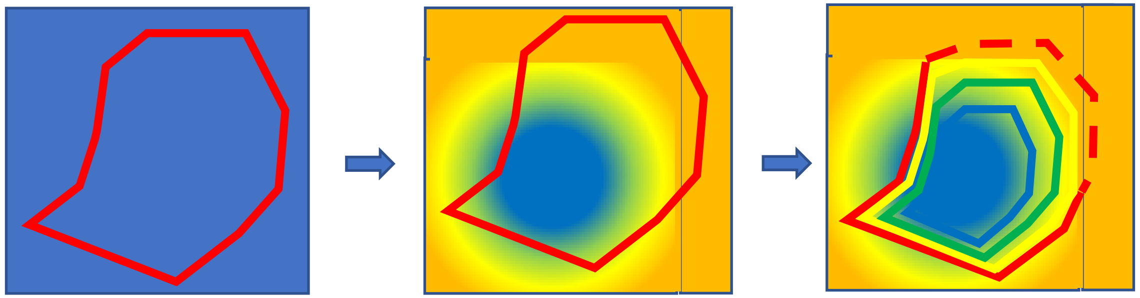
- Evidence of comparable single-axis test results on SDOF and MDOF shakers
- Increased TTF for multi-axis excitation tests, particularly for certain chips
  - Sequential axis testing appears to be more conservative than simultaneous
- Expand test parameters to possibly include:
  - Higher g_{RMS} levels
  - Temperature variation
  - Different fixturing
  - Include rotational specifications



Current clamp fixtures

Team Tensor 18kN

- Performance Envelopes
  - Future Goal: Construct accurate component performance envelopes using MDOF shaker



+confidence in analysis & testing techniques

+UQ in performance

Acknowledgements

Paul Titus

Michael Denison

Adam Mitchell

SNL Vibration Test Lab

Sandia National Labs

Kansas City National Security Campus

Questions?

References

1. Mayes, R.L., Lopp, G.K., Paripovic, J., Nelson, G.D. Schultz, R.A., Testing a Component on a Fixture to Reproduce System Accelerations. In *Proceedings of the 65th Institute of Environmental Sciences and Technology Conference*, Las Vegas, Nevada, 2019
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5. Daborn, P. M., Ind, P. R., and Ewins, D. J. "Replicating Aerodynamic Excitation in the Laboratory", Topics in Modal Analysis, Volume 7. Springer, New York, NY, 2014. 259-272.
6. Beale, D., Owens, B., and Schultz, R. "Analysis of IMMAT Full-Field Responses", Technical report, Sandia National Lab. (SNL-NM), Albuquerque, NM, USA 2019.

