Standard Operating Procedure for Highly Accelerated Life Testing (HALT): Design and Standardization of Fixture Setup for Circuit Boards

by

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This thesis deals with the introduction of Highly Accelerated Life Testing (HALT) in a multinational corporation as part of a reliability improvement process for printed circuit boards (PCBs). More specifically, the thesis focuses on drafting a standard operating procedure (SOP) to standardize the fixture setup process so as to minimize variation in vibrational responses attributed to fixture setup. This study proposes a three phase approach to meet the objective.

The first phase aims to minimize variation in the gauges and the vibration table. A gauge repeatability and reproducibility (gauge R&R) test is conducted on two triaxial accelerometers to determine the most suitable gauge for HALT. Next, a spatial uniformity test is conducted on the vibration table using design of experiments (DOE) method to determine the region with the most consistent vibration levels for testing. The second phase aims to reduce variation in fixture usage by introducing a generic fixture design base on fixture design principles. The last phase involves proposing a short-run statistical process control (SPC) method to detect setup variability.

The results from the gauge R&R test show that mechanically mounted accelerometers have the least gauge variance. Using an SOP, switching from wax-mounting to threaded stud-mounting reduces gauge variance by approximately 90%. However, wax-mounted accelerometers are still relevant for measuring vibrational responses from PCBs due to its non-invasive properties. The drawback will be that the gauge becomes a key contributor to measurement variation. The spatial uniformity test reveals that the center of the vibration table has the least variation and is selected for the fixture setup. Further limitations on the HALT chamber are highlighted. Evaluation on the proposed generic fixture demonstrates that the fixture has met the key design criteria and manage to induce consistent failures to the PCBs. Limitations on the fixture design are also considered. The proposed SPC method is able to detect at least 88% of the assignable sources of variation in a simulation test. Finally, a custom SOP for the fixture setup is drafted for the company.

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Chapter 1. Introduction

Highly Accelerated Life Testing (HALT) is a novel reliability testing method in the field of accelerated life testing. Although there is literature available that introduces the fundamental concepts of HALT, very few works address the details of implementing HALT, from data acquisition to fixture setup. This thesis explores the introduction and standardization of HALT in a multinational corporation as part of a reliability improvement process for printed circuit boards (PCBs). Specifically, it covers the evaluation of gauges for data acquisition, characterization of the HALT chamber’s vibration capabilities and introduction of a generic HALT fixture for PCBs. Ultimately, a suitable standard operator procedure (SOP) for an effective fixture setup for HALT is drafted as part of a larger operating procedure to implement HALT at the company.

Sections 1.1 and Section 1.2 will discuss the background and motivation for the project. Currently, the company is concerned with components with life expectancy issues that are only identified when they reach customers. Existing reliability tests seem ineffective in detecting these latent design flaws early in the product development cycle. The team and company believe that investing in a HALT program will help to identify design issues early and ruggedize the components prior to mass production. The problem statement and team approach used to address these needs are presented in Sections 1.3 and 1.4. Finally, Section 1.5 presents an outline for the rest of the thesis.

1.1 Background

This thesis is based on research conducted at a facility under Waters Corporation, an analytical instrumentation company, located in Milford, Massachusetts. This section presents an overview of Waters Corporation, the role and responsibilities of the Reliability Engineering Group in the product development cycle, as well as the design of printed circuit boards at Waters.

1.1.1 The Industry and Waters Corporation

Waters Corporation is an analytical instrument manufacturer founded in 1958. Currently, the company has two broad operating divisions: Waters Division and TA Division. The Waters Division supplies high performance liquid chromatography (“HPLC”), ultra-performance liquid
chromatography ("UPLC") and mass spectrometry ("MS") technology systems, along with consumable products like chromatography columns and test specimens. The TA Division supplies thermal analysis, rheometry, and calorimetry instruments. In addition to instrumentation, servicing and support forms 30% and 25% of sales in the respective divisions [1]. Waters’ customer base is broad, with the life science industries forming the largest sector. Throughout the years, Waters have been actively investing in Research and Development (R&D) as well as strategic acquisition of other instrument manufacturers to expand its market share. To date, Waters operates 21 United States facilities and 80 international facilities in 27 countries with a total of 6,600 employees in 2015 [1].

The Waters Division has two sub-divisions, the Biochemical and Chemical Analysis Division, based in Milford, Massachusetts, and the Physical Testing Division, based in Manchester, England and Wexford, Ireland. The two featured liquid chromatography (LC) systems, ACQUITY® UPLC® and Alliance® HPLC separations technology systems, are produced by the Biochemical and Chemical Analysis Division, while the mass spectrometry instruments are produced by the Physical Testing Division. Customers can purchase these systems that are complimentary to each other or standalone, depending on their testing needs. For example, the ACQUITY® UPLC® system contains different modules; detectors, solvent managers, sample managers, etc. Combinations of these modules can be made to separate and detect a range chemicals. Figure 1-1 uses ACQUITY® QDa® detector as an example to illustrate the flexibility of the products under the Waters Division. As such, any design issues in a single component can have a profound impact on the performance of multiple systems.

Figure 1-1 ACQUITY® QDa® detector instrument stack system configurations [2]
The TA Division was formed through an acquisition of TA Instruments and is headquartered in New Castle, Delaware. The operation of TA Instruments is independent of the Waters Division. By nature of the equipment, the instruments fulfill different needs of the same market segment. The Waters Division still maintains the main bulk of the sales in Waters with instruments driving most value to the company followed by services [1].

The Waters Division differentiates their technologies through performance, reliability and service. The Waters Division faces competition from companies like Agilent Technologies, Inc., Shimadzu Corporation, Bruker Corporation, Danaher Corporation and Thermo Fisher Scientific Inc. The TA Division main competitors are PerkinElmer, Inc., Mettler-Toledo International Inc., NETZSCH-Geraetebau GmbH, Thermo Fisher Scientific Inc., Malvern Instruments Ltd and Anton-Paar GmbH. Considering the new acquisitions made by Waters, government grants, favorable foreign currency translations and ever-rising competition, Waters has recently invested more aggressively in Research and Development (R&D) to produce new high quality products. Figure 1-2 represents this rise in R&D expenditures from 2013 to 2015. This investment entails more instruments passing through the product development cycle and it is a prime time to introduce better forms of standardization. Thus, the implementation of standardized HALT methods in the Reliability Engineering Group has never been more appropriate.

![Research and Development Process](image)

Figure 1-2 Increasing R&D expenditures at Waters 2013-2015 [1]
1.1.2 The Milford Facility

The company’s main R&D center is located in Milford, Massachusetts which is also the company’s corporate headquarters. The Milford facility maintains quality management and environmental management systems according to ISO 9001:2008, ISO 13485:2003, ISO 14001:2004 and certain pharmaceutical regulations like the FDA Quality System Regulation. Almost all liquid chromatography (LC) products are designed and developed in Milford. Figure 1-3 is a simplified representation of the product development process at Waters along with the involvement of respective departments or project teams.

![Image of product development process]

Figure 1-3 Condensed Waters instrument/product development plan [3]

1.1.3 The Reliability Engineering Group

The Reliability Engineering Group at the Milford Facility fulfills the needs of Waters by providing crucial information on a product’s robustness and its capability to meet the customers’ needs. The department is involved in two ways. Firstly, the group evaluates and supports activities during the instrument development process as outlined in Figure 1-3. An interdepartmental team will then conduct test experiments on the Alpha prototype, a proof of concept design, for economic evaluation and feasibility check. If the prototype does not meet test requirements, an iterative design process ensues. Eventually, a successful design, a Beta prototype, which meets end use environment requirements will be released for full-volume production. Secondly, the group also supports evaluation of existing products. The request for support may arise from the need to do failure analysis of field products, product improvements, or testing when there is a change of supplier for existing product lines. Similarly, a dedicated team of engineers and technicians from different departments are involved in the process. All LC hardware has a warranty period of one-
year and a design life of five-years. Ultimately, the reliability engineers at Milford have to evaluate and ensure that all non-preventive maintenance hardware do not fail within the one-year warranty period. Accelerated tests and functional tests prior to product launch or improvements are common practices to ensure that these goals are achieved. Close collaboration with Marketing, R&D and Quality Departments are necessary to ensure that testing has met end use environment needs, robustness goals and functional requirements of the products. Note that all products at the Reliability Lab are tested for robustness against end use environment stresses and nothing beyond.

1.1.4 Printed Circuit Boards at Waters

This section will describe how printed circuit boards are developed in Waters and provide insights on how the team could potentially standardize the HALT setup for PCBs. Generally, printed circuit boards in Waters are designed by the R&D team. If a printed circuit board is part of a product, product requirements are sent to the R&D team to build Alpha prototypes along with detailed specifications of the board. Circuit boards are designed by electronics hardware engineers to fulfill the functionality and manufacturability of the board. Mechanical engineers then consider how the board will be used and provide feedback on potential mechanical issues. For example, mounting holes are located on regions where connectors are present because they tend to be subjected to pushing and pulling forces during assembly. Geometrically, PCBs at Waters are rectangular in shape and the locations of mounting holes tend to be symmetrical in both axes. Except for tooling holes, the dimensions for mounting holes and studs are not standardized. The smallest board dimension is 1” by 1” while the largest can range up to 13” in length. There are over 200 different types of PCB boards in Waters. Once the design passes through the development procedure, full-scale production is fulfilled by contract manufacturing firms. The manufacturer must conform to certain manufacturing standards set by Waters, and contract to Association of Connecting Electronics Industries (IPC) standards. Each board comes with a bill of materials (BOM), schematic, PCB artwork, PCB Drawing and an assembly drawing. In-production boards at Waters come with an in-circuit test (ICT) fixture and a functional test fixture that rapidly tests the connectivity and functionality of the boards, respectively. The necessity and design of the fixtures are determined by the Test Engineering Group. Figure 1-4 shows examples of such fixtures.
1.2 Research Motivation

In addition to the intricate mechanical components such as columns, pumps, syringes, and valves in the system, the electronic components such as power supplies and printed circuit boards (PCB) that control all of the hardware also play critical roles in the instrument. The field failure rates of electronic components are often higher than that of the mechanical components. Although the reliability of products are evaluated during the design process and post-production process, the unpredictable nature of external stresses during shipment and in the end use environment have led to pre-mature failures of PCBs within the warranty periods. These undetected product flaws eventually reach the customers and reduce customer quality while increasing service costs for Waters. Despite the fact that design verification and instrument evaluation are integral to Waters’ product development process, the current reliability testing methods have yet to leverage on the full benefits of a complete HALT procedure to precipitate latent defects during pre-production. By developing a standard operating procedure (SOP) for Waters based on industry best practices and experimentation, the team believes that it will catalyze the adoption of HALT and subsequently, increase the product’s robustness and reduce warranty costs.
1.3 Problem Statement

The Reliability Engineering Group and Test Engineering Group at Waters have been facing problems identifying root causes of failure, especially for printed circuit boards (PCBs) that fail in the field but pass functional and ICT tests when brought back for testing. Although there have been efforts in implementing HALT, resource availability and opposition from the R&D Group in testing beyond products specifications (see Section 2.1) have delayed the development of a complete HALT procedure. The agglomeration of such issues results in an inefficient and incomplete HALT approach. The team consulted with reliability engineers and found inconsistencies in the way the current HALT procedure at Waters is conducted as compared to industry practices. Although the HALT chamber has been in the Reliability Lab for more than five years, the ineffective use of the resource has meant losses of potential savings [4] from a ruggedized product and depreciation of idle inventories that can otherwise turn into profit. Figure 1-5 shows the evolution of within-warranty service rates for a PCB that would have benefited from proper screening using the HALT chamber prior to its introduction. With HALT, the design flaws on the PCB can be identified earlier and costs incurred from undesirable servicing work especially between the 1st quarter of 2011 and 3rd quarter of 2012 may be avoided. Considering that most operators are uncertain on the best way to utilize the HALT chamber for testing, there is an opportunity to improve overall reliability of Waters’ products and reduce potential costs by incorporating a standard operating procedure for HALT.

![Plunger Drive Board Service Rate (Normalized to Install Base)](image)

Figure 1-5 Service rates for 210000425 showing the period of unplanned quality loss that can be reduced or removed by HALT
The problem at hand is to study the existing use of the HALT chamber and evaluate the available resources at Waters so as to reengineer a new operating process that will lay the foundation of HALT in Waters. To do this, the team will seek to develop a thorough understanding on the execution of HALT, the capabilities of the HALT chamber, appropriate data acquisition practices as well as fixture design and setup principles. After which, the team will determine the appropriate stress profiles and screening criteria for printed circuit boards that matches the company’s reliability or economic goals (see Section 1.1.3).

Issues may arise when considering to what extent these components should be tested. There is often a trade-off that exists between testing costs, improvement costs and cost of quality. For example, a component could be re-designed and improved after numerous reiterations of the HALT process (see Section 2.1) and guarantee zero failures over the life of the component. However, if the improvements in robustness and quality are made at a grossly increased cost that outweighs the potential savings, then further screening may not be desired. There is a need to find the balance between costs and cost of improvement when it comes to component, design, or production changes. A successful HALT program would facilitate efficient screening of these scenarios, further increase product robustness, and reduce unnecessary service and rework costs while providing insights to augment the design.

1.4 Team Objective & Approach

The project begins by selecting a baseline PCB that the team will create and test the SOP around. Three PCBs were taken into consideration due to their history of high field replacement rates. However, the suitability of the PCB in conducting the full HALT process took precedence. The plunger drive board (210000425) was selected because it has a functional test fixture for the team to speed up the root-cause analysis process after stressing the board in the HALT chamber. Only when the weak links in a design are identified can a product be made more robust. Thus, to detect weak links efficiently, a functional test fixture is important. The board’s key functions have to be identified so that the team knows how and where to test for board failure during a HALT experiment. Figure 1-6 shows the functional block diagram of the board where the inputs and outputs of the system are marked. Figure 1-7 shows the PCB’s assembly drawing where the mounting holes and various components are identified. By understanding the drawing, the team
can speculate potential failure modes and plan the best mounting method to secure the PCB to the HALT chamber before the HALT experiment is conducted.

![Block Diagram](image)

**Figure 1-6** Functional block diagram of 21000425 showing the system outputs and inputs

![Assembly Drawing](image)

**Figure 1-7** Assembly drawing of 21000425 with mounting locations highlighted
From the field service rates in Figure 1-5, the plunger drive board represents a robust PCB because the latest version of the board that the team uses have very low field repair rates. Using the operating margins of the board obtained from a full classic HALT, the team can engineer a relationship with the service rates and extrapolate to other circuit boards [5].

In order to achieve the objective, the process is divided into three main parts: Process improvement with respect to data acquisitioning for vibration and standardization of fixture setup for HALT, standardization of HALT stress profiles and cost-benefit analysis of the implementation. This thesis focuses on data acquisitioning and standardization of fixture setup. The details on HALT stress profiles and cost-benefit analysis can be found in both Chang [5] and Singh [6] theses.

1.5 Thesis Outline

The objective of the thesis is to implement an efficient fixture setup protocol for PCBs through scientific and statistical justifications. The approach is split into three main sections. The first is to ensure that the data acquisition devices and measurements for the desired stresses are utilized appropriately. Due to time constraints, the project only implements vibration and thermal stressors, which are the standard basic stressors for a classic HALT. More specifically, data acquisition devices for vibration are evaluated because the large variety of accelerometers are available. A gauge repeatability and reliability (gauge R&R) test is used to objectively characterize the capability of existing accelerometers, from which, decisions can be made to determine when and what accelerometers are to be used for data acquisition. A more efficient data acquisition method is also introduced to speed up the data mining process.

The second objective of the thesis is to establish a list of principles for designing test fixtures for the HALT process and to propose a generic fixture setup for testing PCBs. Design of experiments (DOE), with emphasis on response surface modelling, is used to statistically characterize the spatial uniformity of vibration levels on the shaker table. This allows reliability engineers to decide appropriate regions for the device under test (DUT) to be mounted. To evaluate the new fixture, a simplified modal analysis using finite element analysis (FEA) simulation is introduced to check whether the fixture's natural frequency meet its design requirements. Further
use of DOE is used to evaluate the spatial vibrational response of the fixture to assess its performance and identify areas of improvements.

Finally, a short-run statistical process control (SPC) method is introduced as a check to ensure that fixture setups are consistent and robust against systematic errors like operators’ negligence. By doing so, meaningful conclusions can be made from the HALT experiments and add credibility to the test cases.

The thesis is structured into multiple chapters that provide the necessary background information on the project and follows a logical progression. Chapter 1 introduces Waters Corporation and provides a brief insight on the available resources and the importance of HALT for Waters. Chapter 2 of the thesis covers the existing HALT setup procedures in the industry, design considerations for vibration fixtures and the statistical analytical tools like Gauge R&R, DOE and SPC that will be used in the analysis. Chapter 3 discusses the context that the fixture setup operating procedure is drafted. This is achieved through outlining the HALT-specific resources available at the Reliability Lab. Chapter 4 describes the gauge R&R analysis of mechanical and adhesive mounted accelerometers as well as the approach to characterize spatial uniformity of vibration for the HALT chamber. Chapter 5 proposes a generic fixture setup for PCBs and characterizes of the new fixture’s performance. Chapter 6 outlines the implementation of a short-run statistical process control and evaluates its capability to detect common assignable causes of variations that may occur during fixture setup. Chapter 7 summarizes and consolidates the findings from Chapters 4 to 6. Lastly, Chapters 8 showcases the abridged version of the suggested SOP for fixture setup based on the results and conclusions from Chapter 7. Chapter 9 concludes with recommendations for future work and improvements.
Chapter 2. Theoretical Review

This chapter will provide the theoretical background necessary to establish a dedicated SOP for fixture setup at Waters. Section 2.1 and 2.2 provides an overview of HALT and the classic stress profiles. Section 2.3 and 2.4 outlines the fixture design and setup principles that are recommended by literature and the reliability industry. Section 2.5 to 2.7 provides a review of the underlying statistical methodologies of gauge R&R, response surface modeling (particularly on spatial non-uniformity) and statistical process control that will be applied for the analysis in the following chapters.

2.1 Highly Accelerated Life Testing (HALT) Overview

HALT is a process of increasing the reliability of a new product through corrective action and understanding on its operating limits (OL) and destructive limits (DL) by stressing the product beyond end use conditions. The process evolved from traditional product stressing techniques like Environmental Stress Screening (ESS) which are not aggressive enough to precipitate latent design defects that lie dormant until it reaches the customers [7]. Existing standards like ASTM D4728 and MIL-STD-883E uses pre-defined levels of stresses with some margin of protection against variation in environmental stresses. However, these margins are not wide enough to fully protect against the variations throughout the product’s life cycle [8]. Environmental stresses experienced by the product and the strength of a product can be modelled as a random variable. The overlapping region shown in Figure 2-1 between the stress and strength curves represents probability of field failures, unaddressed by the aforementioned screens. On the other hand, the reiterative nature of HALT constantly removes weak links in the design and has no limits to the degree of improvements to be made on the product. In other words, much higher levels of stress can be continuously applied to a product to precipitate its weak links and corrective actions can be made to remove them. Nonetheless, typically the HALT process stops when sufficient economic benefit is achieved from a more robust product.
HALT is originally used extensively to ensure reliability of electronic systems during product development phase by stressing components, sub-assemblies and large assembly systems with multifaceted stresses. The type of stresses employed are dependent on the components, functionality and specifications of the device under test. Examples of stresses include but are not limited to temperature, random vibration, humidity, pressure, radiation and voltage cycling. All of these stresses can be applied alone or combined to form different stress profiles. The distinctive nature of HALT lies in the ability to combine different stresses and test at levels beyond end use environments. By stressing beyond end use environments, it simulates flaws that may occur when the product ages [8]. Thus, the term “highly accelerated” is used in HALT.

The success of HALT occurs when a failure is identified in the product during stressing and appropriate corrective action is made. The act of error correction results in product ruggedization [7]. Ruggedization shifts the products’ strength far away from the region of overlap between stress and strength distribution, improving the lifespan of the product. Figure 2-2 aptly captures this strengthening process by showing a shift in the product’s strength distribution curve to the right, away from the stress curve. The dotted red line represents the higher stress levels imposed on the product during HALT that helps to precipitate the more weak links so that corrective action can be done. Ideally, any overlaps between the environmental stress curve and product strength curve after HALT are now negligible.

Figure 2-1 Stress and strength curves of a typical product that do not go through HALT
Stress Testing Simulates Aging & Amplifies Unreliability

![Stress Testing Simulates Aging & Amplifies Unreliability](image)

Figure 2-2 Stress and strength curves transformation during and after HALT [8]

The financial benefits from increased product reliability during pre-production provides indirect cost savings by freeing up resources and increasing competitive advantages. For instance, the R&D engineers could focus on developing the next product instead of doing rework and design adjustments to an existing one. Additionally, products could be launched earlier and at a lower costs because the increase in confidence of a robust products means an increase in confidence to leverage on economies of scale. Before reaping the benefits, initial investments involving the HALT setup and operating overheads have to be made. To determine the budget for HALT, a pre-HALT group consisting of test engineers, reliability engineers, R&D engineers designers, technical product manager and global operation engineers will decide on the extent of ruggedization necessary using a cost-benefit analysis [7].

HALT, along with High Accelerated Stress Screening (HASS), a post product development phase screening method that monitors product robustness of all products leaving the manufacturing line, reduces early life failures due to manufacturing and design flaws. Figure 2-3 shows how HALT increases products’ resistance against external stressors by having an ideal zero failure rate at its mid-section of the bathtub curve. The end of the bathtub curve has also become longer, showing the lengthening of product’s life [9]. Additional benefits such as greater customer satisfaction, increased brand loyalty and revenue are not captured in these figures.
HALT increases product life cycle

2.2 HALT Stresses and Stress Profiles

Although there are various ways an operator can stress the DUT, the two common industry recommended stresses are random vibration and temperature. Most off-the-shelf environmental chambers provide these two form of stressing capabilities. Classic HALT involves a 4 step process. The first step is a two-part cold and hot step stressing where the temperature is increased (or decreased) in steps of a definite increment (or decrement) to a set limit. During this step, operating limits (where the DUT returns functionality when stress is removed) and destruct limits (where the DUT fails indefinitely) for thermal stresses, are known. The DUT is stressed to extreme temperatures in this stage. Figure 2-4 captures these thermal profiles that were implemented in this project.
The second stage involves rapid thermal transitions where ramp up (or down) rates are at the maximum. The rapid cycling limits are within the thermal operating conditions identified in the first stage. Figure 2-5 shows the thermal cycling profile that was used in this project.

The next stage requires the use of vibration as a stressor. Similar to the first stage, vibration is introduced in steps with increasing $G_{\text{rms}}$ to a definite limit. Subsequently, the operating limits

---

1 Root-Mean-Squared Acceleration: A statistical measure of vibration levels for random vibration
for vibrational stresses are obtained. Figure 2-6 shows a graphical representation of the vibration step stress profile that is implemented in this project.

![Vibration Step Stress Profile of Alliance 425](image)

Figure 2-6 Vibration step stress profile [6]

The last stage involves a combination of both vibration and temperature with a minimum of 5 phases in this stage. Each phase involves a predefined level of vibration step and a run of the thermal profile from stage 2, but slightly lower than the thermal operating limits. For example, if the vibration destruct limit is $60G_{\text{rms}}$, each thermal cycle has a vibration dwell setting of a multiple of $12G_{\text{rms}}$. Figure 2-7 captures the combined step profile that is used in the project.

