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Comparative Failure Analysis of Components Exposed to Multi-axis and Single-axis Vibration Testing

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ABSTRACT

It has been shown that the dynamic field environment for a component may not be represented well by a single axis shaker environmental test. Here we demonstrate, for a clamped-clamped plate, the effect of testing all the axes of interest in a multi-axis shaker environmental test. The component is a printed wiring assembly (PWA) board mounted to a Team Tensor TE6-900 six degree-of-freedom shaker and an Unholtz-Dickie T1000 shaker. The goal is to expose the PWA boards to a set of sequential single-axis and simultaneous multi-axis environments and evaluate the difference in time to fail (TTF) between the different environments. Interesting mileposts during the process, experimental response and analysis are discussed.

Keywords: 6DOF testing, Failure testing, Sequential single axis, Time to Failure, MIMO, MDOF, Environmental Testing

INTRODUCTION AND MOTIVATION

Currently, component qualification testing contains unknown uncertainty. Not enough measurements are provided to define the component motion in the system field environment, system component boundary conditions and impedances are ignored, and laboratory testing may contain different boundary conditions [1]. These uncertainties sometimes go ignored, and it is implicitly assumed that conservative envelopes on the available system measurements provide confidence in component testing [1]. These envelopes are specified in the individual X, Y, and Z directions and the hardware is tested one axis at a time on single-degree-of-freedom shakers. Traditional laboratory shaker boundary conditions are constrained in the other five degrees of freedom, unlike the field boundary conditions and are therefore unrepresentative of operational environments. There is reporting evidence that the response of a structure excited simultaneously in multiple axes differs from sequential single-axis tests [2, 3]. There is also evidence of difference in fatigue life and failure modes when comparing multi-degree-of-freedom (MDOF) and single-degree-of-freedom (SDOF) testing [4]. To this end, different multi-input multi-output (MIMO) testing strategies are being explored in an effort to create more representative test environments such as impedance matched multi-axis testing (IMMAT) and MDOF shaker tables [5, 6].

This work seeks to understand the effects of conducting environmental testing as a set of sequential single-axis and simultaneous multi-axis environments. Specifically, of interest is how MDOF and SDOF testing affect the time to failure of a component. The component is a printed wiring assembly (PWA) board in a clamped-clamped configuration mounted both on a traditional SDOF shaker (Unholtz Dickie T1000) and MDOF shaker (Team TE6-900). Traditional SDOF tests are controlled using Spectral Dynamics Jaguar and tests on the TE6-900 are controlled using Rattlesnake Vibration Controller which was developed at Sandia National Laboratories. Additionally, SDOF tests are compared on both shakers to understand how the different internal boundary conditions of a SDOF shaker where the other five degrees of freedom are constrained differ from a MDOF shaker that allows the armature to move unconstrained in the other degrees of freedom. Understanding these effects would remove uncertainties in future testing, reduce testing time, and provide benefit in understanding accurate stress and damage potential.

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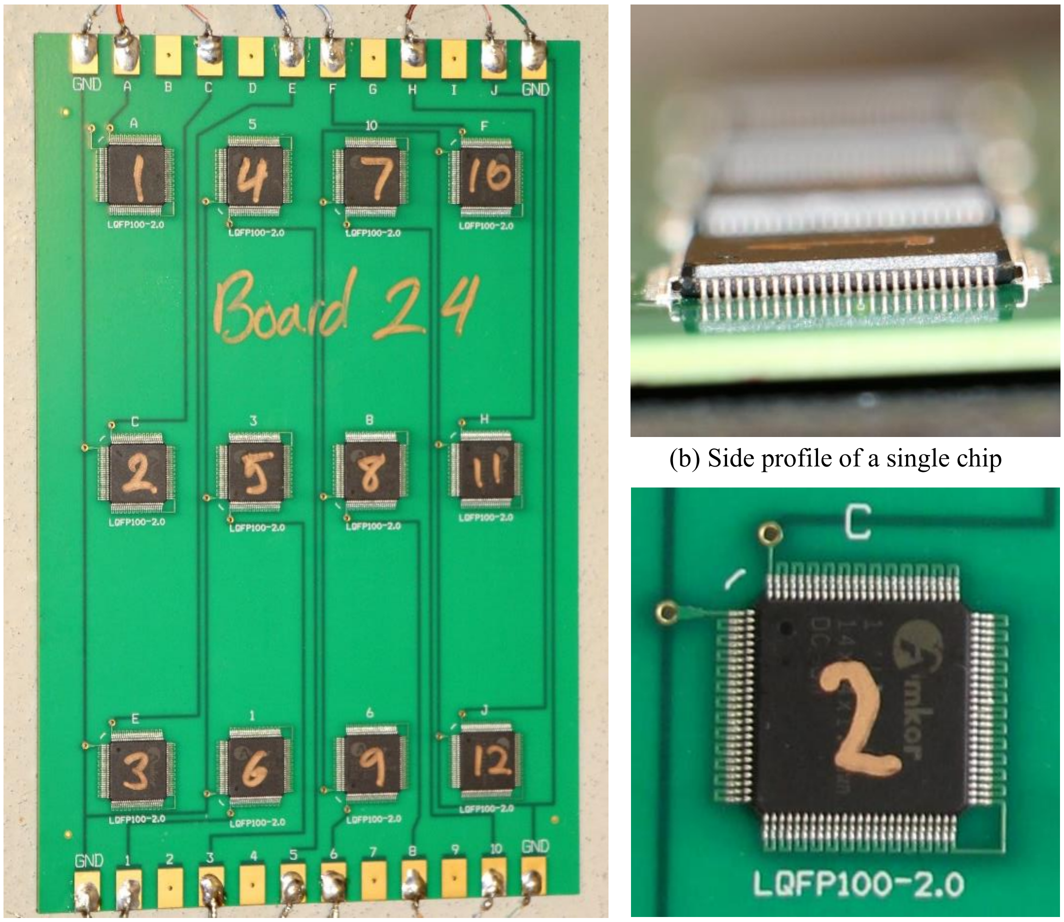
SETUP AND METHODOLOGY