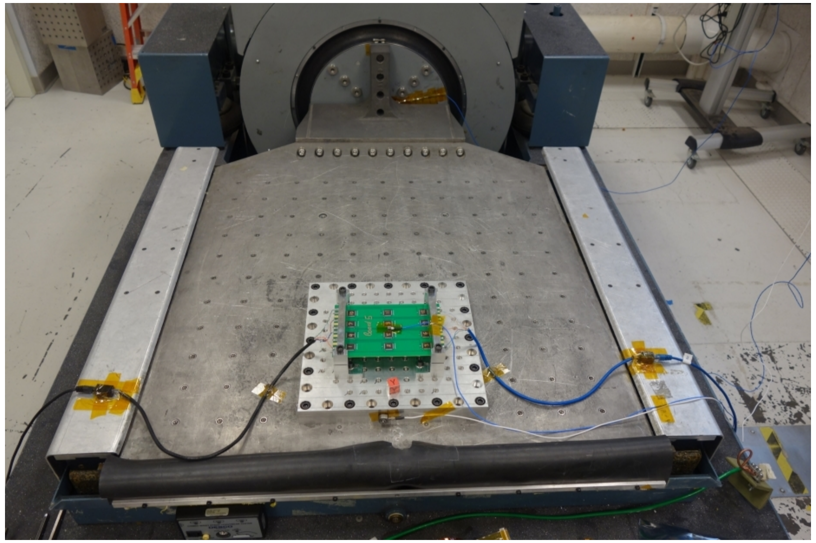
Appendix

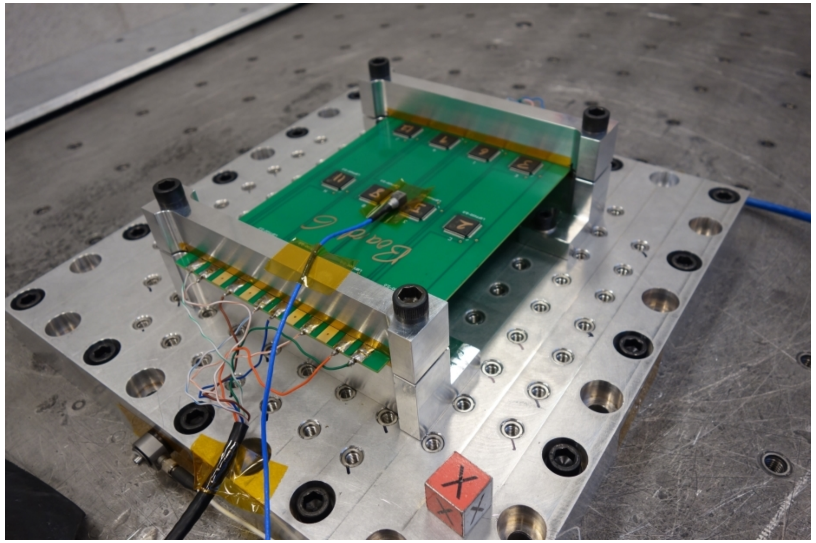
All Tests Completed to Date

Axes	Levels	Frequency	Shaker	Duration (H:M:S)
X	5 g_{RMS}	100-400 Hz	T1000	6:00:00
Y	5 g_{RMS}	100-400 Hz	T1000	6:00:00
Y	5 g_{RMS}	100-2000 Hz	T1000	6:00:00
Z	3.5 g_{RMS}	100-2000 Hz	TE6-900	4:51:37
Z	5 g_{RMS}	100-2000 Hz	T1000	3:00:16
Z	5 g_{RMS}	100-2000 Hz	T1000	1:36:18
Z	5 g_{RMS}	100-2000 Hz	T1000	2:11:22
Z	5 g_{RMS}	100-400 Hz	T1000	0:30:34
Z	5 g_{RMS}	100-400 Hz	T1000	0:27:25
Z	5 g_{RMS}	100-400 Hz	T1000	0:23:54
Z	3.5 g_{RMS}	100-400 Hz	TE6-900	1:32:01
Z	3.5 g_{RMS}	100-400 Hz	TE6-900	3:40:58
Z	5 g_{RMS}	100-400 Hz	TE6-900	0:25:38
Z	5 g_{RMS}	100-400 Hz	TE6-900	0:38:43
Z	5 g_{RMS}	100-400 Hz	TE6-900	0:31:02
Z	5 g_{RMS}	100-400 Hz	TE6-900	0:28:04
Z	5 g_{RMS}	100-400 Hz	TE6-900	0:25:13
Z	5 g_{RMS}	100-400 Hz	TE6-900	0:27:49
Z	5 g_{RMS}	100-400 Hz	TE6-900	0:32:52
XYZ	3.5 g_{RMS}	100-2000 Hz	TE6-900	4:00:00
XYZ	3.5 g_{RMS}	100-400 Hz	TE6-900	3:34:52
XYZ	3.5 g_{RMS}	100-400 Hz	TE6-900	4:36:06
XYZ	5 g_{RMS}	100-400 Hz	TE6-900	0:52:09
XYZ	5 g_{RMS}	100-400 Hz	TE6-900	0:31:46
XYZ	5 g_{RMS}	100-400 Hz	TE6-900	0:51:45
XYZ	5 g_{RMS}	100-400 Hz	TE6-900	0:46:47
XYZ	5 g_{RMS}	100-400 Hz	TE6-900	0:30:48
XYZ	5 g_{RMS}	100-400 Hz	TE6-900	0:25:58
XYZ	5 g_{RMS}	100-400 Hz	TE6-900	0:28:58
XYZ	5 g_{RMS}	100-400 Hz	TE6-900	0:33:08
XYZ	5 g_{RMS}	100-400 Hz	TE6-900	0:32:05