![Combined Temperature and Vibration Cycle for Alliance 425](image)

Figure 2-7 Combined step stress profile [5], [6]
The sequence for HALT is structured to have progressively higher levels of stress [10]. This order is important in precipitating flaws in a hierarchical manner so that design flaws are identified with adequate resolution. Figure 2-8 shows a chart on the percentage of defects found from each of the four stages based on forty-seven products from thirty-three companies representing nineteen industries [7]. Note that the percentages failures are not a result of stresses induced by a single stress profile but an accumulated stress built up by the preceding stress profiles.

One must note that there are multiple interpretations on the recommended dwelling time, ramp rates and limits of testing and corrective action. Presently, the more well-received standards for HALT are those set by Qualmark™, the largest manufacturer of accelerated reliability test equipment [11]. Guidelines by McLean and General Motors (Document GMW8287) on HALT are also well received by the industry (see Appendix A-1). These profiles are very similar in execution and some provided greater detail than the other.

Compulsory functional tests are also necessary to check the impact of the stresses on the DUT and appropriate corrective measures have to be executed to continue with the next phase of the test. Whenever possible, concurrent functional testing on the DUT is recommended to identify the operating limits and destruct limits with better resolution. Ultimately, HALT provides a performance evaluation on a product's design through these limits. From which, the operators will
decide whether the product is considered as sufficiently robust. Figure 2-9 displays the various margins that will be known at end of a HALT Process.

![HALT margin discovery diagram](image)

These HALT guidelines will be used as base references for our proposed stress profiles and fixture setup. More details on HALT stress profiles are covered by Chun [5] and Singh [6].

### 2.3 Principles for HALT Fixture Design

A typical setup for HALT involves the environmental chamber, fixture and data acquisition devices. The fixture design for HALT forms a major section in the SOP. Vibration tables like that in the HALT chamber usually have a defined hole-mounting pattern that allows mounting of structures. Unfortunately, the DUT comes in various forms and mounting points which may not conform to the geometric mounting pattern on the table. As such, a fixture is a structure necessary to address this limitation by behaving as an intermediary component that passes excitation onto the DUT from the vibrating table. A badly design fixture will cause major distortion to the input excitation from the vibration table and limits the capabilities of the HALT chamber. The following sections discusses certain principles expected of a fixture for classic HALT.

#### 2.3.1 Vibration & Transmissibility: Resonant Frequency, Material Choice and Geometry

Pneumatic actuators attached on the underside of the vibration table are responsible for generating the necessary excitation via a series of mechanical impulses. The vibration table then
expresses a broadband frequency excitation [12] onto the DUT through the fixture. Ideally, the input excitation amplitude should be uniformly distributed across the frequency of interest [13] so that structural resonances of the board and component levels could be excited simultaneously without biasness to any frequencies. For our chamber, the frequency of interest would be from 0 kHz to 10 kHz. Although much higher frequencies tend to be present, HALT experts claim that higher order of frequencies contribute little to fatigue because small displacements do not result in sufficient strain. Figure 2-10, shows an ideal power spectral density (PSD) for random vibration test for a turbine powered aircraft equipment as outlined in MIL-STD 810. Notice that the theoretical settings have well defined lines in the PSD curves.

![Graph showing theoretical settings of PSD curves for different aircrafts.]

Figure 2-10 Jet aircraft vibration exposure of different military aircrafts [14]

Similarly, our chamber setting for vibration stress during HALT should have a uniform PSD curve and have its amplitude varies linearly with the input acceleration. However, in reality, resonance frequencies of the table-spring system distorts the uniformity. Some chamber designers leverage on the distortion to select system properties that enhance certain frequencies and suppress others so that typical failures for certain categories of components could be readily detected [15]. However, a uniform excitation across the 0 kHz to 10 kHz is still desired for this thesis.
Ideally, the DUT would be placed directly on the vibration table such that the dynamic response of the system is directly due to the forced input. In practice, securing a fixture introduces another source of variation to the vibrational response of the DUT that may render the results meaningless. The degree of deviations in amplitude, excitation uniformity over frequency range and spatial uniformity of the table is highly dependent on the transmissibility curve which is determined by the resonant frequency of the fixture. Figure 2-11 represents a generic transmissibility curve that shows how the force amplitude ratio approximates to 1 when the frequency ratio of the excitatory force to natural frequency of the fixture is significantly less than 0.5. This behavior is independent of the damping ratio, \( \zeta \), of the system.

When TR is 1, the motion on the fixture output is identical to the motion of the fixture input. To achieve this desired behavior, the fixture’s resonant frequency has to be sufficiently larger than the driving frequency. Some experts have suggested designing the natural frequency of the fixture to be at least 50% higher than the maximum forcing frequency [17]. In our context it should be at
least 15 kHz or higher. One common method is to increase the stiffness of the structure through changing the geometry and material of the fixture.

In addition to the consideration of resonant frequency of the fixture system, by Newton’s second law of motion, acceleration is dependent on the mass of the system. The more massive the fixture, the less acceleration is experienced by the fixture. Although the acceleration of the vibration table is controlled by a feedback controller, a massive fixture will reduce the maximum acceleration that the pneumatic actuators is rated to provide. Additionally, the fixture has to be able to withstand the high stresses during the test to fulfill its purpose of transmitting the necessary forces for vibrating the fixture. As such, a light, stiff and strong fixture is be favored.

Typical material choices for fixture design include aluminum, magnesium and steel. The specific modulus, ratio of Young’s modulus to density \((E/p)\), provides a good gauge on the effects on natural frequency once a geometry is decided. Although having a material with similar ratio may not greatly affect the natural frequency of the fixture, it all depends on absolute value of the specific modulus and density. For example, the three metals have similar specific modulus but steel is very stiff yet it is the heaviest. Thus, aluminum and magnesium might be suitable choices. Besides weight, cost of the material and machinability also plays a part so a cheaper material like aluminum might be the selected choice. Table 2-1 shows some specific modulus and properties of vibration fixture metals recommended by Brüel & Kjaer, a leading global manufacturer of sound and vibration systems.

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<th></th>
<th>Steel</th>
<th>Aluminum</th>
<th>Magnesium</th>
<th>Titanium</th>
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</thead>
<tbody>
<tr>
<td>Young’s Modulus ((E)) N/m²</td>
<td>20.7 x 10¹⁰</td>
<td>6.9 x 10¹⁰</td>
<td>4.14 x 10¹⁰</td>
<td>10.7 x 10¹⁰</td>
</tr>
<tr>
<td>Density ((p)) kg/m³</td>
<td>7840</td>
<td>2770</td>
<td>1800</td>
<td>4510</td>
</tr>
<tr>
<td>(E/p) N m/kg</td>
<td>2.65 x 10⁷</td>
<td>2.49 x 10⁷</td>
<td>2.30 x 10⁷</td>
<td>2.38 x 10⁷</td>
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</table>

Table 2-1 Physical properties of fixture metals suggested by Brüel & Kjaer [18]

Other recommendations for fixture designs for vibration include having a single block element machined instead of fastening multiple pieces. This method helps to reduce variability due to loosening and bolts behaving as springs at high frequencies. However, the costs of production may have to be considered. Additionally, the contact surface between the fixture and the machine has to be as parallel and flat as possible. Any burrs will reduce the stiffness of the test
setup to the fixture alone as opposed to the higher combined stiffness of the fixture and the vibration setup because of reinforcements with the vibration table. A choppy signal may also be introduced if the fixture slaps onto the vibrating table [19]. To reduce opportunity of bolts loosening when securing fixtures to the table, tighten all the bolts as much as the system allows. A reference to a torque chart for fasteners would provide a good estimation of the amount of torque recommended.

With regards to geometric properties and its relation to the fundamental frequencies, Figure 2-12 shows various formulae that relates this relationship for common shapes like plates. There are many different boundary conditions for plates and the formula displayed are just a few but it is sufficient to provide insights on the parameters to vary for the proposed fixture design in this project (see Section 5.2). Regardless of the kinds of fixture used, it is important to characterize the fixture prior to use [7].

### Natural Frequency (hertz), \( f_{ij} \) or \( f_i \)

\[
\lambda_{ij}^2 = \frac{\lambda_{ij}^2}{2\pi a^2} \left[ \frac{Eh^3}{12y(1-v^2)} \right] ; i = 1, 2, 3 \ldots ; j = 1, 2, 3 \ldots
\]

**Free-Free-Free Rectangular Plate**

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**Square Plate, Four Point Supports**

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</table>

*Repetitive values.*

**Figure 2-12 Formulae to calculate natural frequencies of rectangular plates in free-boundary conditions (left) and four point supports (right) [20]**

#### 2.3.2 Uniformity of Airflow: Minimalistic, Height Offset, Low Thermal Mass

Heat transfer within the HALT chamber is predominantly due to convection heating and cooling. A thermocouple measures the overall temperature of the chamber and provides a feedback control to either instruct the activation of liquid nitrogen or heating element. The mixture of hot and cold air is mixed at the top of the chamber prior to release through six 4" flex ducting. Users
have the choice on the number of ducts to be used in the experiment and the placement of the duct relative to the DUT.

The objective of the setup is to allow uniformity of air flow through the entire product so that components heat up more evenly and reach thermal equilibrium at a faster rate. As such, it is recommended to keep fixture designs minimalistic so that air flow will not be hindered. If possible, the fixture should raise the DUT sufficiently to promote airflow on the underside of the DUT as well [7]. This is especially important for PCBs that have components on the underside of the board. Additionally, the thermal mass of the fixture is recommended to be as low as possible [21] so that temperature changes of the fixture are responsive to the profile settings and would not distort the heat flow between the DUT and surroundings.

2.3.3 Meeting Chamber’s Specifications: Small, Strong & Sufficiently High Melting Point

The HALT chamber itself has specifications that imposes limitations on the choice of fixture material and design. Some vibration tables are tuned to vibrate at certain frequencies. Adding a huge plate over the table significantly changes the rigidity of the table and affects its resonant frequency. Thus, a small and light fixture is favorable. Additionally, there is a load limit for the chamber that the springs can withstand. Lastly, the HALT test is meant to cause failures in the DUT and not the fixture. Thus, the experimenter has to also ensure that the fixture has a high enough melting point, fatigue life and strength to remain functional throughout the tests. Aluminum is a popular choice for a cost-effective solution that meets the mentioned fixture characteristics. Section 3.1 provides details on the chamber that is used in this project.

2.4 Principle for HALT Fixture Setup

A typical setup for a classic HALT test involves the use of a HALT chamber, test fixture, liquid nitrogen tanks, and sensors like thermocouples and accelerometers. Data acquisition and processing hardware are also necessary to provide visual interpretations of the DUT’s dynamic response to the stresses. Figure 2-13 provides a graphical representation on how a typical classic HALT experiment is setup.
Figure 2-13 Classic HALT setup and data acquisition process

Fixture design is only one aspect of the setup. The other challenge is to measure and operate the system adequately. Inconsistent setup of the system will yield significantly different results. The following section discusses the various differences that may result from setting up of the HALT chamber and industry best practices for HALT.

2.4.1 Fixture Mounting Considerations

Unlike screening tests like HASS, HALT experts have preached that the boundary conditions at which the DUT is setup do not necessarily follow the end use environment [7]. The justification is that HALT attempts to stimulate failure modes and weaknesses of the product rather than simulating failure modes[7], [22]. The statement is valid because HALT allows the operator to be more informed on the robustness of the product by stressing at levels beyond end use conditions. Nonetheless, if the operator mechanically mounts the DUT differently from end use conditions, it may introduce a different hierarchy of failures. As outlined in Figure 2-8, altering the boundary conditions in which the DUT is mounted, affects the resonant frequency and mode shapes of the DUT. This results in different stresses experienced by the components and potentially different failure modes. To date, there is no consistency in the fixtures used by HALT veterans for printed circuit boards.
2.4.2 Vibration Table Uniformity

HALT relies on the foundation on Miner’s rule where accumulated fatigue damage is exponentially related to the number of cycles of stresses applied to the product. With the exponential nature of accumulated fatigue, if products are inconsistently setup, small differences in stresses, $\sigma$, will result in significantly different failure limits [23]. Equation 2.1 shows this relationship [7]. Essentially, if the fixture setup is not consistent, to conclude that one board is more (less) robust than the other because it fails at a higher (lower) level of vibration setting is no longer be valid.

$$D \approx n\sigma^\beta$$

Equation 2.1

Where
- $D$ is the Miner’s criterion fatigue damage accumulation
- $n$ is the number of cycles of stress
- $\sigma$ is the mechanical stress in force/area
- $\beta$ is the material property (8-12)

One of the key source of variation in fixture setup is the lack of spatial uniformity of vibration on the vibration table. Despite having the same input vibration setting, a non-uniformly distributed vibration level across the table will cause the DUT to experience different level of excitations and stresses when mounted at different locations. If Waters wants to have a standard for qualifying their circuit boards or compare robustness between boards through HALT, it is important to be consistent in setup and location. By characterizing one’s vibration table in all three axes, the experimenter would have a more informed choice on where to place their DUT as part of a standardization process. Figure 2-14 highlights the difference in vibration uniformity across a laminated vibration table (damped and segmented) and a table with solid construction (undamped and solid). The laminated table has greater uniformity in the x, y and z directions as well as spatially across the table’s surface [24].
Figure 2-14 Comparison of spatial uniformity for vibration across a damped, segmented table (top) and an undamped, solid table (bottom) [24]

2.4.3 Accelerometers: Selection Criteria and Mounting Considerations

An accelerometer is an electromechanical transducer that produces a voltage or charge that is proportional to the acceleration that it is subjected to. There are many types of accelerometer technologies. Some widely known technologies include microelectromechanical system (MEMs), piezoresistive accelerometer and piezoelectric accelerometer. Today, piezoelectric accelerometers
are preferred choices for vibration analysis because it has better sensitivity, excellent linearity over dynamic range, higher frequency range and is an active device that gives an electrical charge when there is a change in load without the need for a voltage input [25]. They come in different sizes, weights, mounting mechanisms, range of measurement and sensitivity. Selection of these accelerometers depends on the context of data acquisition and the frequency of interest. Our ideal accelerometer should fit the HALT chamber frequency specifications of 0 kHz to 10 kHz, able to withstand at least 100G_{rms} and has a temperature range up to 200°C. The selection for accelerometers to meet the context of the experiment is straightforward because specifications are reflected in the accelerometer’s datasheet. However, the deviations from specifications during application requires further understanding.

The linear response by the accelerometer is limited by its resonant frequency. A suggeste rule of thumb is to have upper frequency limit for measurements be set at one-third of the accelerometer’s resonant frequency so that error will be less than +12% [26]. An important note is that the mounting considerations affects the useful frequency range of the accelerometer. Figure 2-15 shows the how the various forms of mounting changes the natural frequency of the accelerometer. The experimental results have shown that using a mechanical stud mount with grease gives the best frequency range. In theory, this is the most suitable mounting method for broad frequency ranges like that of HALT experiments.
Figure 2-15 Different mounting methods for piezoelectric accelerometers and their respective resonance frequencies of the accelerometer system [26]

Compared to mechanical stud mounting that requires mounting holes, adhesive mounting provides a non-invasive data acquisition setup that is less time consuming. Although it is convenient to use adhesive to attach accelerometers to test points, readings are recognized to be highly non-repeatable [27]. The thickness of the adhesive is also hard to control and affects the natural frequency of the system. The relationship between the application of adhesive and the natural frequency for wax-mounted accelerometers is shown in Equation 2.2 [28]. The larger the area covered by the wax and thinner the adhesive film used, the higher the natural frequency of the accelerometer. This arrangement is the most desirable for wax mounted accelerometers to achieve a wider usable frequency range.
\[ f_n = 3.13 \frac{AE}{\sqrt{tW}} \]  

Where  
\( f_n \) is the mounted natural frequency in Hz  
\( A \) is the area of wax under accelerometer base in square inches  
\( t \) is the thickness of wax in inches  
\( E \) is the modulus of elasticity of wax in psi  
\( W \) is the weight of accelerometer in pounds

Besides mounting considerations, the accelerometer's main axis of sensitivity and its orientation to the point of measure potentially affects the measurement results. Accelerometers do respond to accelerations on other axes too. As such, mounting positions should minimize transverse response as much as possible [26]. Considering that the vibration table excites in 6 degrees of freedom, a three axis accelerometer is desired for modal analysis. For a three axis accelerometer, all three orthogonal main axes need to be taken into consideration. Slight deviations from these axes will result in variations in the measurements for respective axes. As such, the mounting surfaces are highly recommended to be spot-faced. Dytran recommends a surface parallelism with tolerance of less than 0.001" for a mechanical stud mount. Silicon grease is recommended to lubricate the surface and ensure intimate contact, maximizing transmissibility to the accelerometer [26]. For a threaded stud mounted triaxial accelerometer, shims are recommended to ensure that the position of the three axes are aligned to the desired directions after tightening. Figure 2-16 provides a visual representation of the transverse sensitivity of a single axis accelerometer from Brüel & Kjær.
Figure 2-16 Vector representation of transverse sensitivity and main axis sensitivity [26]

Other good practices include having an accelerometer, no greater than 10% of the weight of test article [29], securing coaxial cables down to reduce triboelectric noise during cable whips during vibration and having an insulating stud between the accelerometer and its mounted surface to reduce ground loop currents.

2.4.4 Air Flow and Air Ducts

There are six 4” air ducts in the HALT chamber own by Waters. They are used to heat up the DUT uniformly and quickly so as to reduce dwelling time during temperature step profiles. There is little publications on the recommended air ducts set up for HALT. However, basic theoretical understanding may shed some light on its desired orientation.

Convection involves combined effects of conduction and fluid motion [30]. By using the ducts, fluid motion is forced to flow along the direction of interest as compared to natural convection where fluid motion is based off buoyancy forces due to density differences induced by
temperature variances. The faster the fluid motion, the greater the convection heat transfer which is favorable for reducing dwell time [22]. By mass conservation, one could theoretically minimize the area of the duct so that fluid flows faster and thermal equilibrium is reached much quicker. However, frictional forces on the surface area of the outlet duct has to be considered when altering the geometrical shape of the output.

Another factor to note is the placement of the duct. Having multiple ducts directly blowing onto the DUT as opposed to directing into the chamber space heat up the board faster but may also induce temperature gradients on the PCB which are unfavorable for uniform heating. Directly opposing ducts may also create stagnation regions, locations with negligible air movement. Fortunately, in our system there is a ventilation fan that creates turbulence in the system to break down air pockets [7]. Ultimately, the best approach to determine the desired configuration is to conduct experiments and compare the results. Nonetheless, if thermal equilibrium is not met, the experimenter can always increase the dwell time for the DUT to reach close to thermal equilibrium before continuing with HALT [22]. The determination of dwell time involving thermal stress profiles can be found in Chang’s thesis [5]. In comparison to vibration, temperature variations tend to be less of a concern to HALT experts unless one would like to conduct an optimization problem.

2.4.5 Data Acquisition and Placement of Sensors

As outlined, classic HALT provides two stresses – temperature and random vibration. This section explores industry suggestions on the locations to mount the sensors during the test.

For temperature, common practices require the use of thermocouples. Typically there are at least two thermocouples, one on the product and one in the chamber used as feedback loop in a temperature control. The purpose of the measurements are to ensure that the DUT receives the necessary stress levels. McLean proposes having thermocouples attached to a point on the product that is representative of the thermal response and he recommends placing it at the geometric center [7]. The GMW8287 and Qualmark’s HALT guidelines also adopt similar recommendations and warns against placing on a heat-generating component or inside an enclosed region. All these locations are not representative of the DUT [21], [31]. After a representative point for the DUT’s thermal response is selected, thermocouples could also be placed on other locations of interest that
may provide insights onto potential areas for failure. These locations include heat generators, thermally sensitive components and components that are designed to respond quickly to heat. Additionally, the temperature response of a region with highest thermal mass on the DUT has to be determined prior to running the stress profiles [21]. This action allows experimenters to identify the necessary dwelling for the DUT to reach thermal equilibrium. As such, multiple thermocouples may be needed before and during the HALT procedure. Kapton tape is recommended to electrically isolate the DUT and ensure measurements are from the DUT and not the air.

For vibrational measurements, Waters uses Integrated Electronics Piezo Electric (IEPE) accelerometers, accelerometers with built-in preamplifier, from Dytran Instruments Inc. This section onwards will refer accelerometers to IEPE accelerometers. IEPE accelerometers are powered by an external current source and outputs voltages that are proportional to acceleration. These voltages are generated by then amplified internally, recorded by a data acquisition (DAQ) system and digitally processed. Typical processing includes digitally filtering out unwanted signals and scaling the millivolts to get acceleration, usually expressed in units of g-force or the acceleration of gravity at sea level. Random vibration by their nature contain a broad band of frequencies, and the root-mean-squared (rms) values of g-force is measured, $G_{\text{rms}}$, as a metric of severity of excitation. $G_{\text{rms}}$ can be obtained by two methods in the time domain. The first method involves filtering of the continuous signal output from the accelerometer to get the desired frequency range and utilize an analog rms converter circuitry to directly display rms values from a DAQ device. The second method involves calculating rms digitally by sampling the entire analog output with the use of anti-aliasing filters, and post-processed using digital filters to get the rms of the interested frequency range [32].

$G_{\text{rms}}$ can also be determined from the frequency domain through the power spectral density (PSD) curve. To get $G_{\text{rms}}$, one can take the square-root of the area under the PSD curve within a specified frequency of interest as shown in Figure 2-17. The PSD curve is obtained from the Fourier transform of an autocorrelation function of a time signal. This curve provides insights on the magnitude of excitation in the frequency domain. The PSD curve is useful to identify resonance frequencies. During modal analysis, the $G_{\text{rms}}$ and PSD curves provide insights on the potential mode shapes and resonant frequencies of the DUT.
If resource permits, accelerometers are typically placed on three components—excitation table, test fixture and the DUT. If only one is available, the most reasonable component to measure is the DUT. During vibration step stress, McLean recommends placing the sensors at the point of largest deflection. For the DUT, the point of highest deflection can be determined by referencing a ‘dummy’ board’s response to a predetermined vibration setting. On the other hand, Qualmark recommends placing accelerometers on component groups like subassemblies to recognize difference in excitation transmitted. The guideline also suggests mounting on massive components which are likely to have significant resonances [21]. Accelerometers should be removed during combined stressing to avoid damaging the accelerometers from the extreme temperatures. GMW8287 did not suggest any potential locations.

Ultimately, the locations to place the sensors are dependent on the expected failure points and available resources which are company and DUT specific. Typically, a pre-HALT meeting involving the designers and test engineers will determine the points of interest due to their expertise and experience of the DUT [7].
2.5 Gauge Repeatability & Reproducibility (Gauge R&R)

Considering that the Reliability Engineering Group at Waters has limited resources especially for accelerometers to conduct measurements, a gauge R&R will provide insights on the capabilities of their existing accelerometers. This section will provide necessary theoretical background for baselining existing measurement systems for vibration and validate the value added by a new SOP. Most of the content in this section is heavily referenced from the *Introduction to Statistical Process Control* book by Montgomery [33].

2.5.1 Overview

Gauge R&R is a statistical tool that utilizes analysis of variance (ANOVA) to measure the amount of variability that arises from the measurement system. As the name implies, the system’s repeatability and reproducibility are two capabilities that are evaluated. Repeatability is defined as the extent of the system to get similar observed data under identical conditions, and reproducibility is defined as the extent of difference in observed data if measured under different conditions [33]. One of the most common conditions is the operator. ANOVA is able to breakdown the variance contributions by checking for significance of operator, part and operator-part interaction.