The printed wiring assembly (PWA) boards each contain twelve surface-mounted low-profile quad flat packages (LQFP) arranged in a 3-by-4 grid as seen in Figure 1(a). Each LQFP chip measures 14 x 14 mm with a body thickness of 1.4 mm and is attached to the PWA board by 100 gull-wing style leads shown in Figure 1(b). Pairs of adjacent leads are connected to one another by solder traces, except for one pair. Each of the leads in this final pair are individually connected to solder pads located on the edges of the PWA board. The configuration of the wiring assembly is such that for each chip, electrical continuity begins at one solder pad and ends at the other, see Figure 1(c).



(b) Side profile of a single chip

(a) Top-down view of PWA board (c) Top-down view of a single chip

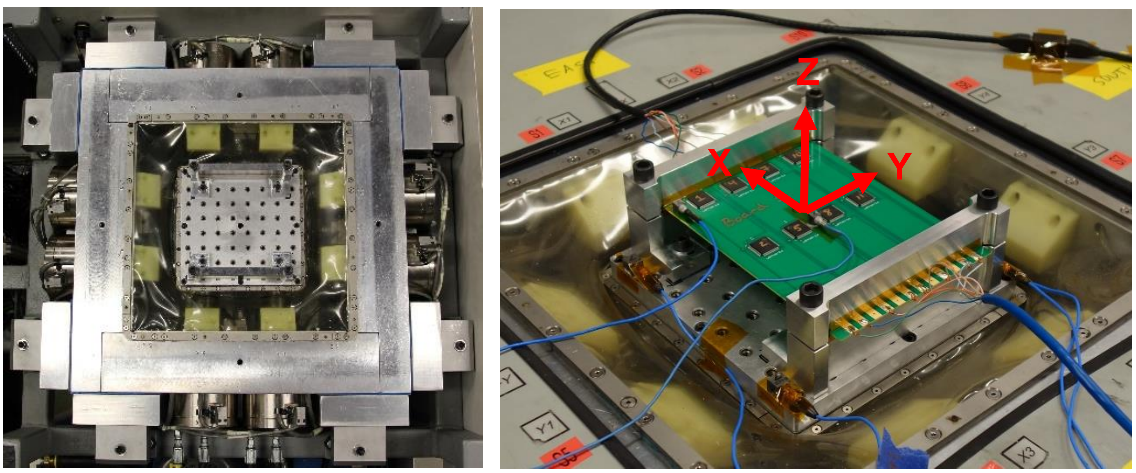
Figure 1: printed wiring assembly (PWA) board used for sequential and simultaneous testing.

This electrical continuity is important for monitoring the failure state of each chip because it provides a path for current to flow through all of the leads. This path has a nominal resistance determined by the specifications of the chip and the wiring assembly, and a change in this resistance would indicate a failure in the components along the path of continuity. To determine the time-to-failure for each chip on the board, we monitor changes in the resistance of the chip or a loss of electrical continuity. A significant change in resistance could indicate fatigue in the leads, and a loss of continuity could indicate fracture.

A National Instruments PXIe-4065 Digital Multimeter and PXIe-2531 Switch Module is used to monitor chip resistance. Twisted pairs of wires from ethernet cabling are soldered to connect the solder pads on the edges of the PWA board to the switch module. A separate pair of wires connects the multimeter to the switch module. The switch module contains a matrix of mechanical relays so that any pair of wires corresponding to a chip could be routed through the multimeter. The data collection script controls the switch module to cycle through the twelve chips and record discrete resistance and time measurements.

Initial observations show that the discrete resistance measurements could fluctuate during testing prior to any significant failure of the chip leads. In order to apply a consistent metric for the time-to-failure of a single chip, the multimeter needs to report an increase in resistance by 100% of the chip's initial resistance for 20 consecutive readings in order to qualify that chip as failed. Each test is conducted until all twelve of the chips had failed, or for as long as the shakers can be run continuously.