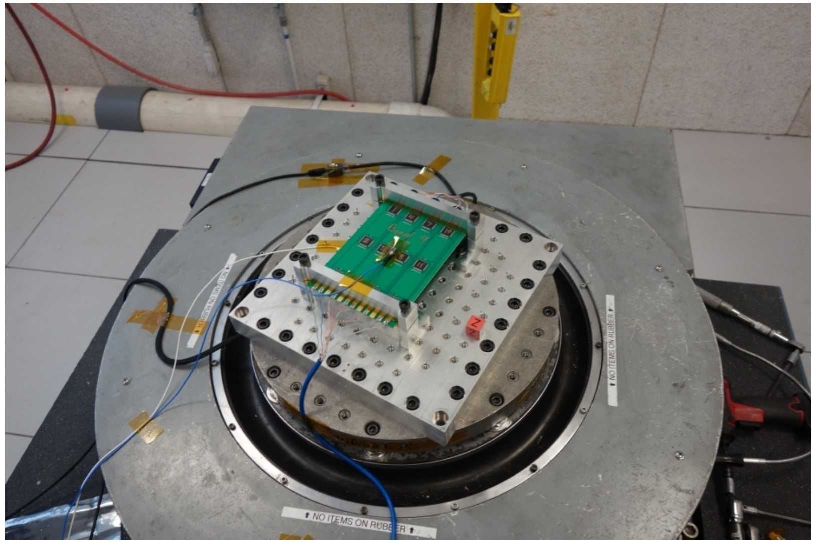
Test duration listed as either TTF of final chip, or the time at which the test was manually stopped, tests used for analysis are highlighted

UD-T1000 Shaker Images



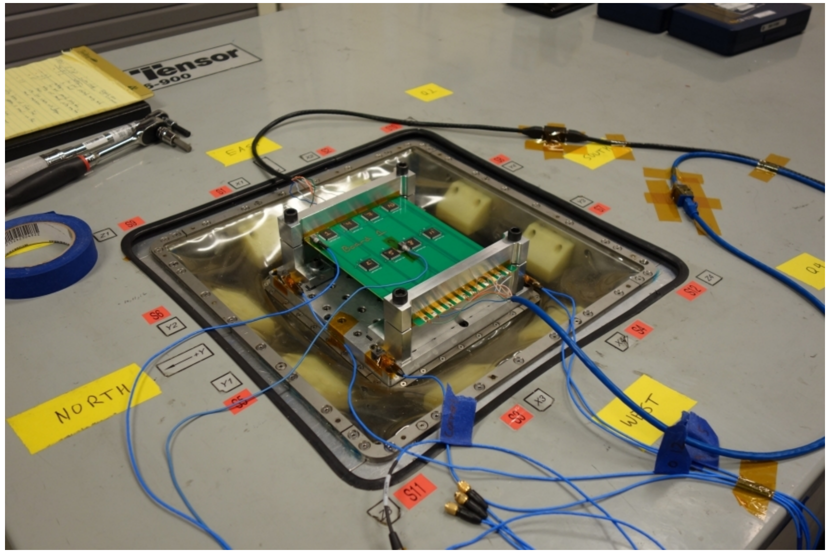


with slip table (X and Y axis tests)