There are other measures of evaluating a system’s capability. Some of them include linearity, bias, and stability of measurements. Linearity refers to the linearity of the relationship between the measurements from measurement gauge and part variation. Bias refers to the difference between the measurements and the “true” value of part. Stability refers to the change in variability in different operating phases [33]. An example is time dependent variation.

Typically, gauge R&R is used for analyzing the measurement’s capability to differentiate good and bad parts. In this thesis, it is used to identify the repeatability and reproducibility of adhesive and mechanical mounts as well as to justify the need to purchase a mechanically mounted triaxial accelerometer (see Section 4.2). The accelerometer is then used for conducting subsequent experiments whose results are used to construct the SOP. Repeatability and reproducibility of the fixture setup is also evaluated in a similar manner.
2.5.2 ANOVA for Gauge R&R

ANOVA is a statistical tool that assesses the significance of one or more factors on the response variable. The execution involves experiments to be tested using factors running at different levels and measuring their impact on the response variable. ANOVA compares variance between group, a single combination of factor levels, means of variance within group to determine whether the factor is significant in affecting the response variable [34].

The factors in gauge R&R are the operator and part. The model that surrounds gauge R&R can be represented in Equation 2.3 where total observed variance ($\sigma^2_{Total}$) is due to part variation ($\sigma^2_{part}$) and gauge variation ($\sigma^2_{Gauge}$). Gauge variation can then further decompose into variation from repeatability and reproducibility.

$$\sigma^2_{Total} = \sigma^2_{part} + \sigma^2_{Gauge}$$

$$\sigma^2_{Gauge} = \sigma^2_{Repeatability} + \sigma^2_{Reproducibility}$$

Equation 2.3

Assume there are $p$ randomly selected parts and $o$ randomly selected operators. Each operator repeats the measurement for every part $n$ times. The model for a measurement ($i =$ part, $j =$ operator, $k =$ measurement) is represented in Equation 2.4.

$$y_{ijk} = \mu + P_i + O_j + (PO)_{ij} + \epsilon_{ijk}$$

where model parameters $P_i$, $O_j$, $(PO)_{ij}$ and $\epsilon_{ijk}$ are all independent random variables that represent the effects of parts, operators, the interaction effects of parts and operators and random error. This is the standard model for gauge R&R experiment. All the parameters except $\mu$ is assumed to be normally distributed with 0 mean and with variances components given in Equation 2.5. $\mu$ represents the true mean value.

$$V(y_{ijk}) = \sigma_p^2 + \sigma_o^2 + \sigma_{PO}^2 + \sigma^2$$

Equation 2.5

Analysis of variance allows users to estimate variance components by deriving the sum of squares of each component and find the mean squares respectively. The mean square can then be used to derive estimates of the variances. Equations 2.6-2.9 shows the steps to derive the estimates.
The Sum of Squares Equation:

\[ SS_{Total} = SS_{Parts} + SS_{Operators} + SS_{PO} + SS_{Error} \]  
Equation 2.6

where each component of the Sum of Squares can be calculated manually using the following equations in Equation 2.7.

\[ SS_{Total} = \sum_{i=1}^{p} \sum_{j=1}^{o} \sum_{k=1}^{n} (y_{ijk} - \bar{y}_{...})^2 \]  
Equation 2.7

\[ SS_{Parts} = on \sum_{i=1}^{p} (\bar{y}_{i.} - \bar{y}_{...})^2 \]

\[ SS_{Operators} = pn \sum_{j=1}^{o} (\bar{y}_{.j} - \bar{y}_{...})^2 \]

\[ SS_{PO} = n \sum_{i=1}^{p} \sum_{j=1}^{o} (\bar{y}_{ij.} - \bar{y}_{i...} - \bar{y}_{.j} + \bar{y}_{...})^2 \]

\[ SS_{Error} = \sum_{i=1}^{p} \sum_{j=1}^{o} \sum_{k=1}^{n} (y_{ijk} - \bar{y}_{ij.})^2 \]

And each component have the following equations:

\[ y_{\ldots} = \sum_{j=1}^{o} \sum_{k=1}^{n} y_{ijk} \]

\[ \bar{y}_{\ldots} = \frac{y_{\ldots}}{on} \]

\[ y_{.j} = \sum_{i=1}^{p} \sum_{k=1}^{n} y_{ijk} \]

\[ \bar{y}_{.j} = \frac{y_{.j}}{pn} \]

\[ y_{ij.} = \sum_{k=1}^{n} y_{ijk} \]

\[ \bar{y}_{ij.} = \frac{y_{ij.}}{n} \]

\[ y_{\ldots} = \sum_{i=1}^{p} \sum_{k=1}^{n} y_{ijk} \]

\[ \bar{y}_{\ldots} = \frac{y_{\ldots}}{pon} \]

In practice, experimenters use computer software packages to obtain the values [33]. Minitab will be used to solve of all these automatically.
The Mean Squares Equation:

\[ MS_p = \frac{SS_{Parts}}{p - 1} \]
\[ MS_o = \frac{SS_{Operators}}{o - 1} \]
\[ MS_{po} = \frac{SS_{po}}{(p - 1)(o - 1)} \]
\[ MS_E = \frac{SS_{Error}}{po(n - 1)} \]

The expected mean squares are as follows:

\[ E(MS_p) = \sigma^2 + n\sigma_{po}^2 + bn\sigma_p^2 \]
\[ E(MS_o) = \sigma^2 + n\sigma_{po}^2 + an\sigma_o^2 \]
\[ E(MS_{po}) = \sigma^2 + n\sigma_{po}^2 \]
\[ E(MS_E) = \sigma^2 \]

Using Equation 2.9, estimates (\( \hat{\cdot} \)) of the variance components are as follows:

\[ \hat{\sigma}^2 = MS_E \]
\[ \hat{\sigma}_{po}^2 = \frac{MS_{po} - MS_E}{MS_{po} - MS_E} \]
\[ \hat{\sigma}_o^2 = \frac{n}{pn} MS_o - MS_{po} \]
\[ \hat{\sigma}_p^2 = \frac{MS_p - MS_{po}}{on} \]

From Equation 2.10, we are able to deduce the higher order gauge capabilities of repeatability and reproducibility using the following formulas and definitions [33]. Equation 2.11 reflects this.

\[ \hat{\sigma}^2 \approx \sigma^2_{Repeatability} \]
\[ \hat{\sigma}_o^2 + \hat{\sigma}_{po}^2 \approx \sigma^2_{Reproducibility} \]
\[ \therefore \sigma^2_{Gauge} = \hat{\sigma}^2 + \hat{\sigma}_o^2 + \hat{\sigma}_{po}^2 \]

The significance of operators, part and operator and part interaction on the observed measurement is revealed from F-values and p-values obtained from the statistical analysis [35].
2.6 Factorial Designs: Response Surface Method

Design of experiments (DOE) is a systematic method to characterize a process by identifying potential and significant relationships between the process inputs (independent variables) to the process outputs (dependent variables). DOE enables users to understand the potential relationships in a given process as well as to identify the factors and corresponding response variables of interest. By identifying the underlying mechanisms in the process and using statistical tools, meaningful conclusions can be drawn and justified from the experimental results [33]. In order to establish a relationship between factors and responses, more than one treatment level for a given factor is required. A factorial experiment is conducted if several factors are involved in the study. Given that there are \( x \) number of factors and each factor has \( y \) levels in the case of discrete categorical levels, there is a total of \( x-y \) possible combinations or experimental conditions that could be setup to test the responses. If all combinations are considered, the experiment is called a \textit{full factorial experiment}. A full factorial experiment is recommended if resources are adequate because it provides a complete picture of all possible individual and interaction effects among all factors. Alternatively, if resources are limited, a \textit{partial factorial experiment} can be conducted by creating alias structures in the experiment design. A significant factor can be statistically determined through ANOVA analysis and is expressed as a low p-value less than a given significance level, \( \alpha \). Due to the nature and ease of data acquisition of samples and replicates, the thesis uses full factorial designs as much as possible.

The response surface model is one method to explore the relationships between factors through effective use of contour plots, and allows for optimization. There are first order and second order effects. Quadratic terms are included in the regression model for the latter. Equation 2.12 defines a second-order model that is explored in the thesis for uniformity analysis. Here \( x \) refers to a factor, \( y \) is the response variable, \( \varepsilon \) is the model error and \( \beta \) are the coefficients that minimize the sum of squares of model errors. This equation can be generated in Minitab.

\[
y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j=2}^{k} \beta_{ij} x_i x_j + \varepsilon
\]

Equation 2.12
To fit a quadratic model, all factors must have at least three levels. Typically, curvature is first tested in a linear model using a $2^k$ factorial experiment where there are two levels and $k$ number of factors. One method to test for curvature is to add center points to a $2^k$ experiment to estimate the significance of curvature [33]. Curvature exists when the average mean response at the center points, $\bar{y}_C$, is significantly greater or less than the average mean response of the factors at the low and high settings, $\bar{y}_F$. This is affirmed by an ANOVA test. Equation 2.13 shows the formula to calculate the F-statistic for curvature [33].

$$SS_{pure\,\,quadratic} = \frac{n_F n_C (\bar{y}_F - \bar{y}_C)^2}{n_F + n_C}$$

Equation 2.13

$$MS_{curvature} = SS_{pure\,\,quadratic}$$

$$F_0 = \frac{MS_{curvature}}{MS_{residual}}$$

If curvature is significant, the next step is to proceed with a quadratic model for a better fit. A central composite design (CCD) can then be introduced where axial points and center points are added to existing corner points. For example, a $2^2$ full factorial with five center points requires only four more axial points to achieve a CCD. This method is widely used in practice for fitting second-order response surfaces. Figure 2-18 shows an example of a surface plot and a contour plot of a second order surface regression model relating temperature and reaction time to expected yield.

Figure 2-18 Example of a surface plot (left) and its respective contour plot (right) [33]
Each continuous line on a contour plot represents a specific value for the response variable. The contour plots can visually indicate the path of steepest ascent or descent to suggest experimental direction for minimizing or maximizing the response variable. Similarly, considering spatial uniformity of a response variable, regions of high uniformity or clustering of similar values can also be represented as locations where contour lines are reasonably spaced far apart.

2.6.1 Spatial Non-Uniformity Metric- Integration Statistic

To create consistency in the HALT fixture setup between different PCB boards, one avenue is to fix the location at which the PCBs are mounted. This requires the understanding of the spatial distribution of the vibration levels on the table. Ideally, the selected region would be as uniform as possible in all three axes of vibration so that boards of different sizes and mounting positions within the region will experience similar excitation levels from the same input $G_{rms}$.

A widely used metric to measure spatial uniformity is the signal-to-noise ratio (SNR). In wafer production, to measure within wafer uniformity, SNR ratio is obtained by taking the ratio of estimated within wafer standard deviation to the grand mean of the measurements. However, when the mean and variance of readings are a function of location and number of measurements taken, the SNR ratio no longer applies. As such, Davis et al. proposed a new metric, the integration statistic ($I$) that is robust to both location and number of measurements [36]. Equation 2.14 illustrates the general expression for the integration statistic, while 2.15 is an approximated equation based on the response surface generated.

$$I = \frac{\int_{r, \theta} h(T - g(r, \theta)) r \, dr \, d\theta}{Vol_{target}}$$

Equation 2.14

Where $h(\cdot)$ is the general loss transformation function (e.g. absolute value or square), a function of the error between the targeted value and the points on the response surface, $g(r, \theta)$. Notice that the integration statistic is a metric representing a function on the volume of error normalized to the volume of the target.

If a functional representation of the surface is unavailable, an evaluation grid of $N \times N$ is generated as a sampling function of the actual response surface. Davis et al. recommends $N \geq 30$
as a good approximation to the actual integral. For example, if there are 13 measurement sites on a wafer, a 30 x 30 evaluation grid is used. If sampling is not uniform, an area weighting function, \( C_j \), has to be introduced. The integration statistic then reduces to a discrete summation,

\[
I \approx \sum_{j=1}^{M} \frac{A C_j h(T - x_j)}{Vol_{\text{target}}}, j \in [1, 13], i \in [1, 900]
\]

Equation 2.15

where \( A \) represents the area of one of the grid elements, \( C_j = \sum_i w_{ij} \) and \( x_j \) is the \( j^{\text{th}} \) measurement value.

The integration statistic is a superior measure of non-uniformity than the SNR because of the use of the response surface modelling to "virtually sample" many points on the wafer. The incorporation of spatial relationships and weighting function based on the measurement site improves the stochastic performance of the metric [36]. The integration statistic provides 35% increase in performance over a small number of measurements in examples presented by Davis et al., supporting and motivating its use for the experiments in this thesis.

2.7 Statistical Process Control (SPC)

Statistical process control (SPC) is one of the many methods to reduce process output variation and is a typical method to ensure quality in a manufacturing process. However, the method is applicable to other contexts that requires monitoring and stabilization as well. As outlined in Section 3.3, there is a lack of awareness amongst operators on the functional health of the HALT chamber or whether experiment setups are replicated appropriately. Having SPC as part of the HALT SOP, creates a foundation to ensure consistency between experiments by monitoring any deviations in process outputs. Similar to all manufacturing processes, the experiment setup itself can be viewed as a functional block diagram with inputs and outputs. The inputs include torque levels on fixture’s fasteners, temperature and vibrational settings. The outputs would be the temperature and vibrational levels on the DUT. By using SPC to monitor the board’s responses, it empowers the user to detect and minimize disturbances to process parameters while adding credibility to each experiment.
This section outlines basic control chart methodology based on Shewhart process model for monitoring process outputs. In the model, process variations in the output is a normally and independently distributed random variable with mean zero and standard deviation. This is appropriate for the HALT process outputs. The following content leverages on the book, *Introduction to Statistical Process Control* by Montgomery.

### 2.7.1 Overview

A process that is in statistical control is defined by Shewhart to have process outputs vary around a fixed mean in a stable or predictable manner [33]. SPC allows users to have a broader view of the process through monitoring of process mean and variations across time. These statistics are plotted in charts called control charts. There are warning limits called control limits within each control chart which indicates whether the process is in statistical control. These charts are useful in separating common causes and assignable causes of variations [33]. In our context, an assignable cause of variation for the table vibration levels might be mechanical wear from the vibrators. A common cause of variation might be air pressure fluctuations to the pneumatic actuators as the system attempts to execute feedback control.

### 2.7.2 Control Charts and Control Limits

This thesis focuses on two control charts, the $\bar{x}$ chart and the $s$ chart. To begin with, to establish the charts, it is important to assume that the process is in statistical control. The best time to check that the HALT chamber is in control would be when it is first shipped or after a maintenance check. Unfortunately, we are unable to do that in the project due to resource limitations. To confirm that process is really in control, Montgomery suggests to have at least 20-25 samples (i.e., subgroups) of 4-6 observations each to establish trial control limits. This is phase I of SPC. For the HALT chamber, data (i.e., observations) are generated at intervals of 0.3 seconds. As such, we can afford to use a larger number of observation set. One minute worth of observation (approximately 150 observations) per sample is utilized. If any points are out of control, a root cause analysis is conducted and trial control limits are reevaluated until the all points meet the criteria of statistical control. Figure 2-16 illustrates what a control chart may look like and outlines the how common cause and assignable causes of variation can be identified.
To develop the $\bar{x}$ chart the centerline, upper control limits (UCL) and lower control limits (LCL) are needed. The centerline is an estimate of the process' true mean ($\mu$) and it is based on the grand mean ($\bar{x}$) established by the subgroups. Equation 2.16 represents this calculation where $m$ refers to the number of subgroups.

$$
Center \ Line = \bar{x} = \frac{\bar{x}_1 + \bar{x}_2 + \ldots + \bar{x}_m}{m}
$$  \hspace{1cm} \text{Equation 2.16}

The control limits of the $\bar{x}$ chart is derived using the process true standard deviation estimate ($\bar{\sigma}$). Equation 2.17 is used to relate sample standard deviation ($s$) to true process standard deviation where $c_4$ is a subgroup size ($n$) dependent constant [38] Note that without the constant, $s$ is not an unbiased estimate of true process standard deviation.

$$
E(s) = \bar{s} = c_4 \bar{\sigma}, \quad c_4 = \frac{2}{\sqrt{n-1}} \left( \frac{n-1}{n-1} \right)! \quad \text{Equation 2.17}
$$

Typically $3\sigma_{\bar{x}}$ above and below the mean are used as control limits. The limits are shown in Equation 2.18. Notice that the variance of the random variable $\bar{x}$ is a function of $n$.

$$
\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}} \quad \text{Equation 2.18}
$$
Substitute Equation 2.17.

\[
UCL_\bar{x} = \bar{x} + \frac{3}{c_4 \sqrt{n}} \bar{s} \\
LCL_\bar{x} = \bar{x} - \frac{3}{c_4 \sqrt{n}} \bar{s}
\]

Similarly, to develop the s chart, we need the centerline, UCL, and LCL. The centerline is an average of the standard deviations for the subgroups (\(\bar{s}\)). Equation 2.19 shows how it is calculated where the standard deviation of the \(i\)th sample is \(s_i\). Typically 3\(\sigma_s\) above and below the mean of subgroup standard deviation (\(\bar{s}\)) are used as control limits where \(\sigma_s = \sigma \sqrt{1 - c_4^2}\).

\[
Center \ Line = \bar{s} = \frac{1}{m} \sum_{i=1}^{m} s_i \\
UCL_s = \bar{s} + \frac{3}{c_4} \sqrt{1 - c_4^2} \bar{s} \\
LCL_s = \bar{s} - \frac{3}{c_4} \sqrt{1 - c_4^2} \bar{s}
\]

Since the industry considers pooled standard deviation as a better estimator of the process standard deviation (\(\sigma\)), the control limits for the s chart and \(\bar{x}\) chart changes [37]. The final form is shown in Equation 2.21. Note that all calculations in the thesis will be executed in Minitab which makes use of pooled standard deviation as outlined in Equation 2.20. This is one of the default settings in Minitab. All control chart constants referenced here can be found in *Understanding Statistical Process Control* by D.J. Wheeler and D.S. Chambers [39].

\[
\sigma \approx \frac{s_p}{c_4 (d + 1)} \quad \text{Equation 2.20}
\]

where \(d = \sum (n_i - 1)\), \(s_p = \sqrt{\frac{\sum \Sigma (x_i - \bar{x})^2}{\Sigma (n_i - 1)}}\)

Control limits for \(\bar{x}\) chart based on pooled standard deviation, Equation 2.20:

\[
UCL_\bar{x} = \bar{x} + \frac{3\sigma}{\sqrt{n}} \\
LCL_\bar{x} = \bar{x} - \frac{3\sigma}{\sqrt{n}}
\]

Equation 2.21
Control limits for s chart based on pooled standard deviation, Equation 2.22:

\[
UCL_s = \left( 1 + 3 \frac{c_4}{c_4} \right) \sigma \\
LCL_s = \left( 1 - 3 \frac{c_4}{c_4} \right) \sigma
\]

Equation 2.22

2.7.3 Detecting Out of Control: Shewhart Control Design

There are multiple decision rules created by industries and regulatory organizations like ISO 8258 to detect non-random patterns on control charts [37]. Montgomery adequately summarizes all the common rules which are widely adopted. The rules are shown in Table 2-2. These rules apply to both control charts and some make use of the control limits established in Section 2.72.

<table>
<thead>
<tr>
<th>Rule</th>
<th>Rule Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>One or more points outside of the control limits</td>
</tr>
<tr>
<td>2.</td>
<td>Two of three consecutive points outside the two-sigma warning limits but still inside the control limits.</td>
</tr>
<tr>
<td>3.</td>
<td>Four of five consecutive points beyond the one-sigma limits.</td>
</tr>
<tr>
<td>4.</td>
<td>Eight consecutive points on one side of the center line.</td>
</tr>
<tr>
<td>5.</td>
<td>Six points in a row steadily increasing or decreasing.</td>
</tr>
<tr>
<td>6.</td>
<td>Fifteen points in a row within one-sigma (both above and below) of centerline</td>
</tr>
<tr>
<td>7.</td>
<td>Fourteen points in a row alternating up and down.</td>
</tr>
<tr>
<td>8.</td>
<td>Eight points in a row on both sides of the center with none within one-sigma control limits</td>
</tr>
<tr>
<td>9.</td>
<td>An unusual or nonrandom pattern in the data.</td>
</tr>
<tr>
<td>10.</td>
<td>One or more points near a warning or control limit</td>
</tr>
</tbody>
</table>

Table 2-2 Rules for Shewhart control charts that detects non-random system behaviors [33]

Generally, these rules indicate situations that are unlikely to occur given the distribution of the random variable output. For example, in Rule 2, having two of three consecutive points beyond 2 standard deviations away from the grand mean raises alarms. The reason for this is because the probability of having beyond 2 standard deviations in a normally distributed random variable is approximately 0.05. Having consecutive points beyond 2 standard deviations would be even more unlikely. This chart would serve as a reference to check on the state of the fixture setup when incorporated in the SOP. Since there is essentially no specification limits for a particular setup and
the reliability engineers do not have a preference for one, having the process in statistical control is sufficient in ensuring consistency in the experimentations.

2.7.4 Cause-Effect Diagram

Once an out-of-control signal is detected, a cause-effect analysis has to be conducted to return the system back to control. An effective way to narrow down the root cause is to use a fishbone (Ishikawa) diagram. A fishbone diagram is a cause-effect diagram that branches off into cause categories that aids in narrowing down the cause(s) of the variation. Typical categories for a manufacturing line include Methods, Machines (Equipment), People (Manpower), Materials, Measurement and Environment [40]. Each category then branches further into process specific elements like high temperature, loosened fasteners and so on. The more detailed the diagram, the more effective it is as a troubleshooting tool [33]. A team with sufficient knowledge about the process should be involved in the generation of the cause-effect diagram. Figure 2-19 shows an example of a fishbone diagram for a tank defect problem. Establishing the fishbone diagram greatly simplifies the analysis of out-of-control situations.

![Fishbone Diagram Example](image)

Figure 2-19 Example of a fishbone diagram (a tank defect problem) [33]
2.7.5 Sampling Frequency

After the trial control limits are established and the process is confirmed to be in statistical control, phase II can be applied. Phase II is a long-term monitoring of the process where samples has to be measured in a structured manner to check whether the process is still in control. The simplistic method to use for the sampling frequency would be the average run length (ARL) as outlined in Equation 2.23 where $p$ is the probability that a point exceeds the control limits [33].

\[ ARL = \frac{1}{p} \]  

Equation 2.23

There are more advanced sampling rates in the book by Montgomery but ultimately, sampling frequency is determined by the sampling effort and economical value. Logical sense has to be made with regards to sampling rates for the HALT chamber. This will depend on how frequent the chamber is used, ease of sampling and the purpose of having SPC in SOP. For the context of HALT, a reasonable sampling frequency could be once before the use of a vibration related stress profile. These include but are not limited to vibration step stress and combined step stress in classic HALT.
Chapter 3. Summary of Existing Resources

The work of the thesis specifically explores the use of the TC-2.5 – Panther™ environmental chamber by HALT&HASS™ Systems Corporation to execute HALT process. The following two sections introduce and evaluates the existing resources available in the Reliability Lab for HALT. This is also the context at which the experiments and SOP is drafted.

The Reliability Lab houses environmental chambers, highly customized fixtures and precision diagnostic tools to evaluate the capability, product life and failure modes of Waters instruments. The common data acquisition devices used during tests are National Instruments Data Acquisition (Ni-DAQ) modules, Agilent Technologies’ data loggers, oscilloscopes and built-in logging software supplied by providers of these chambers. The products tested at the Reliability Lab are usually hardware-based and electromechanical in nature. Figure 3-1 displays an example of a customized test fixture for one of their electromechanical hardware.