The MDOF shaker used for testing is a Team Tensor TE6-900 six degree-of-freedom (6DOF) shaker. It utilizes four electrodynamic shakers in each translational axis (for a total of twelve shakers) to achieve translation in three axes and rotation about three axes, see Figure 2. Separate input voltages are supplied through twelve individual amplifiers to each corresponding shaker. The shakers are coupled to the sides and bottom of the armature, on which the PWA board is mounted in a clamped-clamped configuration. The test setup including the armature, fixtures, and PWA board weighs 14.43 lbs. Four tri-axial control accelerometers (PCB356A33) are placed on the corners of the fixture plate. Prior to and immediately following each test, an additional tri-axial accelerometer (PCB356A04) is placed on the center of the board for a low-level workmanship test. A smaller accelerometer was chosen for the workmanship tests, as to minimize mass loading on the PWA board.

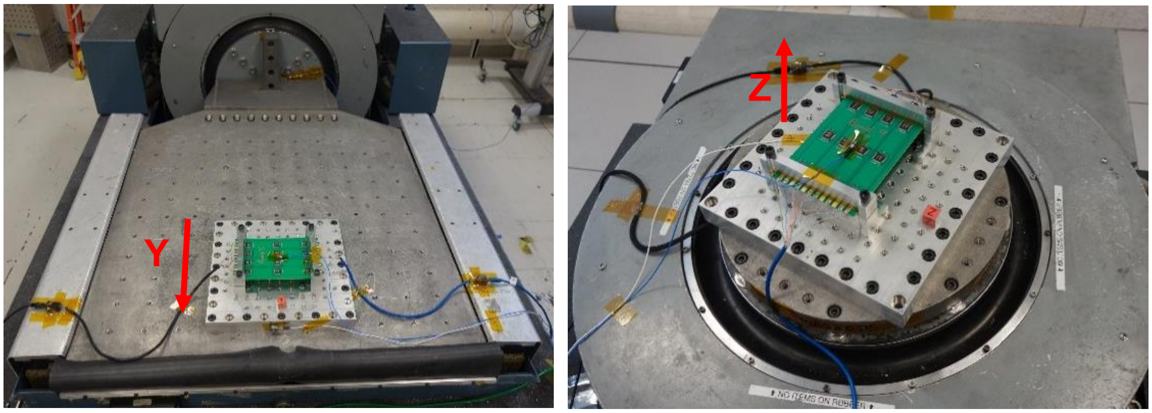


(a) (b)

Figure 2: (a) top-down view of TE6-900 shaker assembly with cover removed, (b) PWA board mounted to TE6-900

The shakers are controlled using Rattlesnake Vibration Controller software. Rattlesnake was created at Sandia National Laboratories as a research and development tool allowing the operator to vary control schemes, inputs, outputs, and other factors for varying MDOF and IMMAT testing. The software interfaces with National Instruments PXIe-4497 and PXIe-4463 Sound and Vibration modules. These modules provide the drive voltages to the twelve shaker amplifiers and receive the response signals from the four control accelerometers. In order to control each translational axis independently, the controller utilizes equal contributions from each of the control accelerometer readings in that axis. For each test performed on the Team Tensor TE6-900, no specification or constraint is provided for the rotation of the table. During single-axis testing on the TE6-900, the off-axis shakers are turned off.

Additional SDOF testing was performed using a Unholtz-Dickie T1000 shaker controlled by Spectral Dynamics Jaguar, using the same clamp fixtures that were used on the Team Tensor TE6-900. For tests in the X and Y axes, a slip table is used in order to preserve the spatial orientation from the Z-axis and MDOF tests, see Figure 3. The test setup for Y and X orientation including the slip table, armature, fixtures, and PWA board weighs 279.6 lbs. For Z axis testing, the test setup including the armature, fixtures, and PWA board weighs 151.8 lbs.



(a) (b)

Figure 3: (a) T1000 shaker setup with slip table (X and Y-axis testing), (b) T1000 shaker setup (Z-axis testing) *(excitation axis indicated on figure)*

Low-level operational random tests were used to determine the environment specifications for time to failure (TTF) testing. These operational random tests use a flat specification from 100-2000 Hz at 1.4 g_{RMS} in each axis (X, Y, and Z). Two lightweight tri-axial response accelerometers are positioned on the PWA board, located in the center and on one of the corners. The resultant frequency response is simplified as a linear piecewise envelope to be used as the specification for TTF testing. A unique envelope exists for each of the three excitation axes, as shown in Figure 4. An additional test specification uses a truncated version of this envelope to encompass a frequency band of 100-400 Hz. Each specification is scaled to 5 g_{RMS} per axis. These specifications are compatible with both the T1000 and TE6-900 shakers and can be run either individually or in combination on the TE6-900 (due to controller limitations, specifications with different frequency ranges cannot be run simultaneously).