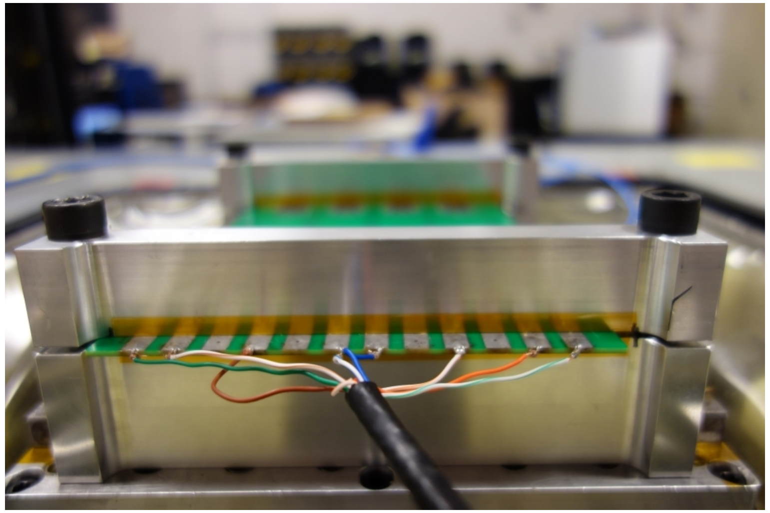


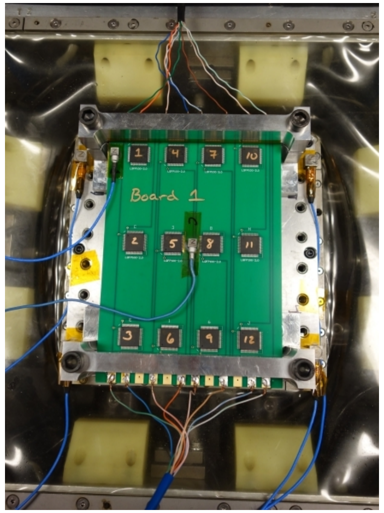
without slip table (Z axis tests)

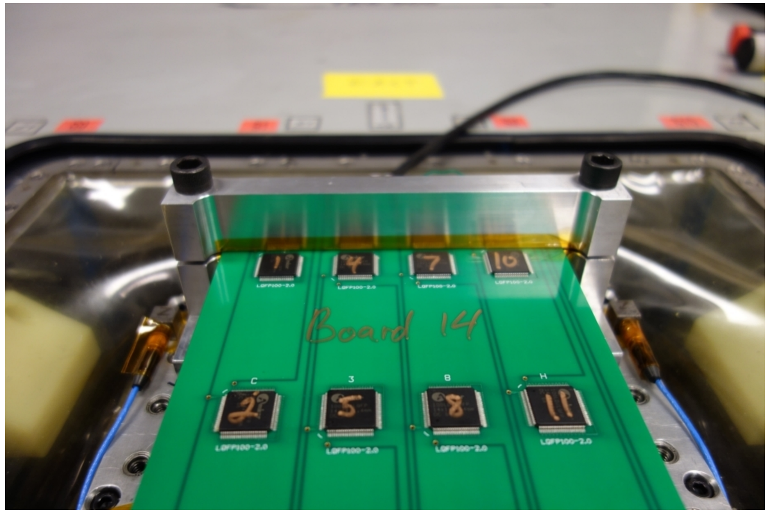
TE6-900 Images and Specifications



TE6-900 Specifications		
	English Units	SI Units
Stroke	+/- 0.25 inch	+/- 6.4 mm
Rotation	+/- 5 deg.	.09 rad.
Velocity	60 in/sec	1525 mm/sec
Force	200 lbf	890 N
Table Wt.	9.02 lbs	4.09 kg