3.1 Highly Accelerated Life Testing (HALT) Chamber- TC-2.5

This section covers the specifications and use of the TC-2.5 environmental chamber. The team is allocated this chamber exclusively to construct and simulate our SOP for the HALT process. A clear understanding on the capabilities of the system is needed (see Appendix A-2
Summary of TC-2.5-Panther™ Specifications for Operation & Installation. Figure 3-2 shows the exterior and interior of the chamber.

![Figure 3-2 Clockwise from left: TC-2.5 – Panther™ environmental chamber, top chamber (6 air outlets, central ventilation fan, and lighting), and mounting table](image)

The chamber was bought in 2010 by Waters from HALT&HASS™ Systems Corporation\(^2\) when setting up the Reliability Lab in Milford. The chamber is made of 304 stainless steel construction providing a 30” by 30” mounting table containing 3/8”-16 UNC holes with 2” centers (see Appendix B-1). The chamber provides two sources of stresses, temperature and vibration, to precipitate design flaws on the device under test (DUT). The temperature stresses from -100°C to +200°C and vibrational stresses from 0 kHz to 10 kHz of random vibration. Users are able to set up stress profiles by varying the temperature (°C) and vibration levels (G\(_{\text{rms}}\)) for the testing process.

\(^2\) Cincinnati Sub-Zero (CSZ) acquired HALT&HASS™ Systems Corporation (HHSC) in July 2011. Waters Corporation’s TC-2.5– Panther™ Environmental Chamber was from HHSC but currently maintained by CSZ.
The temperature is varied and maintained through a feedback control within the system that cools the chamber through the use of liquid nitrogen (LN2) and nichrome heating elements at the top of the chamber. The heated air and LN2 gases mixes in the upper chamber through a fan and gets directed out through 6 4" ducts. Users have the flexibility to adjust the flexible ducts to direct the air flow.

The random vibration it provides is an all-axis broadband (i.e., 3 translations and 3 rotations) vibration. There are 9 pneumatically actuated vibration generators (6 medium sized and 3 smaller sized) mechanically mounted to the underside of the vibration table. These actuators send high magnitude pulses of force on the table, resulting in a broadband excitation spectra in the frequency domain [15]. The actuators are angled approximately 20° from the plane of the plate so that the vibration levels in all 3 axes are approximately uniform. The table is made out of 6061-T6 aluminum plate suspended by 4 springs to allow 6 degrees of motion while passively dampening the excitation to the chamber itself. This configuration allows the table to vibrate in isolation. The table is able to hold up to 388lb of load. A single axis accelerometer is mounted to the underside of the table and provides feedback to the controller on the vibration levels that the operator inputs. The accelerometer provides a bandpass filtered 3-10 kHz signal to the controller. Figure 3-3 provides a visual illustration on the set up.

![Figure 3-3](image)

Figure 3-3 Clockwise from left: TC-2.5 – Vibration table, chamber’s accelerometer, pneumatic vibration actuators, and isolation spring & damper system
3.2 Commonly Used Fixtures

The Reliability Lab has fixtures to mount the DUT to the vibration table. These tools range from clamps and aluminum extrusion channels to 80-20 framing systems and pre-drilled aluminum blocks. Currently, there is no standardized way of selecting the fixtures. As such, some form of standardization is necessary if the team wants to avoid additional variations and constraints imposed by fixtures. Figure 3-4 displays some of these fixtures and fixing tools.

![Figure 3-4 Drawers of fixtures and fasteners for the HALT chamber at Waters](image)

To evaluate the necessity of proposing a new fixture design, a Pugh chart is generated (see Appendix C-1). The Pugh chart is designed based on the fixture design principles (see Section 2.3) and additional design constraints imposed by PCB designs at Waters (see Section 1.1.4). The use of Pugh Chart reveals that the clamp fixture may be the best option among the other designs. It provides a very convenient mounting mechanism for the PCB. However, it still does not accommodate to all PCBs at Waters. Firstly, the fixture limits the boundary conditions only to the exterior of the board. Consequently, any design improvements that changes the boundary conditions at the inner regions of the board cannot be evaluated for robustness. Secondly, the team realizes that thicker PCBs are unable to fit the holding slit of the clamp fixture (see Appendix C-1). As such, a generic standardized fixture for Waters’ PCBs may not be attainable using the current resources. The team decided to propose a new fixture design for PCBs to address these limitations.
3.3 Data Acquisition Method and Accelerometers

To monitor the vibration levels and temperature of the DUT, the Reliability Lab uses Dytran accelerometers and Omega® thermocouples respectively. Unlike the thermocouples, there are 3 different kinds of accelerometers with very different specifications and mounting considerations. There is one adhesively mounted triaxial accelerometer and two single axis accelerometers, one mechanically mounted and the other adhesively mounted. Table 3-1 compares the various accelerometers available for the HALT chamber.

<table>
<thead>
<tr>
<th>Model Number</th>
<th>3224A1-Mini</th>
<th>3030B5</th>
<th>3023A Triax</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphic</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>Axis</td>
<td>Single</td>
<td>Single</td>
<td>Triaxial</td>
</tr>
<tr>
<td>Grms Limit</td>
<td>+/- 900 g</td>
<td>+/- 500 g</td>
<td>+/- 500 g</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>10mV/g</td>
<td>10mV/g</td>
<td>10mV/g</td>
</tr>
<tr>
<td>Frequency Range</td>
<td>0.3 to 20,000 Hz</td>
<td>5 to 10,000 Hz</td>
<td>5 to 10,000 Hz</td>
</tr>
<tr>
<td>Resonant Frequency</td>
<td>&gt;95 kHz</td>
<td>&gt;30 kHz</td>
<td>&gt;40 kHz</td>
</tr>
<tr>
<td>Temperature</td>
<td>-51°C to +149°C</td>
<td>-100°C to 121°C</td>
<td>-51°C to 121°C</td>
</tr>
<tr>
<td>Mass</td>
<td>0.2 grams</td>
<td>6.8 grams</td>
<td>3 grams</td>
</tr>
<tr>
<td>Mounting Technique</td>
<td>Adhesive</td>
<td>10-32 Stud Mount</td>
<td>Adhesive</td>
</tr>
</tbody>
</table>

Table 3-1 Specifications of existing accelerometers [41]–[43]

Currently, operators assume that monitoring the DUT’s response in the axis normal to the vibration table is sufficient as the other axes are not significant. As such, they use the 3224A1-Mini to monitor the board’s response. In reality, the table excites through six degrees of freedom. A DUT may also experience much higher accelerations in the other two translational axes, depending on the mounting location on the table (see Section 2.4.2). Most experiment setups at the lab are based on engineering intuition. A repeatability and reproducibility test will help to objectively evaluate the performance of the accelerometers and select the appropriate one for the given task.
Chapter 4. Methodology: Characterization of Resources

This chapter focuses on introducing a more convenient data acquisition method by addressing the problem of what accelerometers to use for data acquisition and deciding the best location on vibration table to stress the DUT. Section 4.2 and Section 4.3 explore these two aspects of the problem respectively.

4.1 Data Acquisition Setup

As outlined in Chapter 3, one of the key issues in existing practices is data acquisition itself. Before any experiments are conducted, the manner of data acquisition has to be established. Instead of an oscilloscope, the team decided to use National Instruments’ analog input module, NI 9234, as a more efficient method for acquiring data. The NI 9234 has IEPE signal conditioning capabilities as well as anti-aliasing filters that automatically adjusts to a set sampling rate. Anti-aliasing filters help to restrict the bandwidth of the signal to approximately satisfy the Nyquist-Shanon sampling theorem. The sampling theorem states that the sampling rate of the DAQ has to be at least twice the highest frequency of interest of a signal. In our project, the highest frequency of interest is 10 kHz. As such, the sampling frequency should be at least 20 kHz. For convenience, a higher sampling frequency of 40 kHz is chosen to account for transition band due to practical imperfections of anti-aliasing filters. Additionally, a digital filter\(^3\) is applied in Labview to further refine the data after the analog to digital converter (ADC).

There are two data of interests for the vibration analysis, the root mean square of the acceleration (\(G_{\text{rms}}\)) and the power spectrum density (PSD) plot. A fast Fourier transform (FFT) \([\text{Hanning window, RMS averaging and exponential weighting}]\) of the input signal achieves the PSD plot. A sample size of 16384 \((2^{14})\) is used, achieving a frequency resolution of 2.44 Hz. The use of the virtual instruments (VI) in Labview for data processing results in data output of

\(^{3}\) A review of the TC-2.5 Panther’s specification sheet and a check with a HALT Applications Product Engineer at Cincinnati Sub-Zero\(^3\) reveals that the \(G_{\text{rms}}\) value on chamber’s indicator reflects frequencies from 3Hz to 10 kHz. Accordingly, when acquiring accelerometer data, a Butterworth filter 6th order bandpass filter is used to achieve this bandwidth.
approximately 0.3 seconds per data. The setup outputs 3 PSD graphs and stores $G_{rms}$ from 3 accelerometer channels. Figure 4-1 displays the hardware setup while Figure 4-2 shows the virtual dashboard.

Figure 4-1 Data acquisition hardware setup for vibration

Figure 4-2 Example of virtual dashboard (regions of interests are highlighted)
All $G_{\text{rms}}$ data is stored and analyzed. The setup of IEPE sensors follows a standard setup suggested by Dytran Instruments that involves an externally powered current source. The sensitivity of accelerometers are calibrated by Dytran Instruments and taken into account during data acquisition to produce the appropriate $G_{\text{rms}}$ values. To validate of the readings in the proposed acquisition setup, the PSD curves on the LeCroy oscilloscope and virtual dashboard are compared. Figure 4-3 shows the high similarities of the PSD plots in the virtual dashboard. A tuning fork is also used as an excitation source to a thin plate, where an accelerometer is mounted to assure that the PSD is capable of identifying frequencies accurately. Both experiments confirm the accuracy of the setup.

Figure 4-3 Similarities of PSD plots: Oscilloscope (left) and Labview dashboard (right)

4.2 Gauge R&R Analysis of Mechanical and Adhesive Mount Accelerometers

As covered in Section 3.3, there are a variety of accelerometers available at Waters. Considering that all three axes provide information on the excitation level of the DUT, the most suitable and available accelerometer is the adhesive triaxial accelerometer. However, the team suspected huge variability between readings, making it unsuitable for precise data acquisition. As such, a single part gauge R&R is conducted to test this hypothesis. Results revealed that accelerometer selection is largely based on the DUT that is being tested. However, mechanically amounted accelerometers provide the best repeatability and reproducibility and should be used whenever possible. Regardless of the kinds of mounting used, an accompanying SOP on proper setup is required to reduce gauge variation because accelerometers are highly sensitive sensors.
The experiments were set up with input settings of 30\text{G}_{\text{rms}} at 25°C and at a specific location on the vibration table. A bolt and washer are used to hold down the wire to reduce whipping during vibration. Three randomly selected reliability engineers were assigned as operators with 10 measurements each. An average of 200 data points are taken as a single measurement. Data points were obtained during a 2 minute soak time where vibration levels on the table are stable. Each reading required users to mount the accelerometer on a test plate. For consistency, the author personally removes the accelerometer after each measurement.

An ANOVA test is then executed to find the gauge repeatability as well as reproducibility variances and percentage contributions to total gauge variance. Notice that this is a single part experiment. As such, the gauge variability model in Section 2.5 is reduced to the Equation 4.1.

\[
\begin{align*}
\sigma_G^2 &\approx \sigma_{\text{Repeatability}}^2 \\
\sigma_O^2 &\approx \sigma_{\text{Reproducibility}}^2 \\
\therefore \sigma_{gauge}^2 & = \sigma_G^2 + \sigma_O^2
\end{align*}
\]

Equation 4.1

The gauge variance contribution is analyzed using ANOVA in Minitab for all three axes \(<\text{Grms}_X>, <\text{Grms}_Y>\) and \(<\text{Grms}_Z>\) respectively. This chapter runs through the different experimental setups, observations and results for the mechanical and adhesive mounted accelerometers.

4.2.1 Adhesive Wax-mounted Triaxial Accelerometer

To baseline existing data acquisition, a gauge R&R is executed using current practices of acquiring data from adhesive accelerometers. This section evaluates the use of a three axis adhesive mounted accelerometer, 3023A. Each reading involves operators to mount the accelerometer on a plate using petro mounting wax provided by the company. The plate is fixed on the vibration table. The amount of mounting wax is determined by the operators. This method replicates their existing data acquisition approach. Surfaces on the accelerometer and mounting platform are cleaned before each mount. The mounting platform is always on the test plate and operators do not need to remount it. The output \(G_{\text{rms}}\) in all three axes are recorded. See Figure 4-4 for the setup.
Figure 4-4 Experiment setup for the adhesive mounted accelerometer-3023A

Removing a single anomaly from operator 3 measurement 2 because the accelerometer fell off the surface midway during the experiment, we get the following results in Table 4-1.

<table>
<thead>
<tr>
<th>Variance Component</th>
<th>&lt;Grms X&gt;</th>
<th>&lt;Grms Y&gt;</th>
<th>&lt;Grms Z&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{Reproducibility}^2$</td>
<td>3.39</td>
<td>17.77%</td>
<td>12.42</td>
</tr>
<tr>
<td>$\sigma_{Repeatability}^2$</td>
<td>15.70</td>
<td>82.23%</td>
<td>10.69</td>
</tr>
<tr>
<td>$\sigma_{Gauge}^2$</td>
<td>19.09</td>
<td>100.00%</td>
<td>23.11</td>
</tr>
</tbody>
</table>

Table 4-1 Gauge R&R test results for the wax mounted accelerometer

Notice that the gauge variance for $<\text{Grms Y}>$ is 23.1 $\text{G}_{\text{rms}}$. Since the $\text{G}_{\text{rms}}$ outputs on all three axes is normally distributed, the 95% two-sided confidence interval is $\bar{x} - 9.61 \leq \mu \leq \bar{x} + 9.61$ $\text{G}_{\text{rms}}$. In Section 2.4.2, we emphasized on the consequence of even having small deviations in vibration levels. Considering that the gauge variation is very significant in adhesive mounts, to conduct subsequent experiments using the adhesive mount is undesirable. In this case, both repeatability and reproducibility are an issue for the 3023A accelerometer. A new mechanically mounted triaxial accelerometer is proposed.
The following is a list of observations from the experiment which may shed light on the sources of variation for an adhesive mounted accelerometer.

1. Inconsistent use of mounting wax material between operators and within operators. Operator 3 measurement 2 must have applied insufficient wax to the accelerometer causing detachment.
2. Inconsistent pressure applied on the accelerometer between operators and within operators.
3. Wax loses adhesiveness beyond 30°C.
4. Inconsistent pressure applied on the accelerometer between operators and within operators.
5. Wire stiffness is higher in triaxial accelerometers because there are more wires in the coaxial cable. This makes mounting of the accelerometer difficult. A washer and bolt to hold down the wire reduces the springback of a bent wire.
6. The shearing of the accelerometer only affects the x-y plane. As such, the gauge variation in the <Grms_X> and <Grms_Y> is disproportionally larger than the <Grms_Z> because of points 1-5.
7. Comparing with a sample signal in Section 4.2.2, the adhesive wax mounting reduces upper frequency response [44]. Figure 4-5 justifies this statement. Notice that signals in the x-y plane beyond 6 kHz are almost negligible while in Section 4.2.2, the higher frequency signals are captured. Despite the large gauge variations and limitations of adhesively mounted accelerometers, an adhesive mounted accelerometer is still indispensable for acquiring data on a PCB because of its non-invasive interaction with the board.
Figure 4-5 Sample PSD signal (operator 1 measurement 5) from the dashboard with missing higher frequencies (outlined in red) for <Grms_X> and <Grms_Y>.

Other alternatives that may solve some issues outlined in the previous paragraph, include but are not limited to using stronger adhesives like cyanoacrylate or hot melt glue and having a sacrificial mounting base so that the accelerometers are not damaged from removal. The repeatability and reproducibility of these suggestions are not tested to avoid potential damage to the expensive accelerometer. Instead, a mechanically mounted accelerometer is purchased.
4.2.2 Threaded Stud Mount Triaxial Accelerometer

Based on the results from the previous section, the team purchases a threaded stud mounted accelerometer. Figure 4-6 shows an image of the new triaxial accelerometer, Dytran model 3313A3H, and its setup.

![Image of the new triaxial accelerometer, Dytran model 3313A3H, and its setup.](Image)

Figure 4-6 Experiment setup for the threaded stud mounted accelerometer- 3313A3H

Each reading involves users to mount the accelerometer by screwing it onto a plate with a washer sandwiched between the accelerometer and the test plate. The accelerometer is first torqued by hand and then torqued using a torque screwdriver to secure the accelerometer. As suggested in the datasheet for the 3313A3H accelerometer, an applied torque of 6-8 in-lbs is instructed. The final step involves securing the coaxial cable.

The gauge variance contribution is analyzed using ANOVA in Minitab. Removing 2 results (measurements 9 and 10) from operator 1 due to time constraints and early problem detection, following results in Table 4-2 are obtained.

<table>
<thead>
<tr>
<th>Variance Component</th>
<th>&lt;Grms X&gt;</th>
<th>&lt;Grm Y&gt;</th>
<th>&lt;Grms Z&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma^2_{Reproducibility}$</td>
<td>0.00</td>
<td>0.86</td>
<td>0.02</td>
</tr>
<tr>
<td>$\sigma^2_{Repeatability}$</td>
<td>2.30</td>
<td>10.44</td>
<td>0.36</td>
</tr>
<tr>
<td>$\sigma^2_{Gauge}$</td>
<td>2.30</td>
<td>11.30</td>
<td>0.38</td>
</tr>
</tbody>
</table>

Table 4-2 Gauge R&R test results for the threaded stud mounted accelerometer
From the results, using a mechanically mounted accelerometer greatly minimizes gauge variability. Most notably, gauge reproducibility dropped to near zero variance for all cases. The gauge seems to be indifferent to the types of operators. However, repeatability is still an issue especially in the <Grms_Y> axis.

The following is a list of observations from the experiment which displays potential sources of variation.

1. The PSD curve signature is different between certain repeats. Some has very high peaks in the high frequencies while others have the lower peaks in the 8-10 kHz range. Figure 4-7 shows this difference.
2. Final orientation of the accelerometer varies much lesser compared to the adhesively mounted accelerometer. However, slight deviations from the desired orientation are still noticeable.

A root cause analysis was conducted, to identify potential sources of variation. Referencing Figure 4-7, the difference in measurement 3 and 4 is due to low surface parallelism on one side of the washer to the opposing side. This causes the variation in readings for all three axes. The amount of tightening torque affects surface parallelism by varying the extent of the washer surface that is compressed after tightening.

Figure 4-7 Different PSD curves generated for the 3rd, 4th and 6th measurements (<Grms_Y>)

Thus, providing a range of torque values is insufficient to ensure consistency between operators. A well-defined value is required. For measurement 6, despite the digital filter, excitations at higher frequencies are observed beyond 10 kHz. The cause of this variation is
replicated and is attributed to having a loose coaxial cable (¼ turn away from full tightness). An SOP will help to reduce these variations.

4.2.3 Threaded Stud Mount Triaxial Accelerometer with Improved SOP

The finalized SOP uses the same stud mounted accelerometer. This time, a calibrated flat shim is used instead of a washer. The shim that is used is a peel-away brass round shim. Layers can be removed by a utility knife to get the desired thickness and final orientation of the accelerometer. It has a much tighter thickness tolerance of +/- 0.005” [45] compared to a generic washer with 0.01” to 0.02” tolerance. Instead of a range of torque values, a finite torque value of 7 in-lbs was instructed and marked on the torque screwdriver. Additionally, operators were required to physically check the coaxial cable for full tightness after torqueing. Figure 4-8 illustrates the new setup.

![Figure 4-8 Revised setup for the threaded stud mounted accelerometer- 3313A3H](image)

Similarly, all 30 experiments, 10 measurements per operator, are ran and the results analyzed using ANOVA in Minitab. The results are shown in Table 4-3 as follows.

<table>
<thead>
<tr>
<th>Variance Component</th>
<th>&lt;Grms X&gt;</th>
<th>&lt;Grms Y&gt;</th>
<th>&lt;Grms Z&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma^2_{Reproducibility} )</td>
<td>0.15</td>
<td>0.11</td>
<td>0.01</td>
</tr>
<tr>
<td>( \sigma^2_{Repeatability} )</td>
<td>0.30</td>
<td>0.13</td>
<td>0.04</td>
</tr>
<tr>
<td>( \sigma^2_{Gauge} )</td>
<td>0.46</td>
<td>0.24</td>
<td>0.05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variance Component</th>
<th>&lt;Grms X&gt;</th>
<th>&lt;Grms Y&gt;</th>
<th>&lt;Grms Z&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reproducibility</td>
<td>33.83%</td>
<td>45.14%</td>
<td>21.65%</td>
</tr>
<tr>
<td>Repeatability</td>
<td>66.17%</td>
<td>54.86%</td>
<td>78.35%</td>
</tr>
<tr>
<td>Gauge</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Table 4-3 Gauge R&R test results for the improvised threaded stud mounted accelerometer
Placing equal weights to the gauge variance on each direction of the accelerometer, the total weighted gauge variance has been reduced by approximately 18 times using the new SOP for a mechanically mounted accelerometer. Figure 4-9 shows general consistency on the PSD graphs for 10 consecutive measurements by operator 1. The images were taken instantaneously when the $G_{rms}$ indicator on the HALT chamber reaches the desired setting of $30G_{rms}$ and stabilizes.

![Figure 4-9 10 Consecutive PSD curves (operator 1) showing consistent PSD curves](image)

The gauge R&R for the 3 measurement systems have proven that mechanically mounted accelerometers with the right SOP can provide precise readings. Additionally, to ensure consistency in the readings, operators have to be aware that surface parallelism is significant and a standard procedure of measurement is important. Although mechanically mounted accelerometers seem to be a preferred choice, adhesively mounted accelerometer still play a role in data acquisition for places where mounting holes cannot be made. One such application is measuring the response of a printed circuit board. However, mechanically mounted accelerometers should be used whenever the context allows. Other good practices like proper documentation on how the experiment is setup, how data is acquired, processed and the personnel involve will also help to minimize variation in the measurement system. As such, a good SOP for fixture setup and gauge usage has to account for all of these steps.
4.3 DOE: Spatial Uniformity of Vibration on Vibration Table

One of the initial considerations of an SOP for setup for PCBs is the location where they should be mounted for testing. Qualmark's HALT Testing Guidelines suggest that if multiple DUTs are being tested, they should be placed symmetrically with respect to the table quadrants [21]. However, this assumes that the table vibration is uniform. In Section 2.4.2, the importance of table uniformity is highlighted. Unfortunately, the HALT chamber in Waters uses a solid aluminum plate as a vibration table. This configuration suggests that the vibration in three axes is not likely to be uniform. If so, single sample testing is preferred. To confirm this hypothesis, the spatial uniformity of the vibration table is explored using the design of experiments (DOE) method to characterize the vibration levels in all three axes with respect to the x and y position on the vibration table.

4.3.1 Experiment Setup

A $5^2$ full factorial experiment is conducted with the average and standard deviation of the 500 $G_{rms}$ values in all three directions as response variables. The x-y position on a gridded vibration table are the independent variables. A five level full factorial experiment is chosen because of how the table is shaped. The table measures 30”x30”x0.750” with mounting holes of 2” centers. As covered in Section 1.2.6, Waters’ PCB board sizes range up to 13”. It is assumed that the vibration levels on the fixture module will approximate the vibration levels of a single sampling square grid on the table that the module resides in.