Figure 4: Frequency response and envelopes for X-axis *(top)*, Y-axis *(middle)*, and Z-axis *(bottom)*

The enveloped specifications shown in Figure 4 are designed to target specific modal frequencies to reduce the overall TTF. As shown in the figure, the primary modal frequencies are 190 Hz in the Z-axis, 850 Hz in the X-axis, and 240 Hz in the Y-axis. Since many of the modes occur at higher frequencies, they are not captured within 100-400 Hz specification. However, the 100-400 Hz specifications are scaled to $5g_{RMS}$, so the modes below 400 Hz can be excited at greater levels. The two modes that fall within the 100-400 Hz range are at 190 Hz in the z-axis and 240 Hz in the y-axis.

Currently, 13 tests have been conducted using only Z-axis excitation. Of those 13, seven were run on the T1000 and six were run on the TE6-900. 7 tests have been conducted on the TE6-900 using combined X, Y and Z-axis excitation. One X-axis and two Y-axis tests were run on the T1000, each for six hours, but produced no failures. In general, tests run using the 100-2000 Hz profile require many hours of test time to produce failures, whereas those that use the 100-400 Hz profile are usually completed within an hour. For convenience, and in order to gather more data quickly, later tests were run using only the Z and XYZ profiles from 100-400 Hz, which comprise a group of 10 tests. After an initial batch of testing, it was identified that the response error on the TE6-900 was on the order of -3dB resulting in a lower g_{RMS} than expected. Subsequent tests were more closely monitored to ensure proper control and response levels. The 10 tests that had a consistent 5 g_{RMS} level, and frequency range of 100-400 Hz are used in the analysis going forward since they offer the most complete data set and most reliable comparisons. A list of all the tests completed are shown in Table 1, the 10 tests compared in the next section are highlighted in blue. Additional tests will be conducted in the future to expand the data set.

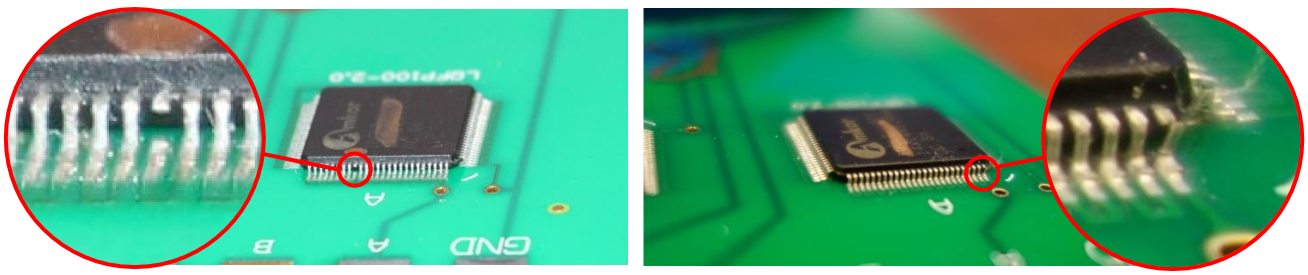
Table 1. List of all tests completed to date

Axes	Levels	Frequency	Shaker	Duration (H:M:S)
Z	5 g_{RMS}	100-400 Hz	T1000	0:38:00
Z	5 g_{RMS}	100-400 Hz	T1000	0:45:00
Z	5 g_{RMS}	100-400 Hz	T1000	0:30:00
Z	3.5 g_{RMS}	100-400 Hz	TE6-900	1:45:00
Z	3.5 g_{RMS}	100-400 Hz	TE6-900	4:05:00
Z	5 g_{RMS}	100-400 Hz	TE6-900	0:41:00
Z	5 g_{RMS}	100-400 Hz	TE6-900	0:47:50
Z	5 g_{RMS}	100-400 Hz	TE6-900	0:45:00
Z	5 g_{RMS}	100-2000 Hz	T1000	3:25:00
Z	5 g_{RMS}	100-2000 Hz	T1000	1:47:00
Z	5 g_{RMS}	100-2000 Hz	T1000	2:15:00
Z	5 g_{RMS}	100-2000 Hz	T1000	1:30:00
Z	3.5 g_{RMS}	100-2000 Hz	TE6-900	6:00:00
XYZ	3.5 g_{RMS} / axis	100-400 Hz	TE6-900	4:00:00
XYZ	3.5 g_{RMS} / axis	100-400 Hz	TE6-900	6:00:00
XYZ	5 g_{RMS}	100-400 Hz	TE6-900	0:53:14
XYZ	5 g_{RMS}	100-400 Hz	TE6-900	0:42:22
XYZ	5 g_{RMS}	100-400 Hz	TE6-900	0:55:36
XYZ	5 g_{RMS}	100-400 Hz	TE6-900	0:53:43
XYZ	3.5 g_{RMS} / axis	100-2000 Hz	TE6-900	4:00:00
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

ANALYSIS

Initial observations from testing on the T1000 shaker show that excitation in the X or Y-axis alone does not result in failure within a manageable time frame (6 hours). For this reason, pure X and Y-axis tests were made low priority for the first round of testing. Using Z-axis excitation or combined XYZ excitation, tests can often be completed within a few hours. Furthermore, the specification spanning 100-400 Hz at 5 g_{RMS} produces much quicker failures than the specification spanning 100-2000 Hz, also at 5g_{RMS}. These observations indicate that the 190 Hz bending mode in the Z-axis is the primary contributor to chip failure. This bending mode is responsible for the maximum displacement along the surface of the board. This displacement reaches a maximum along the center row of chips (numbers 2, 5, 8, and 11, see Figure 1).