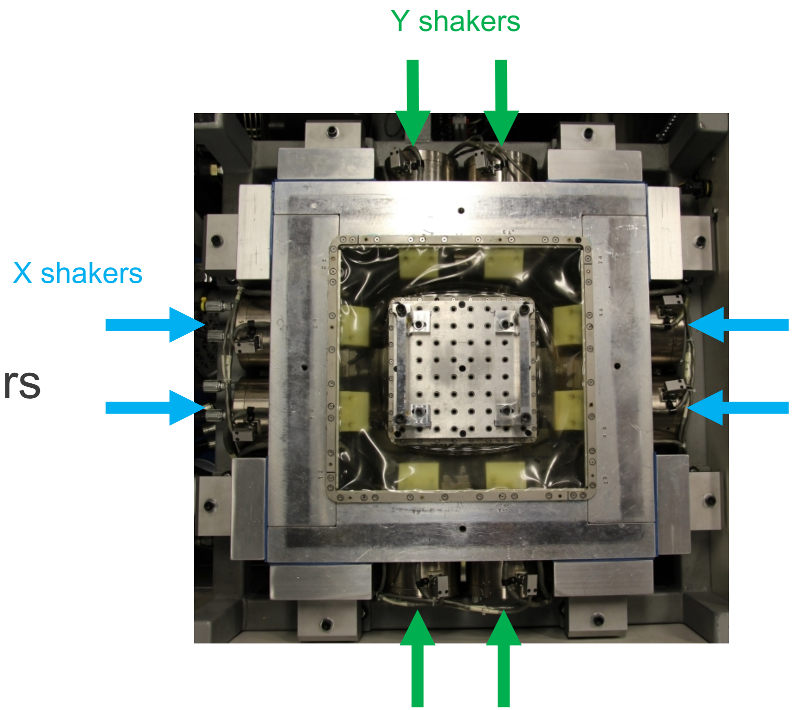


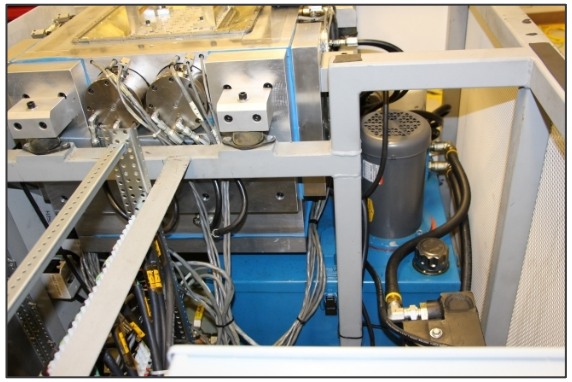




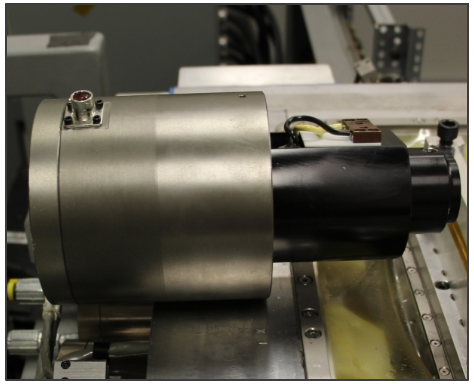
6DoF Shaker Operation

- 12 shakers, 4 per axis
- Hydraulic reservoir and pump located beneath shakers
- Hydraulic oil supplies cooling, bearing lubrication, and preload to shakers
- 3-phase power input supplies power to hydraulics, heat exchanger, shakers, and amplifiers

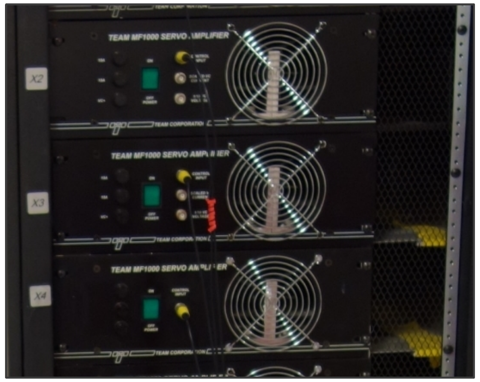




Hydraulic pump



Individual shaker removed from assembly



Amplifiers

Elastic cords holding table down, providing Z-axis pre-load

Rattlesnake Configuration