A compromise between resolution of approximation, sampling effort and Waters’ PCB dimensional considerations is made to segment the vibration table into 6”x6” sampling square grids. There are five levels in the x-direction and five levels in the y-direction. Figure 4-10 illustrates the grid pattern and location of the fixture module relative to the sampling grids. Notice that in this configuration, the fixture module is placed systematically in the same location within the 6”x6” square grids for consistency. Lastly, this experiment was done before the copper shims were procured. As such, the washer is still used as a shim. Nonetheless, only the fixture module is shifted around the table with a single operator to acquire data at different levels of x and y. Thus,
it is reasonable to assume that variations from the gauge are not introduced and table uniformity can still be determined. Fixture setup follows the SOP outlined in Section 5.5.5.

Figure 4-10 Grid layout (left) for the sampling method and the data sampling setup (right)

For convenience, each 6"x6" square grid is call a Block. The sampling pattern is a square pattern, and is considered as uniform sampling. For each combination of x and y levels, there are 500 replicates and six responses (two responses of $G_{\text{rms}}$ value per orthogonal direction). The responses are the averaged in each orthogonal axis ($<G_{\text{rms}}_X>$, $<G_{\text{rms}}_Y>$ and $<G_{\text{rms}}_Z>$) and the respective standard deviations ($\sigma (G_{\text{rms}}_X)$, $\sigma (G_{\text{rms}}_Y)$, $\sigma (G_{\text{rms}}_Z)$). Each run is set at 30$G_{\text{rms}}$ and 30°C.

The location selection criteria and constraints for placing the DUT are as follows:

- Spatial uniformity of means for the respective directional $G_{\text{rms}}$
- Uniformity of the means between the three excitation axis (X,Y,Z) directional $G_{\text{rms}}$ excitation
- Minimum measurement variation within the selected region: Consistency of $G_{\text{rms}}$
- Sufficient space around the location for the placement of six air ducts
- Ability to accommodate all of Waters' PCB (i.e., 3x3 Block constraint)

Note that this is an optimization problem with the constraints of accommodating a 13”x13” region and meeting the above criteria. The approach to this is a two-step process. First, we use the
contour plots of the mean and standard deviation as a visual indication of regions with good uniformity for the average vibration levels and standard deviations. Secondly, we confirm the first test with variance decomposition and find a similar metric to the integration statistic (see Section 2.6.1) to statistically find the right region with the least overall variance in all three axes. Before plotting the response surfaces, a run chart is plotted. Figure 4-11 shows the responses of the $G_{\text{rms}}$ values for all 25 experiments in all three axes of the accelerometer based on the run order. Notice that the mean shifts in the $G_{\text{rms}}$ between locations can be significant and vibration levels within a location can be very different from each other in different axes.

![Run Chart](image)

Figure 4-11 Vibration responses at different spatial locations showing spatial non-uniformity and non-uniformity among the three axes

The experiment is randomly ordered and the run order is generated in Minitab as shown in Figure 4-12. Figure 4-12 also shows an up-close image of the output vibrational responses. Notice from Figure 4-12 that there is a general oscillating pattern in the readings. This observation represents the effect of the feedback control loop from the HALT chamber in maintaining the vibration levels at a set $G_{\text{rms}}Z$ value.
Run Order

<table>
<thead>
<tr>
<th>StdOrder</th>
<th>RunOrder</th>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>1</td>
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<td>4</td>
<td>4</td>
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</tr>
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</tr>
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<td>5</td>
</tr>
<tr>
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</tr>
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<td>4</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
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<td>5</td>
<td>3</td>
</tr>
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<td>24</td>
<td>18</td>
<td>5</td>
<td>4</td>
</tr>
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<td>1</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

Sample X3_Y5

Figure 4-12 Randomly ordered run order (left) and run chart of Grms_Z for X3_Y5 (right)

Before the response surface plots are plotted, normality plots are generated for 500 samples of G_{rms} values when the vibration levels in the HALT chamber have stabilized at 30G_{rms}. Figure 4-13 shows the normality plots and summary reports for 500 samples for the first run (X3_Y5). The normality plots show that the underlying distributions for all the three axes are normal and the p-values for the Anderson-Darling normality test [46] are more than 0.05. Thus vibration outputs are normally distributed.
Figure 4-13 Normality plots and Anderson-Darling normality test for X3_Y5 showing normality in the vibrational responses on the test plate for three axes

4.3.2 Part 1: Response Surface Plots for Average Grms

For each run, the average of 500 samples of vibration from all three axes are calculated. An ANOVA analysis is made using the response surface design tool in Minitab to generate the necessary regression equations, contour plots and surface plots. The results show that there is
spatial dependence of the mean on the x-y direction on the table. Table 4-4 shows the significant factors (p < 0.05) at 95% confidence interval while Table 4-5 shows the R-squared values for each average G_{rms} output. Notice that the R-squared value for the <Grms_{Z}> is low, indicating that the suggested regression function may not be accurate. Nonetheless, this suggests that at least 19% of the data is explained by the function and with high confidence there is a spatial dependence to it.

<table>
<thead>
<tr>
<th>Model Source</th>
<th>&lt;Grms_{X}&gt;</th>
<th>&lt;Grms_{Y}&gt;</th>
<th>&lt;Grms_{Z}&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>134.47</td>
<td>109.22</td>
<td>45.10</td>
</tr>
<tr>
<td>Y</td>
<td>45.56</td>
<td>10.96</td>
<td>38.06</td>
</tr>
<tr>
<td>X*X</td>
<td>32.55</td>
<td>189.44</td>
<td>22.91</td>
</tr>
<tr>
<td>Y*Y</td>
<td>280.32</td>
<td>20.57</td>
<td>75.79</td>
</tr>
<tr>
<td>X*Y</td>
<td>1.768</td>
<td>0.62</td>
<td>14.35</td>
</tr>
<tr>
<td>Error</td>
<td>8.05</td>
<td>-</td>
<td>350.37</td>
</tr>
</tbody>
</table>

Table 4-4 ANOVA results from Minitab with significant terms highlighted in red.

<table>
<thead>
<tr>
<th>&lt;Grms_{X}&gt;</th>
<th>Significant Factors</th>
<th>R-Sq (adj)</th>
<th>Regression Equation (Uncoded Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X, Y, X<em>X, Y</em>Y</td>
<td>70.18%</td>
<td>&lt;Grms_{X}&gt; = 56.84 - 5.33 X - 10.65 Y + 0.682 X<em>X + 2.001 Y</em>Y - 0.133 X*Y</td>
<td></td>
</tr>
<tr>
<td>X, X*X</td>
<td>60.60%</td>
<td>&lt;Grms_{Y}&gt; = 53.58 - 11.11 X - 2.55 Y + 1.645 X<em>X + 0.542 Y</em>Y - 0.078 X*Y</td>
<td></td>
</tr>
<tr>
<td>Y*Y</td>
<td>19.03%</td>
<td>&lt;Grms_{Z}&gt; = 17.91 + 3.25 X + 4.23 Y - 0.572 X<em>X - 1.041 Y</em>Y + 0.379 X*Y</td>
<td></td>
</tr>
</tbody>
</table>

Table 4-5 Response surface regression results from Minitab (Uncoded)

After defining the response surfaces, the 3D response plots and contour plots can be plotted to visualize how the average vibration levels vary with the x-y position. As mentioned in Section 2.6, contour plots can visually indicate more uniform regions of the table. Figure 4-14 shows the 3D surface plots and Figure 4-15 shows the contour plots. From the surface plot, it is clear that the vibration levels on the table are not uniform throughout x-y directions. Among the x,y and z vibration levels, the G_{rms} values are not identical too. This further suggests that the single axis accelerometer controlling the HALT chamber is just an approximation of the state of excitation. This practice may only be followed if the specimen is small, mounted directly on the table with excitation frequencies below 500Hz [19]. Depending on the components to excite, this practice is not ideal; whenever possible, the chamber should control vibration in three axes to achieve better uniformity of vibration levels in all the axes.
From the contour plots, the regions with the most gradual slopes are likely to have better uniformity in the average Grms in the x-y plane. Minitab is unable to divide the extreme regions into further divisions. As such, to better approximate extreme regions, the range values in the region are calculated based on the difference of the lower (upper) bound to the minimum (maximum) values available. From Table 4-6, it is clear that the step intervals are similar to that of the range for <Grms_X> and <Grms_Y>. This means that having a blue region is analogous to having deviations of one contour step. Thus, it is recommended to encompass as many of the dark blue regions as possible to achieve greater uniformity per unit area. However, for the <Grms_Z> plot, the range of the dark green region is about four times the contour step. As such, it is highly...
recommended not to place the DUT within that region due to large variability in the mean. Reasonable regions that meet these criteria are boxed in orange as shown on the contour plots. Generally, regions with less than 3-4 contour divisions and less dark green regions in <Grms_Z> are preferred. The orange regions are created using a 3x3 Block and moving the Block around. Any possible areas will be treated as a suitable set to form the recommended region as outlined in Figure 4-15.

4.3.3 Part 1: Response Surface Plots for Standard Deviation G_rms

Similar to the previous section, this section creates a response surface regression to discover how the measurement variation (i.e., standard deviations) in each Block varies with the x-y position. Table 4-7 shows the ANOVA results, while Table 4-8 shows the regression equations and R-squared values for each measurement standard deviation. Notice that the R-squared value for the σ (Grms_Z) is small, indicating that the suggested regression function may not be accurate. Nonetheless, 6.47% of the data is explained by the model and there is a spatial dependence to it.

<table>
<thead>
<tr>
<th>Model Source</th>
<th>σ (Grms_X)</th>
<th>σ (Grms_Y)</th>
<th>σ (Grms_Z)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MS Effect</td>
<td>P-Value</td>
<td>MS Effect</td>
</tr>
<tr>
<td>X</td>
<td>0.11</td>
<td>-0.19</td>
<td>0.06</td>
</tr>
<tr>
<td>Y</td>
<td>0.15</td>
<td>0.22</td>
<td>0.06</td>
</tr>
<tr>
<td>X*X</td>
<td>0.09</td>
<td>0.28</td>
<td>0.13</td>
</tr>
<tr>
<td>Y*Y</td>
<td>0.40</td>
<td>0.61</td>
<td>0.00</td>
</tr>
<tr>
<td>X*Y</td>
<td>0.01</td>
<td>-0.07</td>
<td>0.00</td>
</tr>
<tr>
<td>Error</td>
<td>0.01</td>
<td>-</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 4-7 ANOVA Results from Minitab with significant terms highlighted in red.

<table>
<thead>
<tr>
<th>&lt;Grms&gt;</th>
<th>Significant Factors</th>
<th>R-Sq (adj)</th>
<th>Regression Equation (Uncoded Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;Grms_X&gt;</td>
<td>X,Y,X<em>Y,Y</em>Y</td>
<td>79.22%</td>
<td>σ(Grms_X) = 1.334 - 0.2325 X - 0.3736 Y + 0.0356 X<em>Y + 0.0760 Y</em>Y - 0.00933 X*Y</td>
</tr>
<tr>
<td>&lt;Grms_Y&gt;</td>
<td>X,Y,X*Y</td>
<td>50.23%</td>
<td>σ(Grms_Y) = 0.912 - 0.2813 X + 0.0199 Y + 0.0436 X<em>Y + 0.0043 Y</em>Y - 0.00460 X*Y</td>
</tr>
<tr>
<td>&lt;Grms_Z&gt;</td>
<td>X</td>
<td>6.47%</td>
<td>σ(Grms_Z) = 0.458 + 0.009 X + 0.020 Y - 0.0016 X<em>Y - 0.0132 Y</em>Y + 0.0133 X*Y</td>
</tr>
</tbody>
</table>

Table 4-8 Response surface regression results from Minitab (Uncoded)

Similarly, the 3D response surface plots and contour plots are graphed in Figure 4-16 and Figure 4-17, respectively. The results also show clear dependence of standard deviations on x-y positions.
From the contour plots, it is noticeable that the regions with greater spatial uniformity and least standard deviation (i.e., blue region) are preferred because they have better spatial uniformity in the measurement variation as well as the lower measurement variation. Reasonable regions that meet these criteria are boxed in orange as shown in the contour plots. From Table 4-9, it is also clear that the deviations in value per contour step is an order of magnitude smaller than the contour step for the average values. It may be assumed that the variation in measurements is of lower importance than the spatial variation of the mean vibration levels.
As outlined in both sections, the preferred mounting location for the DUT that balances all design criteria seem to be at the center. To further affirm the results on the contour plots, an optimization problem is created in Minitab to gain greater insights on the potential location. The optimization problem is set to have the average of all three axes to achieve a target of 30Gms and to minimize variation in all three axes. The list of solutions suggested by Minitab as shown in Table 4-10 suggests the center region (approximately near X=3, Y=3) as well.

<table>
<thead>
<tr>
<th>Solution</th>
<th>X</th>
<th>Y</th>
<th>&lt;Grms X&gt;</th>
<th>&lt;Grms Y&gt;</th>
<th>&lt;Grms Z&gt;</th>
<th>σ(Grms X)</th>
<th>σ(Grms Y)</th>
<th>σ(Grms Z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.4</td>
<td>2.6</td>
<td>31.3</td>
<td>31.2</td>
<td>29.7</td>
<td>0.41</td>
<td>0.50</td>
<td>0.55</td>
</tr>
<tr>
<td>2</td>
<td>3.1</td>
<td>2.6</td>
<td>31.7</td>
<td>31.4</td>
<td>29.5</td>
<td>0.42</td>
<td>0.50</td>
<td>0.54</td>
</tr>
<tr>
<td>3</td>
<td>3.3</td>
<td>2.3</td>
<td>31.8</td>
<td>31.3</td>
<td>29.5</td>
<td>0.43</td>
<td>0.49</td>
<td>0.55</td>
</tr>
<tr>
<td>4</td>
<td>3.0</td>
<td>2.7</td>
<td>31.7</td>
<td>31.4</td>
<td>29.4</td>
<td>0.42</td>
<td>0.51</td>
<td>0.54</td>
</tr>
<tr>
<td>5</td>
<td>2.9</td>
<td>2.6</td>
<td>31.9</td>
<td>31.6</td>
<td>29.4</td>
<td>0.43</td>
<td>0.51</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Table 4-10 Reponse surface optimization results from Minitab

4.3.4 Part 2: Spatial Uniformity Metric: Total Variance Metric

To quantitatively compare the variation between possible regions on the vibration table where a DUT could be placed, an aggregate variance metric is formed to represent the variation in a given 3x3 Block. In this section, the metric is derived to quantitatively identify the region of least variance for placing the DUT. Unlike the integration statistic (I) outlined in Section 2.6.1, the samples are uniformly sampled in a square grid. As such, the weights in Equation 2.14 are all the same. Using decomposition of variance, every G RMS value measured at a given position is represented by Equation 4.2. Notice that all the terms are spatially dependent.

\[
G_{rmsX/Y/Z}(x, y) = f_{meanX/Y/Z}(x, y) + w_{measureX/Y/Z}(x, y) \quad \text{Equation 4.2}
\]

\[
f_{meanX/Y/Z}(x, y) = \mu_{Regression\ Plot} + N(0, \sigma^2_{mean})
\]

\[
w_{measureX/Y/Z}(x, y) = N(0, \sigma^2_{Regression\ Plot} + \sigma^2_{measure})
\]

where
- \(G_{rmsX/Y/Z}(x, y)\) is the G RMS value measured at point (x,y) in a given X/Y/Z direction
- \(f_{meanX/Y/Z}(x, y)\) is the mean regression plot outlined in Section 4.3.2
- \(w_{measureX/Y/Z}(x, y)\) is the measurement variance which has its own regression plot

Taking the variance of the random variable \(G_{rmsX/Y/Z}(x, y)\), we get Equation 4.3.
\[ \text{Var}(G_{\text{rms}_x/y/z}) = \frac{A}{\iint dxdy} + \sigma^2_{\text{Regression Plot}} + \sigma^2_{\text{measure}} \quad \text{Equation 4.3} \]

where \( A = \iint (f_{\text{mean}_x/y/z}(x,y) - \bar{f}_{\text{mean}_x/y/z})^2 dxdy \)

This equation shows that the variance at any point within any given selected region is the sum of variances of the means within that given region and the variance from the measurement itself at that point. We have defined the region at each point of our experiment measurement to be called a Block. Since we have a 3x3 Block constraint and Table 4-8 has shown that the z-axis regression model for measurement variance is not an accurate representation of the actual distribution, it is more accurate for the variance to be calculated discretely. Assuming that the response from the test plate is a good representative of the response for a Block, we can discretize the equation.

We define a 3x3 Block region as a Cell. Equation 4.4 represents the equation for the total variance of a Block within a given Cell. Here \( n \) refers to the \( n^{th} \) Cell and \( j \) refers to the \( j^{th} \) measurement out of 500 samples within the \( i^{th} \) Block that is nested in the \( n^{th} \) Cell. There are a total combination of nine different possible Cell arrangements as shown in Figure 4-18 and Figure 4-20. Figure 4-18 shows the variance of means between Blocks within a given Cell and Figure 4-19 shows the measurement variance per Block.

\[ \text{Var}(G_{\text{rms}_x/y/z})_n = \text{Var}(\mu) + \text{Var}(B_i)_n + \text{Var}(W_{j(i)})_n \quad \text{Equation 4.4} \]

where \( n \in [1,9], i \in [1,9], j \in [1,500] \)

- \( \text{Var}(B_i)_n \) is the Block to Block Variance of the Mean G_{rms} in the \( n^{th} \) Cell
- \( \text{Var}(W_{j(i)})_n \) is the within Block Variance of the Block \( i \) in the \( n^{th} \) Cell
- \( \text{Var}(G_{\text{rms}_x/y/z})_n \) is the Variance of G_{rms} in the X/Y/Z direction at Block \( i \) in the \( n^{th} \) Cell
VARIANCES BETWEEN MEANS

Example Grouping:
Cell 1

<table>
<thead>
<tr>
<th>Cell</th>
<th>45.14</th>
<th>27.39</th>
<th>27.96</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell 1</td>
<td><img src="image1.png" alt="Image" /></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell 2</td>
<td><img src="image2.png" alt="Image" /></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell 3</td>
<td><img src="image3.png" alt="Image" /></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell 4</td>
<td><img src="image4.png" alt="Image" /></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell 5</td>
<td><img src="image5.png" alt="Image" /></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell 6</td>
<td><img src="image6.png" alt="Image" /></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell 7</td>
<td><img src="image7.png" alt="Image" /></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell 8</td>
<td><img src="image8.png" alt="Image" /></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell 9</td>
<td><img src="image9.png" alt="Image" /></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Legend
- Smallest Value
- 2nd Smallest Value

Figure 4-18 Block-to-block variance of means for each possible Cell (<Grms_X>)

<table>
<thead>
<tr>
<th>1.528</th>
<th>0.712</th>
<th>0.988</th>
<th>0.449</th>
<th>0.835</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.626</td>
<td>0.294</td>
<td>0.322</td>
<td>0.353</td>
<td>0.293</td>
</tr>
<tr>
<td>0.487</td>
<td>0.265</td>
<td>0.161</td>
<td>0.216</td>
<td>0.26</td>
</tr>
<tr>
<td>0.339</td>
<td>0.27</td>
<td>0.369</td>
<td>0.248</td>
<td>0.256</td>
</tr>
<tr>
<td>0.871</td>
<td>0.361</td>
<td>0.383</td>
<td>0.414</td>
<td>0.446</td>
</tr>
</tbody>
</table>

Figure 4-19 Within Block variance (i.e., measurement variance) per Block (<Grms_X>)

To create a variance metric for comparison among Cells, we sum up the variances in all nine Blocks for a given Cell as in Equation 4.5.

\[
Var(G_{rms,X/Y/Z_{Total}})_n = \sum_{i=1}^{9} Var(G_{rms,X/Y/Z_i})_n
\]

Equation 4.5

Where \( n \in [1,9], i \in [1,9] \)
- \( Var(G_{rms,X/Y/Z_i})_n \) is the Variance of \( G_{rms} \) in the X/Y/Z direction at Block \( i \) in \( n \)th Cell
- \( Var(G_{rms,X/Y/Z_{Total}})_n \) is the Variance of the \( n \)th Cell

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Since Grms_X, Grms_Y, Grms_Z, are equally important in generating accelerated fatigue in a HALT process, to create a metric of comparison that incorporates these three excitations, the total variance metric is created for a given Cell. It represents the weighted sum of the variance metric in all three axes. Since each excitation direction is important, each direction is weighted equally. Equation 4.6 shows the final metric of comparison between Cell configurations. From Figure 4-20, the Cell with the smallest metric is at the center of the table, colored in green.

\[
Var(G_{rms, Metric})_n = Var(G_{rms, X_{Total}})_n + Var(G_{rms, Y_{Total}})_n + Var(G_{rms, Z_{Total}})_n \quad \text{Equation 4.6}
\]

Where \( n \in [1,9] \)

\( Var(G_{rms, X_{Total}})_n \) is the total variance of Grms in the X direction in n\textsuperscript{th} Cell

\( Var(G_{rms, Y_{Total}})_n \) is the total variance of Grms in the Y direction in n\textsuperscript{th} Cell

\( Var(G_{rms, Z_{Total}})_n \) is the total variance of Grms in the Z direction in n\textsuperscript{th} Cell

<table>
<thead>
<tr>
<th>METRIC OF VARIATION PER CELL EQUALLY WEIGHTED</th>
</tr>
</thead>
<tbody>
<tr>
<td>903.92</td>
</tr>
<tr>
<td>Cell 1</td>
</tr>
<tr>
<td>369.58</td>
</tr>
<tr>
<td>Cell 4</td>
</tr>
<tr>
<td>622.82</td>
</tr>
<tr>
<td>Cell 7</td>
</tr>
</tbody>
</table>

Figure 4-20 Final weighted average variance metric for three axes. Cell 5 has the lowest value that presents itself as the best location for the DUT.

From the two part analysis we can conclude that there are significant differences in the total excitation levels for the HALT chamber at Waters and the excitations are spatially dependent. This further confirms the experimental results presented by Page and Weinmann [24] (see Section 2.4.2). Although operators are not recommended to test multiple DUTs for HALT, we know that the center region is the most uniform location to place the fixture such that the variation in excitation levels among different boards sizes are minimized.
Chapter 5. Methodology: Standardization of Fixture Design

Before we conduct initial HALT experiments to determine suitable HALT stress profiles for the PCBs, we identified in Section 3.2 that the existing fixtures did not meet the desired fixture design requirements outlined in Section 2.3. As a result, a new fixture for the HALT process is designed to cater to the majority of PCBs at Waters. This chapter describes the new fixture design and the attempts to evaluate its’ performance. Section 5.1 will present the design requirements, with the resulting proposed design in Section 5.2. Simulations of the proposed fixture are presented in Section 5.3. The relationship between vibration outputs and process inputs (vibration and temperature setpoints) is explained using design of experiments and presented in Section 5.4. Finally Section 5.5 describes the experiments that are conducted to evaluate the fixture’s performance through its resonant frequency, spatial uniformity as well as repeatability and reproducibility.

5.1 Summary of Design Requirements

The approach in designing the fixture is crucial in establishing a standard operating procedure because fixtures come in different physical properties that will greatly affect the results if not well planned (see Section 2.3). The following is a summary of HALT fixture design principles that the proposed fixture design process follows.