A closer inspection of the chip leads confirms that the Z-axis bending mode is the likely cause of failure for many of the failed chips. On some chips, the fracture in the leads is visible. The gull-wing style leads that connect the chip to the board consist of two 90-degree bends. The visible damage to these leads would suggest that as the surface of the board curves upward or downward while the chip itself remains flat, the angle of the bends must change to remain in contact with the two surfaces. This oscillatory bending can eventually cause fracture at one or both bends, as shown in Figure 5. Due to the geometry of the board, only the leads which attach to the edges of the chip parallel to the clamps experience this fatigue. For those leads which attach to the other two edges, no visible fractures have been observed.



(a) (b)

Figure 5: (a) two fractures in a single lead (center portion of lead missing), (b) single fracture in a chip lead

Throughout testing, a significant pattern developed defining the order in which chips would fail. The corner chips (numbers 1, 3, 4, and 10) fail the quickest, followed by chips 2 and 11. The six chips that occupy the center two columns (numbers 4-9) survive the longest. This pattern is present in every test which incorporates Z-axis excitation, as shown in Figure 6. The results of the pure Z-axis tests show that this pattern is reproducible on both the T1000 and TE6-900 shakers.

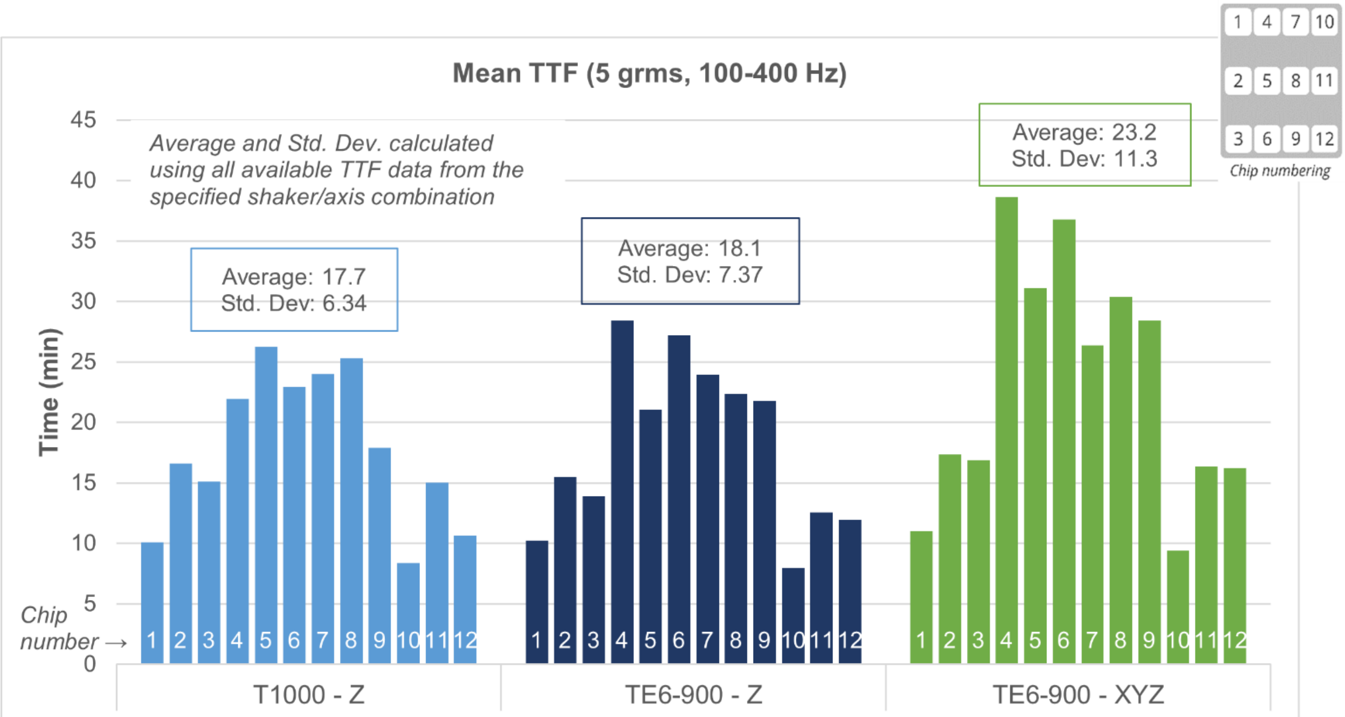


Figure 6: mean time to failure (TTF), average taken for each chip number, grouped by shaker/axes used

Two major physical differences are present between these two shakers. Firstly, the T1000 has more moving mass than the TE6-900 due to the larger armature and fixture plate. Secondly, the TE6-900 table is suspended between its individual shakers, allowing unconstrained off-axis vibration. Despite these differences, the results in Figures 7 and 8 show that the TE6-900 and T1000 shakers produce comparable failure times for each individual chip. In Figure 7, the TTF is shown for each chip in six separate tests, three of which were run on the T1000 and three of which were run on the TE6-900. Figure 8 displays the TTF for each chip averaged by shaker and standard deviation ($\pm\sigma$).