1. Have a fundamental resonant frequency at least 50% higher than the highest frequency of excitation from the HALT chamber.
2. Have a vibrational response that varies linearly with the input vibration.
3. Have a simple single-part design to reduce risk of reproducibility issues.
4. Have symmetrical features so that modal analysis is easier and point of highest displacement can be easily deduced.
5. Use light-weight, stiff, low-thermal mass and cost effective materials.
6. Have sufficient height, at least 1-2 inches away from the vibration table’s surface so that air can flow uniformly throughout the surfaces of the PCB.
7. Able to withstand fatigue and stresses imposed by the HALT chamber.
8. Occupy a small area of the vibration table so that the rigidity of the table will not be significantly affected. Affected table would express vibration modes different from what it is designed for.

9. Do not change the desired end use boundary conditions of the PCB as much as possible so that failures observed in the HALT process reasonably reflects failures of the weakest link in the design.

10. Modular in nature to suit most available PCBs in Waters.

11. Accommodates to HALT improvements made on the board. For example, additional standoffs, longer standoffs and different components.

12. Torque all fasteners according to the given industry ratings to provide suitable reproducibility. An SOP should be provided along with the fixture design.

13. Use as many fasteners possible to fasten the fixture to the table to increase the resonant frequency of the fixture system.

5.2 Proposed Design Features

Figure 5-1 shows the final CAD design of the proposed fixture to be used for HALT testing for Waters PCBs. The design is a modularized 3” by 3” by 0.5” plate of 6061-T6 aluminum with 2” center mounting points for securing the fixture to the vibration table. The design is originally specified for 7075-T651 but the availability of 6061-T6 is more common and the influence in resonant frequency of the fixture is insignificant compared to the lack of availability and additional costs. Aluminum is a cost effective material that meets the design criteria.

The design begins with the priority to standardize across PCBs at Waters. Thus, the first step was to speak to R&D engineers on geometrical shapes and similarities across Waters’ PCBs (see Section 1.1.4). Since there are no standardized screw sizes, aspect ratio of the boards or locations of standoffs, a modular design is proposed such that each module is able to serve as a platform where standoffs can be mounted. Modularity and simplicity are favored to allow reduction in manufacturing costs, and versatility to allow mounting features situated at the inner regions of the PCBs. A technical drawing of a HALT PCB fixture module is showed in Appendix B-2 while the actual fixture setup is shown in Figure 5-2.
EXAMPLE OF AN ASSEMBLY

Serrated Washers
Resists vibration and loosening of standoffs

Printed Circuit Board (PCB) or Device Under Test (DUT)

Recess/Bored Holes
Allows flat planar surface for different types of PCBs to be mounted unhindered by any bolt head extrusions

Mounting Standoff(s)
Selected specifically to emulate the actual standoffs used in the field

PROPOSED DESIGN FIXTURE MODULE

6061-T6 Aluminum Fixture Module

Standoff Mounting Hole changes relative position wrt. PCB layout

Nord-Lock* Washers
High vibration resistant washers to ensure proper contact between the plate and vibration table.

Figure 5-1 Design overview of the proposed modular fixture plate for PCBs

Figure 5-2 Modular fixture plates in actual use within the HALT Chamber
The design starts with iterations from the most fundamental single bolted square to a four point bolted plate. The deciding factor is when the natural frequency of the block, given its boundary conditions, reaches about 15 kHz. The frequency analyses are from Solidworks Frequency Analysis simulation which considers boundary conditions like the bolted points (see Section 5.3).

Initial iterations reveal that having a bolt may hinder the deflection of the PCBs during vibration because of the relatively short height of standoffs that Waters uses for their PCBs. To allow sufficient deflection in the PCB, the 2” center mounting points are counterbored and low profile alloy steel socket head cap screws are used. When more material is bored out it reduces the stiffness of the plate. Using low profile screws allow lesser material to be removed while achieving still the desired flat planar surface. Torque values of the fasteners are based on the torque values suggested by the manufacturer.

In order to replicate end use environment boundary conditions, each setup requires careful selection of male-female standoffs and the respective material. In particular, the critical dimensions are material, hex size and length of the standoff. Hex standoffs are used in all situations so that sufficient torque can be applied when securing the standoffs to the fixture plate. A close approximation for the above-mentioned critical dimensions has to be made if the actual mounting standoffs are of different geometric shapes.

Nord-Lock® washers are used instead of the more abundant helical spring washers that engineers at the Reliability Lab commonly use. A point to note is that helical spring washers are meant to compensate for loosening but not preventing loosing. On the other hand, serrated washers like Nord-Lock® washers increase friction of contact with surfaces. These washers’ sole function is to prevent loosening which is appropriate for our setup [47]. The spring washers may also add springs into the system which may alter the intended natural frequency of the module. Thus, for the fixture setup in Figure 5-1, all washers have serrated exteriors. Nord-Lock® washers are used as a standard fixture setup because it is designed for resisting vibration. Junker tests by the company have shown that these washers can be reused more than 30 times [48] and are superior in resisting vibration (i.e., maintaining bolt tension) when compared to other fastening methods.
5.3 Solidworks Frequency Analysis Simulation of Fixture Design

A common practice in fixture designing is to do a modal analysis using a finite element analysis software. From the simulation the mode shapes can be identified with their respective resonant frequencies. Figure 5-3 shows the results of the frequency analysis simulation in Solidworks for a fixture module. The simulation adopts an eigenvalue approach to determine the natural modes of vibration with boundary conditions and loads [49]. A total of five modal frequencies are found.

![Mode Shapes](image)

**Figure 5-3** Simulation results from Solidworks frequency analysis for -425 fixture module

To simulate the boundary conditions imposed on the design by the socket head cap screw, a cylindrical constraint in the radial direction from the center of each hole is imposed. Another constraint is a 0.65” flat surface constraint normal to the surface of the plate where the bolt is mounted. As a result, if we analyze the constraints at each hole in isolation, only rotational motion is allowable. Vertical loading by weight of PCBs is simulated and found to have negligible effects on the resonant frequencies of the plate. As such, subsequent designs do not include the weight of the PCBs. Material properties of 60601-T6 aluminum used in the simulation are shown in Table 5-1. The properties are adapted from the materials library in Solidworks and was checked with other sources [50].
<table>
<thead>
<tr>
<th>Physical Property</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic Modulus</td>
<td>6.90E+10</td>
<td>N/m²²</td>
</tr>
<tr>
<td>Poisson's Ratio</td>
<td>0.33</td>
<td>N/A</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>2.60E+10</td>
<td>N/m²²</td>
</tr>
<tr>
<td>Mass Density</td>
<td>2700</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>310000002.1</td>
<td>N/m²²</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>275000000.9</td>
<td>N/m²²</td>
</tr>
<tr>
<td>Thermal Expansion Coefficient</td>
<td>2.40E-05</td>
<td>/K</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>166.9</td>
<td>W/(m·K)</td>
</tr>
<tr>
<td>Specific Heat</td>
<td>896</td>
<td>J/(kg·K)</td>
</tr>
</tbody>
</table>

Table 5-1 Material properties of aluminum 6061-T6 used in the simulation

The simulation has shown that the fundamental frequency of the plate meets the design criteria of being approximately 1.5 times higher than 10 kHz. Considering that the simulation does not account for the boundary condition imposed by surface contact with the vibration table, the simulated frequencies are considered as conservative. This safety margin is justified to ensure that the actual resonance frequencies are robust against deviations in the actual boundary conditions arising from the loosening of fasteners or other potential sources of variation that decouple the motion between the plate and the vibration table. The designs were sent to the Waters' machine shop for fabrication.

5.4 DOE: Relationship between Vibration Outputs with Profile Settings

To validate the proposed design, a series of experiments has been conducted. The first experiment aims to characterize the relationship between the input stresses and the vibrational response of the plate. A $2^2$ full factorial experiment is conducted. The factors are the temperature and input vibrational settings with two levels, -10°C and 70°C, as well as 20G_rms and 70G_rms, respectively. Levels are not chosen at the extremes to avoid potential damage to the system and accelerometer, as well as to cater to the extreme test points in a central composite design (CCD) for the later experiment. There are five center points in the experiment to check for curvature. Using Minitab, a randomized run order is generated as shown in Table 5-2.
Table 5-2 Run order of the $2^2$ experiment

Similar to gauge R&R, the response variable for this experiment is the average output $G_{rms}$ over 200 consecutive data points from an accelerometer that is mounted on the center of a test plate. The average is used instead of instantaneous values because the nature of feedback control in the HALT system is to maintain a suitable average root-mean-squared stress on the DUT. Figure 5-4 shows the location and setup of the test on the vibration table. The location is chosen because it is within the proposed grid where the PCB tests will occur (see Section 4.3) and close to the center of the region of interest. The exact geometric center is not chosen because the mounting hole at the center of the vibration table is of a different size. Note that the triaxial accelerometer is taped to prevent the coaxial cable from loosening at high vibration levels.

![Figure 5-4 Experiment setup (left) and sampling position on the vibration table (right)](image-url)
From the experiment, ANOVA reveals the significant factors and the proposed regression line. Curvature is determined with the results from five center point replicates. Table 5-3 shows the results of the ANOVA analysis and Table 5-4 gives the respective regression models.

<table>
<thead>
<tr>
<th>Model Source</th>
<th>&lt;Grms_X&gt; Effect</th>
<th>&lt;Grms_X&gt; P-Value</th>
<th>&lt;Grms_Y&gt; Effect</th>
<th>&lt;Grms_Y&gt; P-Value</th>
<th>&lt;Grms_Z&gt; Effect</th>
<th>&lt;Grms_Z&gt; P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.57</td>
<td>0.76</td>
<td>1.75</td>
<td>-1.32</td>
<td>0.25</td>
<td>-0.50</td>
</tr>
<tr>
<td>B</td>
<td>2353.22</td>
<td>48.51</td>
<td>1916.86</td>
<td>43.78</td>
<td>0.00</td>
<td>1319.69</td>
</tr>
<tr>
<td>A*B</td>
<td>0.00</td>
<td>0.98</td>
<td>0.78</td>
<td>-0.885</td>
<td>0.01</td>
<td>-0.10</td>
</tr>
<tr>
<td>Curvature</td>
<td>3.59</td>
<td>-0.01</td>
<td>30.54</td>
<td>-0.01</td>
<td>7.46</td>
<td>-0.00</td>
</tr>
<tr>
<td>Error</td>
<td>0.07</td>
<td>-0.00</td>
<td>1.61</td>
<td>-0.00</td>
<td>0.03</td>
<td>-0.00</td>
</tr>
</tbody>
</table>

*<Grms> = Temperature, B = Vibration

Table 5-3 ANOVA results from Minitab with significant p-values highlighted in red

<table>
<thead>
<tr>
<th>&lt;Grms&gt;</th>
<th>Significant Factors*</th>
<th>R-Sq (adj)</th>
<th>Regression Equation (Uncoded Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;Grms_X&gt;</td>
<td>A, B, Curvature</td>
<td>99.98%</td>
<td>&lt;Grms_X&gt; = 1.726 + 0.00703 A + 0.97034 B - 0.000003 A*B + 1.289 Ct Pt</td>
</tr>
<tr>
<td>&lt;Grms_Y&gt;</td>
<td>B, Curvature</td>
<td>99.34%</td>
<td>&lt;Grms_Y&gt; = 1.08 + 0.0025 A + 0.8901 B - 0.000322 A*B + 3.707 Ct Pt</td>
</tr>
<tr>
<td>&lt;Grms_Z&gt;</td>
<td>A, B, Curvature</td>
<td>99.98%</td>
<td>&lt;Grms_Z&gt; = 2.831 - 0.00298 A + 0.72812 B - 0.000035 A*B + 1.832 Ct Pt</td>
</tr>
</tbody>
</table>

*<Grms> = Temperature, B = Vibration

Table 5-4 Factorial regression results from Minitab (Uncoded)

From the experiment, it is evident that the main effects for all the responses come from the input vibration itself (factor B). Looking at the coefficients of the uncoded regression, vibration levels approximately match a 1-1 ratio from the inputs to the outputs except for <Grms_Z>. This result further justifies the vibration non-uniformity between the x-y-z directions. An interesting point to note is that temperature is a statistically significant factor in affecting changes in the vibrational response for <Grms_X> and <Grms_Z>. However, the effect of temperature on the average Gms values is negligible relative to the input vibration. From the regression equations, the coefficients for temperature are two orders of magnitude lower than input vibration. Additionally, curvature is significant in all models. To investigate further, four more experiments are conducted to meet the requirements of a CCD and a response surface regression plotted. Table 5-5 shows the 13 operating points necessary for the CCD. Table 5-6 and Table 5-7 show the results of the ANOVA analysis and the regression models, respectively.
Table 5-5 Run order of the CCD experiment

<table>
<thead>
<tr>
<th>StdOrder</th>
<th>RunOrder</th>
<th>Coded</th>
<th>Uncoded</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>-1</td>
<td>-10</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>-1</td>
<td>-10</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>13</td>
<td>-1.41</td>
<td>32.78</td>
</tr>
<tr>
<td>6</td>
<td>11</td>
<td>1.41</td>
<td>122.78</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>0</td>
<td>45</td>
</tr>
<tr>
<td>8</td>
<td>12</td>
<td>1.41</td>
<td>80.36</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>0</td>
<td>45</td>
</tr>
<tr>
<td>10</td>
<td>8</td>
<td>0</td>
<td>45</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>0</td>
<td>45</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>0</td>
<td>45</td>
</tr>
<tr>
<td>13</td>
<td>4</td>
<td>0</td>
<td>45</td>
</tr>
</tbody>
</table>

Table 5-6 ANOVA results from Minitab with significant p-values highlighted in red

<table>
<thead>
<tr>
<th>Model Source</th>
<th>&lt;Grms X&gt;</th>
<th>&lt;Grms Y&gt;</th>
<th>&lt;Grms Z&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MS</td>
<td>Effect</td>
<td>P-Value</td>
</tr>
<tr>
<td>A</td>
<td>2.00</td>
<td>1.00</td>
<td>0.00</td>
</tr>
<tr>
<td>B</td>
<td>4760.61</td>
<td>48.79</td>
<td>0.00</td>
</tr>
<tr>
<td>A*A</td>
<td>0.10</td>
<td>0.24</td>
<td>0.40</td>
</tr>
<tr>
<td>B*B</td>
<td>16.62</td>
<td>-3.10</td>
<td>0.00</td>
</tr>
<tr>
<td>A*B</td>
<td>0.00</td>
<td>-0.01</td>
<td>0.98</td>
</tr>
<tr>
<td>Lack-of-Fit</td>
<td>0.14</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pure Error</td>
<td>0.07</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*A = Temperature, B = Vibration

Table 5-7 Surface regression results from Minitab (Coded)

Results from the surface regression analysis show vibration as the primary driving force of the responses which is consistent with the linear regression. For <Grms Z>, the inclusion of higher order terms eliminates temperature as part of the significant factor. However, for <Grms X>, temperature is still statistically significant at 95% confidence level along with the quadratic term of vibration. From the factorial plots in Figure 5-5, one can notice that for <Grms X> the
relationship with vibration is not as linear as that of <Grms_Y> and <Grms_Z>. Temperature seems to also have a slight positive relationship with <Grms_X>. Lastly, there is a lack-of-fit present in the model for <Grms_Y> and <Grms_Z> suggesting that there may be higher order interaction terms present which are not captured in the model.

![Figure 5-5 Factorial plots of temperature (A) and vibration (B) against <Grms>](image)

Nonetheless, from a practical stand point, the high R-squared value, relative magnitudes of the main effects of the factors, and factorial plots strongly suggest linearity between the input vibrational settings on the HALT chamber and the response on the plate. The slight dependence on temperature may suggest interaction effects between different expansion rates of the measurement tool and the plate, or sensitivity changes in the accelerometer at higher temperatures. From the datasheet of the accelerometer, sensitivity deviation increases beyond 94°F (34.4 °C) [51]. Table 5-8 and 5-9 show the coded and uncoded surface regression equations removing non-significant effects.

<table>
<thead>
<tr>
<th>&lt;Grms&gt;</th>
<th>Significant Factors*</th>
<th>Lack-of-Fit (p-value)</th>
<th>R-Sq (adj)</th>
<th>Regression Equation (Coded Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;Grms_X&gt;</td>
<td>A, B, B*B</td>
<td>N.A.</td>
<td>99.99%</td>
<td>&lt;Grms_X&gt; = 47.073 + 0.500 A + 24.394 B - 1.561 B*B</td>
</tr>
<tr>
<td>&lt;Grms_Y&gt;</td>
<td>B, Lack-of-Fit</td>
<td>0.03</td>
<td>97.72%</td>
<td>&lt;Grms_Y&gt; = 43.460 + 24.03 B</td>
</tr>
<tr>
<td>&lt;Grms_Z&gt;</td>
<td>B, Lack-of-Fit</td>
<td>0.00</td>
<td>99.47%</td>
<td>&lt;Grms_Z&gt; = 36.615 + 19.260 B</td>
</tr>
</tbody>
</table>

*A = Temperature, B = Vibration

<table>
<thead>
<tr>
<th>&lt;Grms&gt;</th>
<th>Significant Factors*</th>
<th>Lack-of-Fit (p-value)</th>
<th>R-Sq (adj)</th>
<th>Regression Equation (Uncoded Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;Grms_X&gt;</td>
<td>A, B, B*B</td>
<td>0.366</td>
<td>99.99%</td>
<td>&lt;Grms_X&gt; = -2.304 + 0.00909 A + 1.2066 B - 0.002498 B*B ≈ -2.304 + 1.2066 B</td>
</tr>
<tr>
<td>&lt;Grms_Y&gt;</td>
<td>B, Lack-of-Fit</td>
<td>0.03</td>
<td>97.72%</td>
<td>&lt;Grms_Y&gt; = 0.21 + 0.9610 B</td>
</tr>
<tr>
<td>&lt;Grms_Z&gt;</td>
<td>B, Lack-of-Fit</td>
<td>0.00</td>
<td>99.47%</td>
<td>&lt;Grms_Z&gt; = 1.946 + 0.7704 B</td>
</tr>
</tbody>
</table>

*A = Temperature, B = Vibration

Table 5-8 Remodeled surface regression results from Minitab (Coded)

Table 5-9 Remodeled surface regression results from Minitab (Uncoded)
From the remodeled and uncoded regression equations, it is noticeable that the vibration levels on the plate vary approximately linearly with the input vibration. Assuming that the geometric center of the plate is representative of the spatial behavior of the plate, the plate has fulfilled its functionality of ensuring that the vibrations onto the fixture vary linearly with the input. This is one of the key fixture criteria outlined in McLean’s HALT practices [7]. One point to note is that there are mean shifts and differences in sensitivity of how the output vibration varies linearly with input vibration. For example, from the regression equation in Table 5-9, <Grms_Y> varies with almost a 1:1 ratio, while the <Grms_Z> has a larger mean shift along with less sensitive translation.

Another observation made during the experiment was the behavior of the controller as vibration increases. It was observed from the HALT chamber’s vibration indicator that the controller was having an increasingly harder time controlling the input vibration to its desired set point. Figure 5-6 shows the run chart of the vibration responses from the accelerometer setup when a stepwise vibration input is created from 10G_{rms} to 90G_{rms}. The response on the plate can be seen to have a larger measurement variance in all three dimensions beyond 70G_{rms}.

Expanding the analysis further, a similar surface regression analysis is made for the standard deviation of the vibration levels for each axis. Table 5-10 shows the results of the uncoded surface regression and Table 5-11 shows the results without insignificant factors. Note that some of the statistically significant factors like A*B and B*B can be removed from \( \sigma (\text{Grms}_Y) \) and yield a better fit. Figure 5-7 shows the factorial plots which confirms that the HALT chamber’s
controller do lose its precision in controlling the vibration levels of the table at higher vibration set points.

<table>
<thead>
<tr>
<th>σ(Grms)</th>
<th>Significant Factors*</th>
<th>Lack-of-Fit (p-value)</th>
<th>R-Sq (adj)</th>
<th>Regression Equation (Uncoded Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ(Grms_X)</td>
<td>B, B*B</td>
<td>0.830</td>
<td>95.32%</td>
<td>σ(Grms_X) = 0.257 - 0.00069 A + 0.00051 B - 0.000009 A<em>A + 0.000196 B</em>B + 0.000051 A*B</td>
</tr>
<tr>
<td>σ(Grms_Y)</td>
<td>A, B, B<em>B, A</em>B</td>
<td>0.546</td>
<td>98.19%</td>
<td>σ(Grms_Y) = 0.014 + 0.00098 A + 0.01188 B + 0.000004 A<em>A + 0.000189 B</em>B - 0.000067 A*B</td>
</tr>
<tr>
<td>σ(Grms_Z)</td>
<td>B,B*B, Lack-of-Fit</td>
<td>0.013</td>
<td>80.90%</td>
<td>σ(Grms_Z) = 0.533 + 0.00188 A - 0.0252 B - 0.000031 A<em>A + 0.000577 B</em>B + 0.000017 A*B</td>
</tr>
</tbody>
</table>

*A = Temperature, B = Vibration

Table 5-10 Surface regression results from Minitab (Uncoded)

<table>
<thead>
<tr>
<th>σ(Grms)</th>
<th>Significant Factors*</th>
<th>Lack-of-Fit (p-value)</th>
<th>R-Sq (adj)</th>
<th>Regression Equation (Uncoded Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ(Grms_X)</td>
<td>B, B*B</td>
<td>0.694</td>
<td>94.67%</td>
<td>σ(Grms_X) = 0.199 + 0.00228 B + 0.000202 B*B</td>
</tr>
<tr>
<td>σ(Grms_Y)</td>
<td>A, B, B<em>B, A</em>B</td>
<td>0.654</td>
<td>98.38%</td>
<td>σ(Grms_Y) = 0.010 + 0.00133 A + 0.01210 B + 0.000187 B<em>B - 0.000067 A</em>B</td>
</tr>
<tr>
<td>σ(Grms_Z)</td>
<td>B,B*B Lack-of-Fit</td>
<td>0.031</td>
<td>85.26%</td>
<td>σ(Grms_Z) = 0.531 - 0.0262 B + 0.000596 B*B</td>
</tr>
</tbody>
</table>

*A = Temperature, B = Vibration

Table 5-11 Remodeled surface regression results from Minitab (Uncoded)

Figure 5-7 Factorial plots of temperature (A) and vibration (B) against σ (Grms)

This experiment tests the validity of the linear responses of the plate with respect to the input vibration and demonstrates the feedback capabilities of the HALT chamber. During the experiment, another potential source of variability from mechanical gauge is identified. At high vibrational levels, the coaxial cable to the accelerometer becomes loose. As such, there is a need to ensure that the coaxial cable is secured sufficiently to the accelerometer for future experiments. If needed, taping the coaxial cable to the accelerometer seems to be a feasible solution for room temperature operation.
5.5 Nature of Vibrational Responses of Fixture Module

An ideal fixture should have a transmissibility ratio of 1 [52]. As identified in Section 4.3, the vibration table used at Waters is not uniform. Besides the non-uniformity, the vibrational excitations cannot be isolated to individual axes to conduct well-controlled experiments. Literature on designing and testing vibration fixtures, like that of Reddy and Hamsini, uses vibration tables which have the capability to isolate axes of vibration to achieve a more accurate measure of input acceleration [52]. A vibrational response experiment designed by Kendre used small single axis electrodynamic shakers that had a greater spatial uniformity and precision of vibration [53]. As such, to identify transmissibility using the HALT chamber's vibration table is highly inaccurate. To aid in characterizing the plates, small experiments are conducted to identify the vibrational response of the fixture.

5.5.1 Pseudo Impact Hammer Test: Plate Resonance Frequencies

To obtain rough insights on the plate's actual performance, a simulated impact hammer test is conducted to identify the potential resonant frequencies of the fixture plate. Assuming an extreme scenario, the resonant frequency of the fixture is identified based on a free boundary condition. The plate is suspended using a string to achieve this condition. While suspended, the plate is struck with a hammer at six sides of the plate. Two different hammers are used to identify and remove any other frequencies picked up by the PSD response which may have been introduced by the hammer's structural characteristics. The accelerometer picks up two distinct frequencies on the PSD curves from both excitation sources. The setup and hammers are shown in Figure 5-8 [54].
Figure 5-8 Suspended plate with accelerometer (left) and the hammers used (right)

The weight of the accelerometer is approximately 4 grams, two orders of magnitude smaller than the weight of the plate. Thus, having the accelerometer mounted is unlikely to influence the dynamic properties of the plate.

From Figure 5-9, one can see that the resonant frequencies of the plate seem to be around 8.75 kHz and 11.25 kHz. A point to note is that the plate has a free boundary condition. If bolted down, the fundamental frequency would be higher. Limitations of this experiment include the lack of a proper impact hammer that would allow the impact force to be measured so that the operator can ensure consistency in data acquisition for modal analysis for the test. Without knowing the impact force, we assume that the dynamic impact force to the weight of the block ratio is more than 0.1 to 0.5% so that the impact was sufficient to excite the main modes of the structure [55].

Figure 5-9 PSD curves for the suspended plate with free boundary conditions
From the results and assuming worst case scenario, the plate’s resonance is 8.75 kHz (below 15 kHz). If the plate still resonates, using the equation for a four point support square plate as shown in Figure 2-12, doubling the thickness should double the resonant frequency and meet the design criteria. This hypothesis will be validated in Section 5.5.4 where a 1-inch plate is used to observe the difference in vibration response and spatial uniformity of vibration.

5.5.2 DOE: Spatial Uniformity of Vibration within Fixture Module

Assuming that the previous experiment is valid and considering worse case, the plate should theoretically resonate under the excitation of the table. Similar to Section 4.3, a design of experiments is conducted to represent the spatial uniformity of the module. Ideally, we want the plate to be rigid and if the table’s excitation is uniform, there should be negligible spatial non-uniformity. However, the table is non-uniform and we should expect a spatial variation in the vibration levels within the plate. Nonetheless, it is important that we know the spatial variation within the plate because the PCBs will be mounted on a certain x-y coordinate on the plate itself. The test plate is split into x-y direction with three levels. Figure 5-10 shows the fixture module that is used to conduct this experiment, its location relative to the table and the three different levels in the x-y direction.
Figure 5-10 Experiment setup for within plate spatial variation (left) and the sampling position on the vibration table (right)

This is a full $3^2$ full factorial experiment with $x$ and $y$ as factors and the average vibration levels and variance at three different axes as the response variables. The settings on the HALT chamber are at 30G$_\text{rms}$ and 25°C. The sampling on the plate follows a uniform square grid sampling. Surface regression analysis is conducted in Minitab to construct the distribution of means on the plate. The underlying distribution of the mean vibration outputs for 200 consecutive samples in all three directions, $<\text{Grms}_X>$, $<\text{Grms}_Y>$ and $<\text{Grms}_Z>$ are normally distributed. Table 5-12 shows the randomized run order of the experiment and the data.

<table>
<thead>
<tr>
<th>StdOrder</th>
<th>RunOrder</th>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>9</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 5-12 Run order of the $3^2$ experiment
Sending the data into Minitab to perform a surface regression analysis yields the respective regression equations, surface and contour plots. The results from Minitab are shown in Table 5-13 to Table-14, Figure 5-11 and Figure 5-12, respectively. The residuals for three axes are randomly distributed along the line in a normal probability plot suggesting that the regression plot is reasonable and the remaining error unexplained by the model is normally distributed about zero mean.

<table>
<thead>
<tr>
<th>&lt;Grms&gt;</th>
<th>Significant Factors</th>
<th>R-Sq (adj)</th>
<th>Regression Equation (Uncoded Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;Grms X&gt;</td>
<td>X<em>X, Y</em>Y</td>
<td>88.97%</td>
<td>&lt;Grms X&gt; = 61.66 - 10.59 X - 18.60 Y + 3.623 X<em>X + 5.059 Y</em>Y - 1.402 X*Y</td>
</tr>
<tr>
<td>&lt;Grms Y&gt;</td>
<td>X*X</td>
<td>77.08%</td>
<td>&lt;Grms Y&gt; = 99.4 - 47.9 X - 28.8 Y + 13.82 X<em>X + 7.99 Y</em>Y - 2.59 X*Y</td>
</tr>
<tr>
<td>&lt;Grms Z&gt;</td>
<td>x</td>
<td>68.86%</td>
<td>&lt;Grms Z&gt; = 32.10 + 0.57 X - 8.77 Y + 1.00 X<em>X + 2.67 Y</em>Y - 1.084 X*Y</td>
</tr>
</tbody>
</table>

Table 5-13 Surface regression results from Minitab (Uncoded)

<table>
<thead>
<tr>
<th>&lt;Grms&gt;</th>
<th>Significant Factors</th>
<th>R-Sq (adj)</th>
<th>Regression Equation (Uncoded Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;Grms X&gt;</td>
<td>X<em>X, Y</em>Y</td>
<td>76.75%</td>
<td>&lt;Grms X&gt; = 67.27 - 13.39 X - 21.40 Y + 3.62 X<em>X + 5.06 Y</em>Y</td>
</tr>
<tr>
<td>&lt;Grms Y&gt;</td>
<td>X*X</td>
<td>74.51%</td>
<td>&lt;Grms Y&gt; = 109.7 - 53.0 X - 33.9 Y + 13.82 X<em>X + 7.99 Y</em>Y</td>
</tr>
<tr>
<td>&lt;Grms Z&gt;</td>
<td>X</td>
<td>64.39%</td>
<td>&lt;Grms Z&gt; = 33.10 + 2.401 X - 10.94 Y + 2.67 Y*Y</td>
</tr>
</tbody>
</table>

Table 5-14 Remodeled surface regression results from Minitab (Uncoded)

Figure 5-11 Surface plots of <Grms X>, <Grms Y> and <Grms Z> in Minitab

Figure 5-12 Contour plots of <Grms X>, <Grms Y> and <Grms Z> in Minitab
From the regression model and contour plots, one can see that there is spatial dependence in the x and y directions. Although the regression model in Table 5-13 highlights the significant factors at 95% confidence level, removing contributions by non-significant factors as a whole reduces R-squared (adj) values by almost 20%. As such, some of the terms are retained in the simplified remodeled surface regression to maintain a reasonable model for prediction as shown Table 5-14. Particularly for the <Grms_X> and <Grms_Y>, the vibration levels seem to taper off as the distance away from the four mounting holes increases.

The variances of measurements are also plotted and the residuals are normally distributed as shown from the normality plots provided by Minitab. Using data from Table 5-15, the results from ANOVA show that the position on the plate generally has weak influence on the variance of the vibration levels except for Var (Grms_X). Table 5-16 shows the p-values for the respective sources influencing the variance of the vibration output per direction. The R-Squared (adj) values are also very low, indicating that the models are not a good representation of the variances. All of these observations may suggest that the variances are influenced by other factors which are more complex than spatial. Figure 5-13 and Figure 5-14 shows the surface plots and contour plots for Var (Grms_X), Var (Grms_Y) and Var (Grms_Z), respectively.

<table>
<thead>
<tr>
<th>Model Source</th>
<th>p-values</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Var (Grms X)</td>
<td>Var (Grms Y)</td>
<td>Var (Grms Z)</td>
</tr>
<tr>
<td>X</td>
<td>0.93</td>
<td>0.79</td>
<td>0.33</td>
</tr>
<tr>
<td>Y</td>
<td>0.84</td>
<td>0.30</td>
<td>0.11</td>
</tr>
<tr>
<td>X*X</td>
<td>0.09</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Y*Y</td>
<td>0.04</td>
<td>0.20</td>
<td>0.24</td>
</tr>
<tr>
<td>X*Y</td>
<td>0.01</td>
<td>0.72</td>
<td>0.10</td>
</tr>
</tbody>
</table>

| R-Sq | 95.49% | 76.26% | 86.33% |
| R-Sq(adj) | 87.97% | 36.70% | 63.55% |
| R-Sq(pred) | 45.00% | 0.00%  | 0.00%  |

Table 5-15 ANOVA results from Minitab

<table>
<thead>
<tr>
<th>Var(Grms)</th>
<th>Significant Factors</th>
<th>R-Sq(adj)</th>
<th>Regression Equation (Uncoded Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Var(Grms_X)</td>
<td>Y<em>Y, X</em>Y</td>
<td>87.97%</td>
<td>Var(Grms_X) = 0.405 - 0.0051 X - 0.0903 Y + 0.0509 X<em>X + 0.0719 Y</em>Y + 0.1005 X*Y</td>
</tr>
<tr>
<td>Var(Grms_Y)</td>
<td>N.A.</td>
<td>36.70%</td>
<td>Var(Grms_Y) = 2.821 - 1.477 X - 1.207 Y + 0.342 X<em>X + 0.253 Y</em>Y + 0.042 X*Y</td>
</tr>
<tr>
<td>Var(Grms_Z)</td>
<td>N.A.</td>
<td>63.55%</td>
<td>Var(Grms_Z) = 0.813 - 0.302 X - 0.274 Y + 0.0581 X<em>X + 0.0384 Y</em>Y + 0.0435 X*Y</td>
</tr>
</tbody>
</table>

Table 5-16 Surface regression results from Minitab (Uncoded)
Since we know that the distribution of the means on the plate is spatially dependent, the variance metric in Equation 4.3 can be used to obtain a metric for vibration uniformity of the plate. The goal is to combine both variations coming from the spatial pattern of $G_{rms}$ mean (e.g., $f_{mean_x}$), and the position-dependent variance of $G_{rms}$ measurements (i.e., $\sigma^2_{Regression\ Plot}$). To calculate the variance across the 3” by 3” by 0.5” plate of spatially dependent means at a given location, we have

$$Var(G_{rms_X/Y/Z}) = \frac{\iint (f_{mean_{X/Y/Z}(x,y)} - \bar{f}_{mean_{X/Y/Z}(x,y)})^2 \, dx \, dy}{\iint dx \, dy} + \sigma^2_{Regression\ Plot} + \sigma^2_{measure}$$

An example to calculate spatial variance for $<G_{rms_X}>$:

$$\bar{f}_{mean_X} = \frac{\iiint f_{mean_X}(x,y) \, dx \, dy}{\iiint dx \, dy} = \frac{\iiint 67.27 - 13.39x - 21.40y + 3.62x^2 + 5.06y^2 \, dx \, dy}{4} = 35.3$$
\[ \text{Var}_{\text{mean}}(G_{\text{rms}_X}) = \frac{\int_{-1}^{1} (f_{\text{mean}_X}(x,y) - (35.3))^2 \, dx \, dy}{\int_{-1}^{1} dx \, dy} = \frac{17.141}{4} \approx 4.29 \text{ (s.f.)} \]

An example to calculate total measurement variance across the block \(<\text{Grms}_X>\):

\[ \int_{-1}^{1} \sigma^2_{\text{regression plot}_X} \, dx \, dy = \int_{-1}^{1} (0.405 - 0.0051x - 0.0903y + 0.0509x^2 + 0.0719y^2 - 0.1005xy) \, dx \, dy \approx 1.38 \text{ (s.f.)} \]

Similarly, using the regression equations in Table 5-14 and Table 5-16, the calculations are made for other axes. By summing up the total measurement variance and the variance due to the systematic spatial pattern of the means in each direction, a variance metric for each direction is obtained. Summing up the variance metric of each direction, we get the total variance metric of the plate that can be used for spatial uniformity comparison with other plate designs. Note that the variance metrics are not representative of the vibration level variances, but rather serve as a measure of vibration uniformity of the readings across the entire plate.

Assuming that the table is ideal and excitation levels from the table to the plate have the desired mean of 30G\text{rms} in all three axes, we can use the grand mean to create an approximated transmissibility check. Equation 5.1 shows the equation for transmissibility [53] where a true rigid body will have a transmissibility of 1. However, from Figure 5-16, we know that the levels of input excitation may actually be much higher than the profile set point. Thus, the values are estimations and may be inaccurate. True transmissibility is unable to be found unless the vibration levels on the table are well controlled spatially. Table 5-17 shows the variance of means, sum of measurement variances, estimated transmissibility and variance metrics in the 3" by 3" by 0.5" plate for all axes.

\[ \text{Est. Transmissibility} = \frac{\text{Output}_{\text{rms}}}{\text{Input}_{\text{rms}}} \quad \text{Equation 5.1} \]
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Grms X</th>
<th>Grms Y</th>
<th>Grms Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grand Mean</td>
<td>35.3</td>
<td>30.2</td>
<td>27.6</td>
</tr>
<tr>
<td>Est. Transmissibility</td>
<td>1.18 ≈ 1</td>
<td>1.01 ≈ 1</td>
<td>0.92 ≈ 1</td>
</tr>
<tr>
<td>Variance of Means</td>
<td>4.29</td>
<td>25.6</td>
<td>2.58</td>
</tr>
<tr>
<td>Sum of Measurement Variances</td>
<td>1.38</td>
<td>0.80</td>
<td>1.01</td>
</tr>
<tr>
<td>Variance Metric</td>
<td>5.67</td>
<td>26.40</td>
<td>3.59</td>
</tr>
<tr>
<td>Total Variance Metric</td>
<td></td>
<td></td>
<td>35.66</td>
</tr>
</tbody>
</table>

Table 5-17 Plate uniformity parameters (3" by 3" by 0.5" Plate)

5.5.3 Table Excitation Levels at Bolted Joints

To further investigate the transmission from the table to the plate, the average of 200 samples of data from the four bolted points of the plates are measured. Similarly, samples are collected at 30G<sub>ms</sub> and 25°C. The experiment is setup by tapping a single bolt and mounting the threaded stud mount triaxial accelerometer on the bolt. The bolt is secured to the table using the SOP established in Section 4.2.3. The experiment setup is displayed in Figure 5-15.

![Figure 5-15 Table vibration experiment setup](image)

Figure 5-15 Table vibration experiment setup

Figure 5-16 shows the average excitation levels on the four bolts, while Figure 5-17 and 5-18 illustrates the PSD curves at each bolt and the plate, respectively.
From both figures, we can observe the following:

1) Comparing Figure 5-10 and Figure 5-6, it seems that transmissibility of the plate is approximately 1 for the four corners where the sources are situated and drops towards the center.

2) The vibration table excites mainly in the high frequencies between 2 kHz to 8 kHz in the $x$-$y$ direction and is relatively broadband in the $z$-direction.

3) From Figure 5-17, the table system (inclusive of boundary conditions and entire setup) seems to be resonating at distinct frequencies at about 2.375 kHz and 7.375 kHz. A point to note is that these peaks are expressed onto the plates as well, as seen in Figures 5-17 and 5-18 that compare the PSD curves expressed by the table and the plates. Notice that the plate resonances found in Figure 5-9 are not expressed. Frequencies from the table seem to be more dominant. A more thorough analysis has to be done to affirm the resonances and operating frequencies of the table.

4) Comparing Figures 5-17 and 5-18, a flatter and broader spectrum is expressed on the plates. Considering that an ideal PSD curve is a flat horizontal line, this is desirable.

![Figure 5-16 Mean $<\text{Grms}>$ at respective bolts for three axes at 30G$_{\text{rms}}$](image-url)
Figure 5-17 PSD graphs at the respective bolts for three axes at 30G$_{\text{rms}}$

Figure 5-18 PSD graphs at the respective x-y positions on the test plate at 30G$_{\text{rms}}$
5.5.4 Vibrational Response of a Thicker Plate

Besides understanding that the table has a non-uniform excitation, we also notice from the previous experiments that there is significant spatial non-uniformity on the plate as well. Although there are no significant indicators from the PSD graphs that the plate is resonating during vibration, a thicker plate is introduced to confirm this hypothesis. This section will test the hypothesis that the 0.5” thick plate is not resonating by comparing the differences in vibrational responses with a 1” thick plate.

Theoretically, a thicker plate will have a higher resonant frequency. From the equations in Figure 2-12, doubling the thickness will quadruple the thickness to mass ratio and double the resonant frequency. Replicating the hammer test in the previous experiment, the thicker plate and PSD curves are shown in Figure 5-19. The resonance frequencies observed on the plate with free boundary conditions are approximately 10.5 kHz, 15.25 kHz, 19.25 kHz and 22.25 kHz. Since the fundamental frequency at free boundary condition is already beyond 10 kHz, securing it down onto the plate is likely to meet the desired criteria of at least 15 kHz.

![Figure 5-19 PSD curves from impact hammer test (left) and the 1-Inch thick plate (right)
The same spatial experiment is replicated on the thicker 1-inch plate using the same run order. Tables 5-18 and 5-19 show the surface regression results from Minitab for the means of the 200 samples, while Figures 5-20 and 5-21 show the surface and contour plots respectively. Note that the surface regression selected in Table 5-19 is based on a combination of factors that gives a reasonable R-squared value and simplicity for calculations.

<table>
<thead>
<tr>
<th>&lt;Grms&gt;</th>
<th>Significant Factors</th>
<th>R-Sq (adj)</th>
<th>Regression Equation (Uncoded Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;Grms_X&gt;</td>
<td>N.A.</td>
<td>51.39%</td>
<td>&lt;Grms_X&gt; = 69.2 - 30.7 X + 11.7 Y + 6.35 X<em>X - 3.97 Y</em>Y + 1.63 X*Y</td>
</tr>
<tr>
<td>&lt;Grms_Y&gt;</td>
<td>X*X</td>
<td>62.97%</td>
<td>&lt;Grms_Y&gt; = 51.9 - 20.53 X + 1.82 Y + 6.71 X<em>X + 1.09 Y</em>Y - 2.90 X*Y</td>
</tr>
<tr>
<td>&lt;Grms_Z&gt;</td>
<td>X, X<em>X, Y</em>Y</td>
<td>89.52%</td>
<td>&lt;Grms_Z&gt; = 57.66 - 14.57 X - 20.43 Y + 4.688 X<em>X + 5.367 Y</em>Y - 0.843 X*Y</td>
</tr>
</tbody>
</table>

Table 5-18 Surface regression results from Minitab (Uncoded)

<table>
<thead>
<tr>
<th>&lt;Grms&gt;</th>
<th>Significant Factors</th>
<th>R-Sq (adj)</th>
<th>Regression Equation (Uncoded Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;Grms_X&gt;</td>
<td>N.A.</td>
<td>51.39%</td>
<td>&lt;Grms_X&gt; = 69.2 - 30.7 X + 11.7 Y + 6.35 X<em>X - 3.97 Y</em>Y + 1.63 X*Y</td>
</tr>
<tr>
<td>&lt;Grms_Y&gt;</td>
<td>X*X</td>
<td>69.07%</td>
<td>&lt;Grms_Y&gt; = 48.33 - 20.53 X + 6.16 Y + 6.71 X<em>X - 2.90 X</em>Y</td>
</tr>
<tr>
<td>&lt;Grms_Z&gt;</td>
<td>X, X<em>X, Y</em>Y</td>
<td>88.36%</td>
<td>&lt;Grms_Z&gt; = 61.03 - 16.26 X - 22.12 Y + 4.69 X<em>X + 5.37 Y</em>Y</td>
</tr>
</tbody>
</table>

Table 5-19 Remodeled surface regression results from Minitab (Uncoded)

Figure 5-20 Surface plots of <Grms_X>, <Grms_Y> and <Grms_Z> in Minitab

Figure 5-21 Contour plots of <Grms_X>, <Grms_Y> and <Grms_Z> in Minitab
Comparing at the surface plots in Figure 5-20 with Figure 5-11, the spatial distribution and values from the thicker plate are different from the thinner plate. Nonetheless, both plates display similar responses in that the excitation points nearer to the source are generally higher and lowest near the center. For the thicker plate, \(<\text{Grms}_X>\) has a saddle-like surface plot, with maximum vibrations somewhere at the mid-edges. Reviewing the divisions and density of lines on the contour plots in Figure 5-12, the thicker plate seems to exhibit lesser spatial variation of means than the thinner plate.

Similarly, the variance of the measurements is also investigated. Tables 5-20 and 5-21 illustrate the ANOVA and surface regression results respectively. Figures 5-22 and 5-23 present the visual plots of the respective regression equations.

### Table 5-20 ANOVA results from Minitab

<table>
<thead>
<tr>
<th>Model Source</th>
<th>p-values</th>
<th>Var (Grms X)</th>
<th>Var (Grms Y)</th>
<th>Var (Grms Z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>0.171</td>
<td>0.560</td>
<td>0.095</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>0.832</td>
<td>0.690</td>
<td>0.689</td>
<td></td>
</tr>
<tr>
<td>X*X</td>
<td>0.430</td>
<td>0.257</td>
<td>0.228</td>
<td></td>
</tr>
<tr>
<td>Y*Y</td>
<td>0.976</td>
<td>0.798</td>
<td>0.086</td>
<td></td>
</tr>
<tr>
<td>X*Y</td>
<td>0.157</td>
<td>0.370</td>
<td>0.890</td>
<td></td>
</tr>
<tr>
<td>R-Sq</td>
<td>71.72%</td>
<td>55.64%</td>
<td>83.03%</td>
<td></td>
</tr>
<tr>
<td>R-Sq(adj)</td>
<td>24.58%</td>
<td>0.00%</td>
<td>54.76%</td>
<td></td>
</tr>
<tr>
<td>R-Sq(pred)</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td></td>
</tr>
</tbody>
</table>

### Table 5-21 Surface regression results from Minitab (Uncoded)

<table>
<thead>
<tr>
<th>Var(Grms)</th>
<th>Significant Factors</th>
<th>R-Sq (adj)</th>
<th>Regression Equation (Uncoded Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Var(Grms_X)</td>
<td>N.A.</td>
<td>24.58%</td>
<td>(\text{Var(Grms}_X) = 1.484 - 0.637 \times X - 0.230 \times Y + 0.0790 \times X^2 + 0.0028 \times Y^2 + 0.1154 \times X \times Y)</td>
</tr>
<tr>
<td>Var(Grms_Y)</td>
<td>N.A.</td>
<td>0.00%</td>
<td>(\text{Var(Grms}_Y) = 0.331 - 0.199 \times X + 0.127 \times Y + 0.0623 \times X^2 - 0.0124 \times Y^2 - 0.0332 \times X \times Y)</td>
</tr>
<tr>
<td>Var(Grms_Z)</td>
<td>N.A.</td>
<td>54.76%</td>
<td>(\text{Var(Grms}_Z) = 0.569 - 0.143 \times X - 0.326 \times Y + 0.0486 \times X^2 + 0.0812 \times Y^2 + 0.0034 \times X \times Y)</td>
</tr>
</tbody>
</table>
Similar to the 0.5” plate, the variances on the thicker plate have no significant spatial dependence at 95% confidence interval. The divisions in the contour plots in Figure 5-23 are in the order of a hundredth, indicating that the measurement variances are also relatively more uniform as compared to the 0.5” plate. To affirm these observations, the total variance metric is calculated again once more to compare the uniformity of vibration levels. Results are shown in Table 5-22.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Grms X</th>
<th>Grms Y</th>
<th>Grms Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grand Mean</td>
<td>48.0</td>
<td>37.1</td>
<td>27.9</td>
</tr>
<tr>
<td>Est. Transmissibility</td>
<td>1.6</td>
<td>1.24</td>
<td>0.93 ≈ 1</td>
</tr>
<tr>
<td>Variance of Means</td>
<td>6.95</td>
<td>5.07</td>
<td>6.74</td>
</tr>
<tr>
<td>Sum of Measurement Variances</td>
<td>2.26</td>
<td>1.08</td>
<td>0.72</td>
</tr>
<tr>
<td>Variance Metric</td>
<td>9.21</td>
<td>6.15</td>
<td>7.46</td>
</tr>
<tr>
<td>Total Variance Metric</td>
<td></td>
<td></td>
<td>22.82</td>
</tr>
</tbody>
</table>

Table 5-22 Plate uniformity parameters (3” by 3” by 1” Plate)
Comparing the total variance metric with the thinner plate, the thicker plate has a lower variation for the vibration levels on the plate. Additionally, comparing the grand means of the axes, the excitations on the thicker plate seem higher except for the z-axis (see Table 5-17). This is an interesting observation. One of the reasons could be the feedback control of the system seeking to maintain the same excitation levels in the z-axis for a more massive plate. As a result, more energy is excited in the z-axis while the x-y plane experiences even greater excitations but the two axes are unregulated. Note that that the aluminum table is 0.75 inches thick while the thicker block is 1 inch thick. This extra mass may also cause localized physical changes to the vibration table. Comparing PSD plots, the higher frequencies between 8 kHz-10 kHz are no longer expressed in the thicker plate, which suggests that the interaction between the thicker plate and table results in a different vibration response. Figure 5-24 highlights this distinction in the vibrational responses between the different.