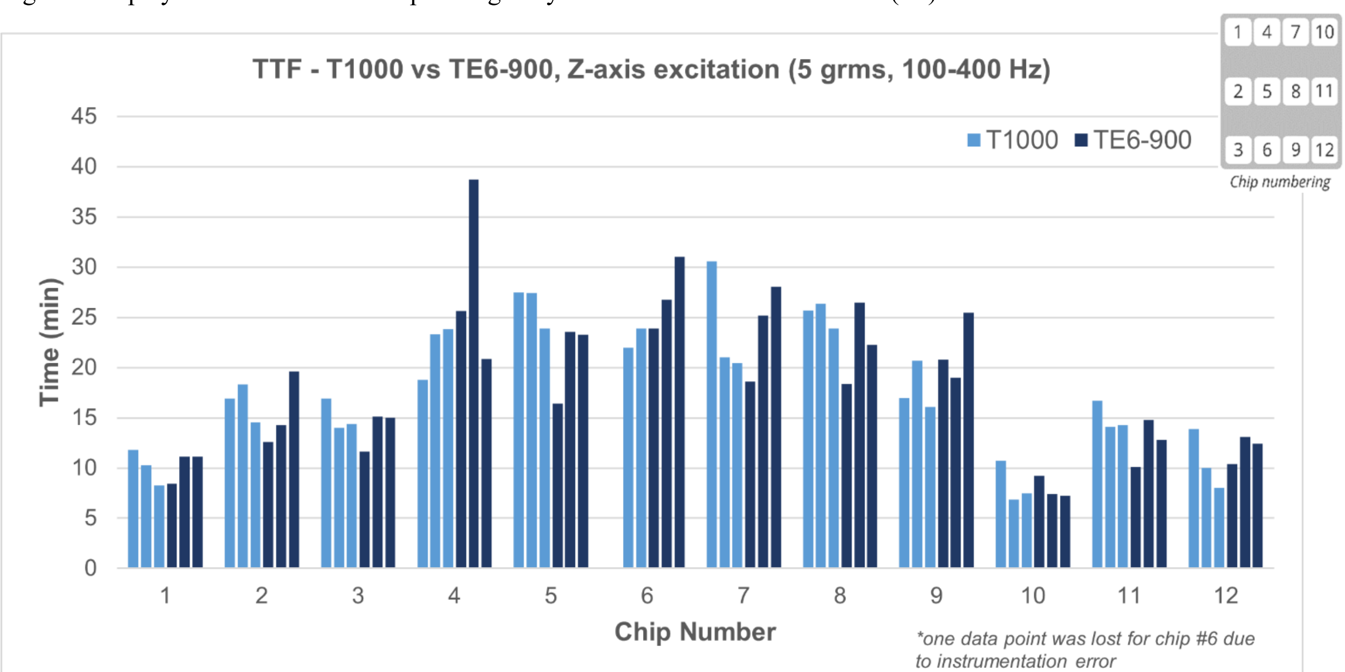


Figure 7: TTF for Z-axis excitation on the T1000 and TE6-900 shakers

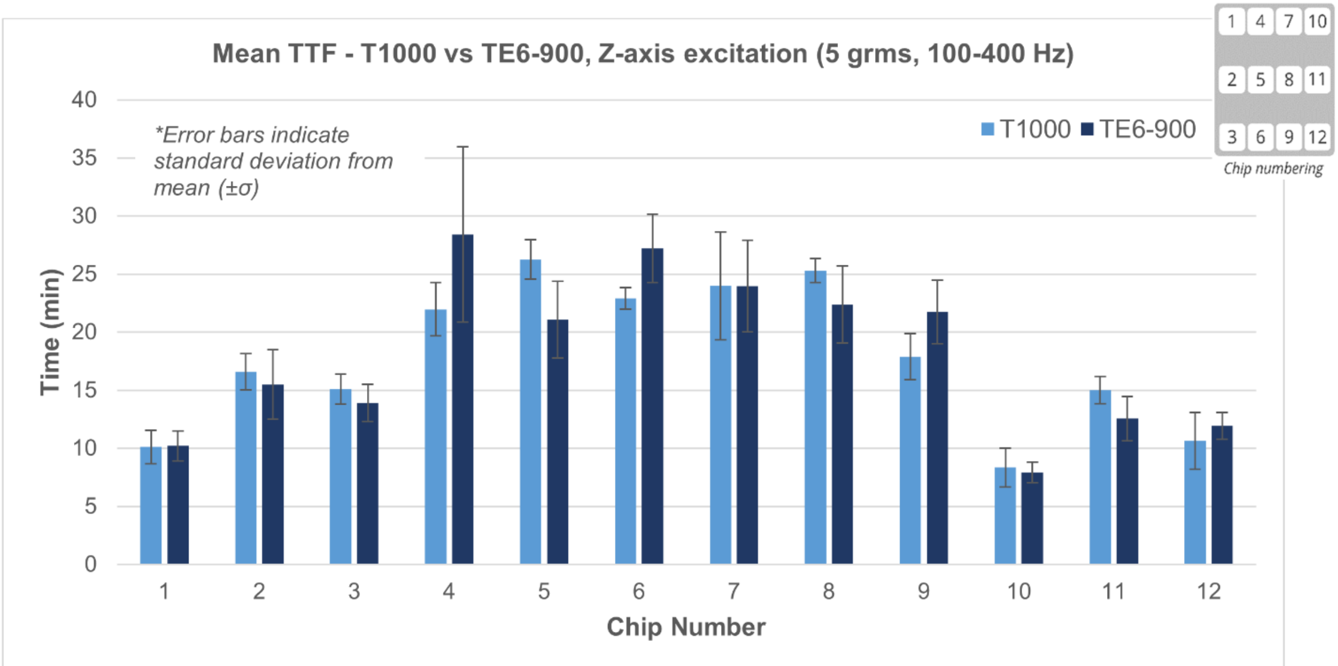


Figure 8: Mean TTF for Z-axis excitation on the T1000 and TE6-900 shakers

Having established that comparable results are obtainable from the two shakers in a single axis, we can begin to inspect the differences between the single-axis and multi-axis results. The addition of X and Y-axis excitation on the TE6-900 resulted in larger TTF, particularly for the center two columns of chips (numbers 4-9). A slight increase in TTF is also present for the outer columns of chips (numbers 1-3 and 10-12). It is important to note that the standard deviation in TTF for each chip increased substantially during the MDOF tests. These results, shown in Figures 9 and 10, suggest that additional excitation increased the overall TTF. However, given the large deviations among very few tests, it is unclear whether this indicates dynamic behavior unique to MDOF excitation or rather an inaccurate replication of the independent environments when excited simultaneously by the TE6-900. While input voltages were monitored, they were not recorded. Future testing will record input voltages, employ non-contact measurements of the chips (i.e. laser Doppler vibrometer or digital image correlation), and explore additional control laws in Rattlesnake. Improving confidence in these experimental results will require more tests and deeper investigation into the accuracy of the input specifications that Rattlesnake achieves.

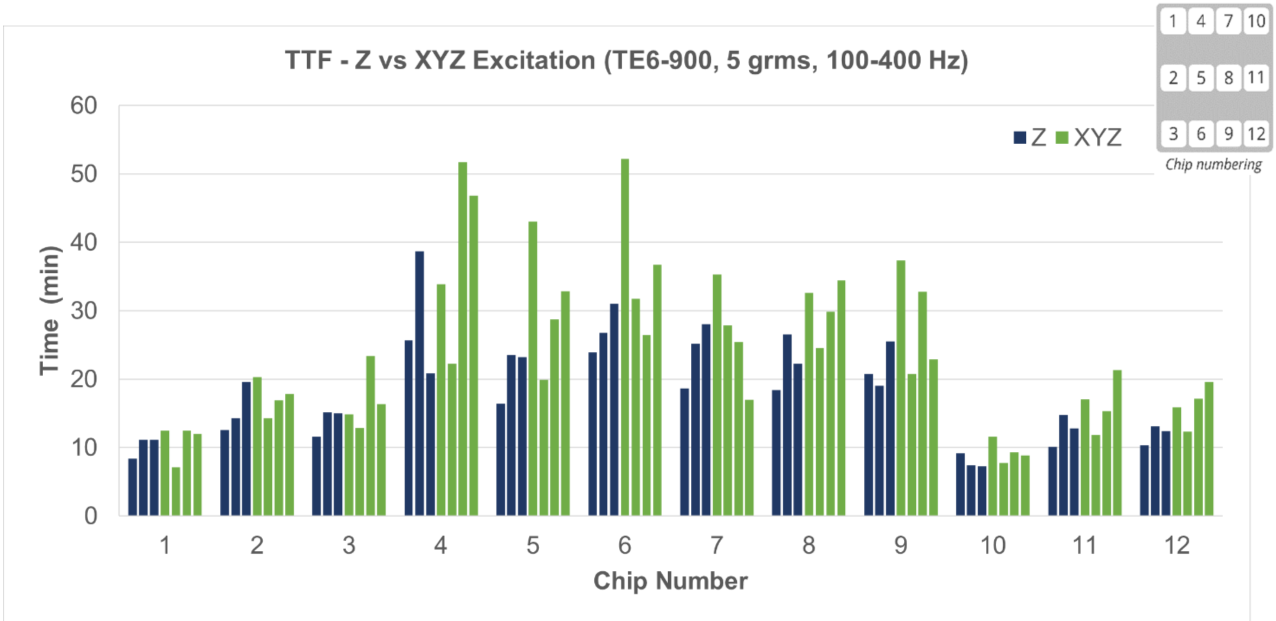


Figure 9: TTF for Z-axis and combined XYZ excitation on the TE6-900

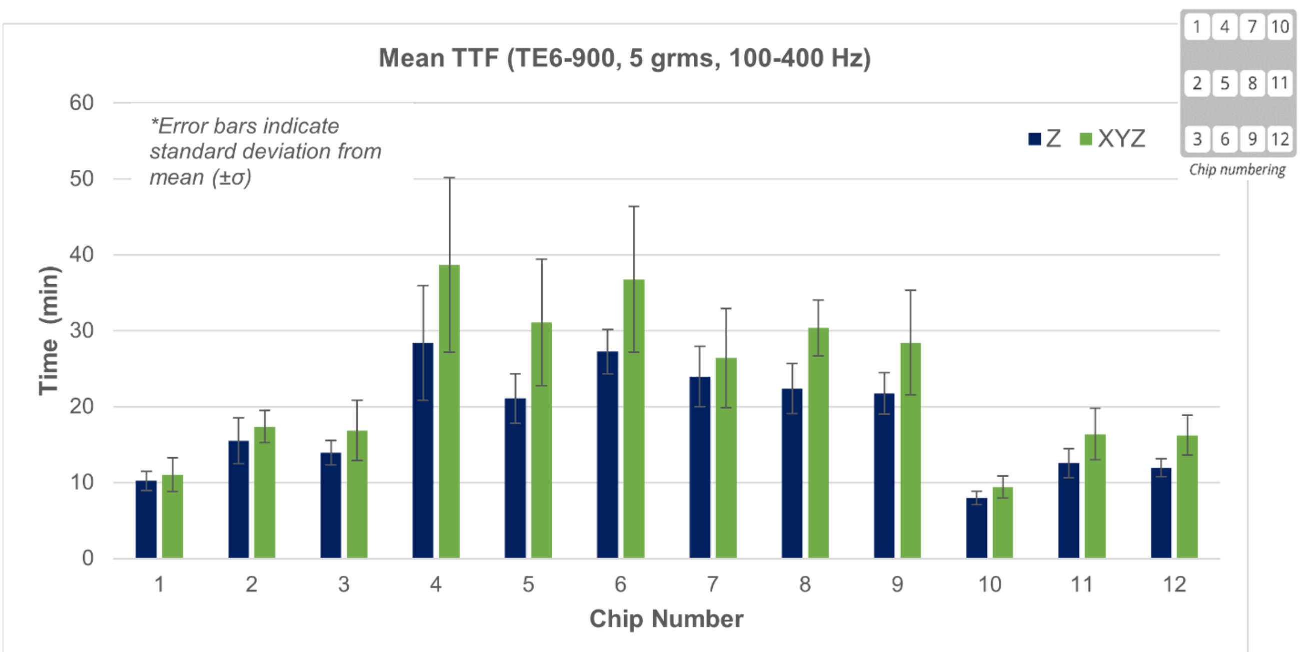


Figure 10: Mean TTF for Z-axis and combined XYZ excitation on the TE6-900

CONCLUSION AND FUTURE WORK

Although the tests conducted so far are few, they provide useful comparative data between MDOF and SDOF testing procedures. The indication that single-axis testing can be performed on an SDOF or MDOF shaker to obtain the same result would, if proven consistent through continued testing, confirm the single-axis operation of the TE6-900 as a reliable SDOF testing apparatus. It could also help to streamline the continued testing that will be needed to further investigate the effects of MDOF testing on TTF for additional PWA boards. Initial results suggest that MDOF testing has a higher TTF when compared to equivalent SDOF tests. Moving forward, additional testing will be conducted to expand the dataset and provide more definitive conclusions to be made from a larger statistical distribution.

A major obstacle of this study has been the limited component supply as well as the time that is required to complete each test. As testing proceeds, concurrent investigation will be made into the accuracy of the environmental reproduction by the TE6-900 during MDOF testing. Improved data collection practices and test monitoring will help to verify the accuracy of the specified environment. New control algorithms for the Rattlesnake controller will be explored, which could lead to improvements in test accuracy and expedite certain logistical processes involved with the testing procedure.

Many avenues may also be explored to expand the parameters of the study. We are currently using printed wiring assemblies to identify the time to failure, but other forms of failure (i.e. chatter) exist. Future work may include taking field components and identifying how sequential versus simultaneous affect chatter TTF. All these efforts are steps to use the MDOF testing procedures to develop component performance envelopes. Approaching environmental testing as a performance envelope problem will lead to better understanding the limitations of equipment, design, and functionality of the device under test. Instead of a component being tested to a suite of environments, a component is tested to the limits of different metrics (i.e. levels, axes, temperature) and a performance envelope is generated plotting the confidence of the survivability of the plot against these metrics. This work is ongoing.

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