![Comparison of PSD curves](image)

Figure 5-24 Comparison of PSD curves by 0.5” and 1” thick plate at position X3_Y2 at 30Grms

Considering that the surface plots of the thicker and thinner plates are similarly shaped and that the thicker plate costs twice as much and has a lesser broadband frequency spectrum, the thinner plate seems like a better option for use in the SOP.
5.5.5 Repeatability and Reproducibility Test for Fixture Module

Similar to Chapter 4, a repeatability and reproducibility test for the single fixture module is also explored. This experiment is necessary to characterize the capability of the fixture to give consistent excitation levels to the PCBs independent of the operator and repeated setups. The only difference in the experiment setup from Chapter 4 is that the threaded stud mounted accelerometer is always connected to the coaxial cable and fixed to the plate together with its brass shim. In this way, any variation measured will be from the use of the fixture module. In this experiment, operators mount only the fixture to the same location shown in Figure 4-4. Taking lessons from the gauge R&R (see Section 4.2), specific instructions are given as to how to mount the fixture. For example, operators have to torque the four screws at 23 ft-lbs using a torque wrench with their master hand while the other hand presses down on the point of rotation to ensure good contact. The instructions also require the use of an Allen key to first secure the screws down followed by a torque wrench. Figure 5-25 shows the torque wrench and Allen key that are used for the experiment. For more detailed instructions on the SOP refer to Appendix C-2.

![Figure 5-25 Torque wrench and allen key used to secure the fixture onto the vibration table](image)

The fixture setup variance contribution is analyzed using ANOVA in Minitab. As usual, there are three operators, 10 measurements per operator and each measurement is the average G_{rms} of 200 data points in all three axes <Grms_X>, <Grms_Y> and <Grms_Z>. Data points are obtained during a two minute soak time when vibration levels on the table are stable. The following results are shown in Table 5-23.
As expected, the variances in all three axes are smaller than the gauge variances introduced during data acquisition using either accelerometer (See Section 4.2). An interesting point to note is that the variance in the x-axis seems to be approximately three times larger than in the other axes. This may be due to the table’s vibrational response being more sensitive to certain directions. Nonetheless, the variance contribution to the average output values by the fixture is relatively negligible compared to the measurement system for adhesive mount. If an adhesive wax mounted accelerometer is used for data acquisition on the PCB and the SOP for fixture mounting is closely adhered to, the fixture contribution to the variation in measurements can be neglected.

Another important observation from this experiment is that the socket head screws have approximately a usage life of about twenty runs before observing some wear and tear. The hex driver also starts to deform slightly due to repeated use. A possible solution is to purchase a material that has higher shear modulus for the screws to reduce deformation during torqueing and a stiffer hex driver. Figure 5-26 shows a comparison between worn out socket heads and new socket heads. A check for wear is required in the SOP when securing the fixture module to the table.

Figure 5-26 From right to left: Deteriorating condition of the hex drive insert due to wear
Chapter 6. Methodology: Statistical Process Control

The purpose of adopting statistical process control (SPC) is to ensure consistency over numerous individual vibration tests. From experience, operator error and multiple fasteners used for the fixture may add up to significant variation among experiments. The HALT chamber also contains multiple actuators for vibration which, as highlighted in the chamber manual, are easily subjected to wear and tear. The need to test multiple samples and share the HALT chamber among different testing projects, greatly advocates for a procedure that checks for consistency in the fixture setup for a given DUT.

A typical classic HALT process lasts about two weeks per design iteration. Within this period, at least 10 vibration runs are required. There are 5 samples per design iteration with 2 vibration runs (1 vibration step and 1 combined stress) each. This section will introduce a suitable SPC method and evaluate the capabilities of the method to detect assignable causes of variation.

6.1 Setting Up Control Charts

The critical parameter to measure at the process output is the vibrational response of the board. In this experiment, the plunger drive board (210000425) and the associated fixture plates are used. The point of measure has to capture variation contributions from as many potential sources as possible. As such, the center of the board is used as a point of measure. Since only wax mounted accelerometers are suitable for measuring the PCB response, a less massive single axis accelerometer 3224A1-Mini is used (see Table 1-3 for the specifications of existing accelerometers) was used. The tendency of having the 3224A1-Mini falling off is much lower than the 3023A because it is 15 times less massive. Since the pneumatic actuators provide multi-axis vibration, results from a single axis accelerometer are sufficient to capture machine variation. The experiment setup is shown in Figure 6-1.
Initially, the team constructed $\bar{x}$ and $s$ control charts based on 150 samples for 20 subgroups. The fixture setup uses the SOP from Section 5.5.5. Each subgroup is a 1 minute run at 30G$\text{rms}$ at 20°C with 150 samples extracted during steady state\(^4\). Every subgroup requires remounting of the accelerometer to ensure that it remains in contact with the point of measure. The control limits are generated using Equation 2.22 (see Section 2.7.2). The control charts produced many out-of-control points on the $\bar{x}$ chart with occasional out-of-control points on the $s$ chart. Figure 6-2 shows $\bar{x}$ and $s$ control charts for the 20 subgroups. The out-of-control points in the $s$ chart are caused by the sampling of data from a transient portion of the sample output and not the steady state. This is considered as incorrect sampling and the $s$ chart captures that. Figure 6-3 shows the corrected data and an example of the correction that was made by resampling from the steady state region for Run 2. Unfortunately, multiple out-of-control points on the $\bar{x}$ chart still persist.

\(^4\) Steady state is the state of the chamber when the vibration level shown on the chamber’s indicator hovers around the input vibration set point.
A more careful analysis of the control-charting procedure reveals that the main problem is the choice of standard deviation used to establish the control limits for the $\bar{x}$ control chart. The control limits established for out-of-control conditions on the $\bar{x}$ control chart are too tight and do not provide a valid basis for corrective action. The vibration levels measured at each run are obtained at a particular adhesive state of the accelerometer and state of the chamber's feedback response, both of which are uncontrollable states. Knowing that the system states vary between runs, the measurements at a particular run are likely to be very similar. Thus, it is reasonable to
believe that there will be more variation in average $G_{rms}$ between runs rather than within runs. The solution is to treat the average $G_{rms}$ in steady state as a single measurement and use an individual control chart and moving-range chart to detect variation in the setup. This case is very similar to Example 6.11 as outlined in the *Introduction to Statistical Process Control* book by Montgomery [33]. The standard deviation chart can still be used to check for sampling error and controllability of the HALT chamber. Figure 6-4 shows the proposed control charts to be used. The average $G_{rms}$ was checked to be normally distributed, with $p > 0.05$ ($p = 0.90$) in the Anderson-Darling normality test, prior to establishing the individual control chart.

![I-MR-R/S Chart of Vibration Response (Grms)](image)

Figure 6-4 Individual, moving-range and $s$ control charts for vibration responses

### 6.2 Evaluation

After trial limits are established, we need to evaluate the capabilities of the chart. To do so, several key assignable causes of variations are deliberately induced in Runs 21-23. Table 6-1 shows the list of variations induced onto the fixture setup and the responses of the three charts. Assuming that the process is in statistical control in the previous section, the control limits are fixed. Minitab follows the rules for Shewhart control charts as outlined in Table 2-2. Figure 6-5 shows an example of an assignable cause, a loosened mounting screw, detected successfully by the proposed SPC chart.
<table>
<thead>
<tr>
<th>No.</th>
<th>Cause of Variation</th>
<th>Rule Violation/Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Loosened One Bolt in a Fixture Plate</td>
<td>s-Chart. TEST 1. One point more than 3.00 standard deviations from center line. Test Failed at points: 21, 22, 23</td>
</tr>
<tr>
<td>2</td>
<td>Loosened Two Bolts in a Fixture Plate</td>
<td>Undetected. But mean shift is obvious. 2 more readings required to violate Rule 3 of the Shew Chart Control Charts</td>
</tr>
</tbody>
</table>
| 3   | Loosened Three Bolts in a Fixture Plate       | I-Chart. TEST 5. 2 out of 3 points more than 2 standard deviations from center line (on one side of CL). Test Failed at points: 22, 23  
|     |                                               | s-Chart. TEST 1. One point more than 3.00 standard deviations from center line. Test Failed at points: 21, 23  |
| 4   | Remove Three Bolts in a Fixture Plate         | I-Chart. TEST 1. One point more than 3.00 standard deviations from center line. Test Failed at points: 21  
|     |                                               | MR-Chart. TEST 5. 2 out of 3 points more than 2 standard deviations from center line (on one side of CL). Test Failed at points: 22, 23  
|     |                                               | s-Chart. TEST 1. One point more than 3.00 standard deviations from center line. Test Failed at points: 21  
|     |                                               | I-Chart. TEST 1. One point more than 3.00 standard deviations from center line. Test Failed at points: 21, 22, 23  |
| 5   | Loosened a Single Mounting Screw to Standoff | I-Chart. TEST 1. One point more than 3.00 standard deviations from center line. Test Failed at points: 21, 22, 23  
|     |                                               | MR-Chart. TEST 5. 2 out of 3 points more than 2 standard deviations from center line (on one side of CL). Test Failed at points: 22, 23  
|     |                                               | s-Chart. TEST 1. One point more than 3.00 standard deviations from center line. Test Failed at points: 21  
| 6   | Loosened Standoff                            | I-Chart. TEST 1. One point more than 3.00 standard deviations from center line. Test Failed at points: 21, 22, 23  
| 7   | 180° Rotation of PCB/Different Position      | I-Chart. TEST 5. 2 out of 3 points more than 2 standard deviations from center line (on one side of CL). Test Failed at points: 22, 23  
|     |                                               | s-Chart. TEST 1. One point more than 3.00 standard deviations from center line. Test Failed at points: 21  
| 8   | Grms Setting: 35 Grms                        | I-Chart. TEST 1. One point more than 3.00 standard deviations from center line. Test Failed at points: 21, 22, 23  
|     |                                               | MR-Chart. TEST 5. 2 out of 3 points more than 2 standard deviations from center line (on one side of CL). Test Failed at points: 22, 23  
| 9   | New Redesigned PCB                           | I-Chart. TEST 1. One point more than 3.00 standard deviations from center line. Test Failed at points: 21, 22, 23  
|     |                                               | MR-Chart. TEST 1. One point more than 3.00 standard deviations from center line. Test Failed at points: 21  
|     |                                               | s-Chart. TEST 1. One point more than 3.00 standard deviations from center line. Test Failed at points: 21  

Table 6-1 Simulated assignable causes of variation and the respective rule violations (Minitab)
When using control charts to check whether the setup is within the range of acceptance, the operator has to understand the potential reasons for rule violation. Sometimes, some rule violations may or may not be taken into account. For example in Case 3, the increase in average vibration levels gave a valid warning because there are probably less constraints on the plate, allowing more deflection to occur. However, to attribute the violation due to lower standard deviation (better measurement precision) might be a mistake. The phenomenon may just be that the state of the machine and adhesive accelerometer are behaving more precisely at that particular moment.

Additionally, sometimes slight changes in the vibration levels may not be reflected in the individual control chart because detection depends on the tightness of the trial control limits that are initially set. Nonetheless, if more measurements are made prior to the start of the experiment, one can easily notice a bias in the individual control chart. The proposed number of readings to monitor the setup before each experiment is three runs. However, like in Case 2, the operator can go for two more runs if the he or she suspects a bias. The more runs an operator executes before starting the experiment, the earlier an assignable cause of variation can be detected.
Overall, the system is successful in detecting eight out of nine assignable causes of variations, including a method sampling error captured at the beginning of the experiment. A caveat for this screening method is that the operator has to ensure that the SOP is followed very closely during the first 20 measurements or else wrong limits will be set. While setting the trial limits, the control charts provide warning for out-of-control points. However, not all sources of variation are accounted for. For example, using a different washer at the start may cause a mean shift from the true value, but the systematic error remains undetected unless the operator realizes it himself or herself. Thus, the first setup has to be as ideal as possible.
6.3 Fishbone Diagram

Based on the past experiments, analysis of multiple PSD curves and understanding of the physical processes behind HALT chamber’s vibration stresses, a preliminary list of potential causes of variations has been generated. This list is represented by a cause-and-effect (fishbone) diagram in Figure 6-2, which serves as a reference for the reliability engineers.

![Fishbone Diagram](image.png)

Figure 6-2 Fishbone diagram of the fixture setup process
Chapter 7. Results and Conclusion

The previous chapters have explored three different yet complementary approaches to establish the necessary standard operating procedure (SOP) for fixture setup for a HALT process. To recap, the purpose of the SOP is to create standards that enable quality results by reducing potential variations. The three approaches outlined in Chapters 4 to 6 are aligned to this objective and the learnings are integrated into the SOP that operators are encouraged to follow. This chapter summarizes the findings and discusses the limitations, assumptions and recommendations for Waters' HALT fixture setup.

7.1 Gauge Choices and Applications

We begin the project by acknowledging issues with the existing data acquisition method used at Waters for vibration analysis which may hinder affect subsequent and future HALT experimental results. As such, the process is improved through the use of automatically calibrated acquisition hardware. Once the process of data acquisition is established, limitations on the existing gauges at Waters are identified and highlighted using the gauge repeatability and reproducibility test. The gauge R&R test in Section 4.2, proves that the wax mounted accelerometers have the largest gauge variance while stud mounted accelerometers have the least gauge variance. We introduced a new SOP for the stud mounted accelerometer that reduces the gauge variance for existing vibrational data acquisition by approximately 90%. Table 7.1 summarizes the gauge variances of the experimental results and relative variances as a percentage of the adhesively mounted accelerometer.

<table>
<thead>
<tr>
<th>Source</th>
<th>Variance</th>
<th>&lt;Grms X&gt;</th>
<th>&lt;Grms Y&gt;</th>
<th>&lt;Grms Z&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wax</td>
<td>$\sigma^2_{Gauge}$</td>
<td>19.09</td>
<td>100.00%</td>
<td>23.11</td>
</tr>
<tr>
<td>Stud</td>
<td>$\sigma^2_{Gauge}$</td>
<td>2.30</td>
<td>12.00%</td>
<td>11.30</td>
</tr>
<tr>
<td>Stud+SOP</td>
<td>$\sigma^2_{Gauge}$</td>
<td>0.46</td>
<td>2.39%</td>
<td>0.24</td>
</tr>
<tr>
<td>Fixture</td>
<td>$\sigma^2_{Fixure}$</td>
<td>0.10</td>
<td>0.53%</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Table 7-1 Summary of total variances from repeatability and reproducibility tests for accelerometers and fixture setup

While the stud mounted accelerometer is more favorable for precise data acquisition purposes, for practical reasons, the wax mounted accelerometer is still necessary for HALT
experiments. The limitation of the stud mounted accelerometer that the adhesive mount addresses is the non-intrusiveness of the mounting. Adhesive mounts are suitable for measuring DUT responses for small and sensitive devices like PCBs because they do not disrupt the functionality of the board. However, as shown in Figure 4-5, higher frequency responses beyond 6 kHz may not be observable. Then again, resonances of PCBs tend to be of frequencies much lower than 6 kHz. Thus, in terms of the frequency range, wax mounted accelerometers are still viable options.

Unfortunately, little can be done to effectively reduce the relatively large gauge variation of the wax mounted accelerometer except to introduce a better way to dispense the adhesive or use alternative adhesives that bond better. One of such adhesives is methylcyclo acrylate cement. The use of this adhesive is not experimented in this thesis because of the risk and inconvenience that comes along with a stronger adhesive bond. Figure 7-1 shows a table, from ISO 5348, on the suggested selection criteria for the type of mounting methods for accelerometers. Additionally, wax mounted accelerometers are only restricted to temperatures below 25°C. As such, the only occasions where responses from PCBs may be measured are before the HALT process and during the vibration step. The purpose of measuring the board’s response is to better understand potential failure modes for root-cause analysis, design improvements and to clarify hypotheses during the pre-HALT meeting. Combined step stress do not require measurements of board response [6].

<table>
<thead>
<tr>
<th>Mounting Method</th>
<th>Resonance Frequency</th>
<th>Temperature</th>
<th>Mass of Hardware and Stiffness of Mounting</th>
<th>Resonance Magnitude &amp; Q</th>
<th>Importance of Surface Preparation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stud</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methylcyclo acrylate cement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beeswax</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double-sided tape</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quick mount</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vacuum mounted</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Handheld</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Depends entirely on distance between board and measured surface.

Legend: ■ High ■ Average □ Poor

Figure 7-1 Selection criteria on mounting methods for accelerometers [56]
For experimental purposes, like characterization of spatial response on the vibrational table, and large structures, like casing and support frames, the use of stud mounted accelerometers are very useful in getting the much needed precision. Using the standard operating procedure that the team provides produces reliable and consistent readings. Based on the available accelerometers at the Reliability Lab, a decision tree is created for Waters to select the appropriate mounting methods for a HALT experiment (see Appendix C-3).

Table 7-1 also highlights on the importance of consistency when using the accelerometers during data acquisition. Comparing the fixture variance to the gauge variance of the wax mounted accelerometer, the fixture variance can be neglected if the fixture setup SOP is followed.

7.2 Limitations of HALT Chamber

7.2.1 Non-Uniform Spatial Distribution of Vibration and Among Axes

Through thorough investigations and experiments on the resources at the Reliability Lab, another main source of variation that needs to be understood is the vibration uniformity on the table. By understanding how the vibration varies on the table, we can choose the right region for PCBs to be tested. In Section 4.3 we proved that both mean and variances of the vibration vary spatially across the table. The region that has the least spatial variance and measurement variance is at the center. Figure 7-2 shows a visual depiction of the mean vibrational levels across the table.
Since the objective is to standardize a setup for a generic product category, a region has to be chosen as part of the selection constraint to accommodate the range of sizes of PCBs. As proven by Miner’s Rule, accumulated fatigue is extremely sensitive to varying levels of stresses. Having the fixture at the center of the table minimizes the discrepancies in excitation levels between different circuit boards. This lays the best available foundation for comparing the robustness between different types of circuit board designs.

Fortunately, having the fixture at the center will also allow sufficient space for all of the air ducts to be directed at the PCB and utilized for rapid thermal transitions of the product, reducing ramping time and energy. Figure 7-3 shows how 6 ducts can be used for a HALT experiment based on this configuration.

![Figure 7-3 HALT Experiment: Six duct placement configuration](image)

### 7.2.2 High Frequency Excitations

In Section 5.5.3, an analysis on the vibrational response of the table at 30G$_{rms}$ showed that excitation levels on the fixture from the table is biased to frequencies between 2 kHz to 8 kHz range. This bias is predominantly observed for the x-y plane while a small amount of low frequency excitations are observed in the z-axis. Assuming a free boundary condition, using the
plate equation from Figure 2-10, the first five modes of resonant frequencies of the table are between 100-500Hz. A possible reason for high frequencies getting expressed on the table is the complex interaction between the nine pneumatic vibrators, springs and dampers mounted to the underside of table. Similar observations on the PSD curves from past experiments obtained from the oscilloscope by the reliability engineers also affirm this observation. The PSD curve in Figure 7-4 confirms the bias towards high frequencies and displays a distinct resonance peak of the vibration table near 2 kHz. The results are obtained from an old experiment conducted at 20G<sub>rms</sub> set point in 2014 with a different fixture. This shows that the frequency bias of the vibration table system is very dominant and has a profound impact on the excitation on the fixture and the DUT.

![Diagram of DAQ Settings](image)

**Figure 7-4 PSD curve from an old experiment in 2014 (Grms Z)**

A common failure mode for electronic devices is interconnect failure [57]. Multiple experiments aims to precipitate electromechanical failures, like solder joint failures, using excitation levels below 2 kHz [58]-[61]. A study by Amy, Aglietti and Richardson also found high correlation between the board’s surface strain and electronic component failures [58]. This strong correlation suggests that the resonant frequency of the board itself tend to be the source of failure. These frequencies tend to lie at the lower end of the frequency spectrum. The higher the frequencies, the lower the amplitude of deflections, surface strain and failure rates. As such, the frequency bias from the HALT vibration table may not be suitable for precipitating these low frequency failures. Nonetheless, there are multiple board sizes at Waters, with different boundary conditions and maybe some resonant frequencies may fall into the range supported by the chamber.
7.2.3 High Variation at High Excitation Levels

We also noticed that as the vibrational settings are set beyond $70G_{\text{rms}}$, the controller for the HALT chamber faces difficulties in maintaining at the set vibration level. According to McLean, a Class A Guard Band (screening limit suggested by McLean for a robust PCB) for vibration stresses for PCBs is $28G_{\text{rms}}$ [7]. Considering this, there may be no need to test at higher $G_{\text{rms}}$ levels and the system variation will still be within reasonable limits for comparisons to be made across different PCBs. Unfortunately, the high frequency range of excitations from the table may require higher vibrational levels before failures are precipitated. This situation risks entering the high measurement variability zone of the HALT chamber where precision of failure may be an issue.

7.3 Fixture Design

A list of fixture design principles have been generated in Section 5.1 and a fixture design module is proposed to standardize how PCBs at Waters would receive vibrational excitation. By standardizing the fixture, we reduce variation in failure modes due to poor and inconsistent fixture design. This allows a more accurate test of the board’s design and comparison of robustness among boards. The versatility of the fixture plates are tested and have been successful so far in fitting five different types of boards, including the smallest board at Waters. Additionally, decision making during pre-HALT meeting in fixture design will be greatly reduced because the design is now straightforward.

The fixture design is also proven to have a desirable linear relationship with the vibrational excitations. However, spatial tests show that vibration levels are generally higher near the mounting holes of the plate and lower in the center, which may arise from the uneven excitations from the table itself. The team believes that the plate’s response is more complex and involves the table and the mounted components to be analyzed as a system. Nonetheless, considering board’s symmetry, spatial symmetry on the plates and a broader excitation range provided by the plate, these plates are reasonable fixtures for the HALT experiment at Waters. A total of seven trial HALT experiments are conducted using the proposed fixture and mounting SOP on two different boards. The proposed setup is successful in obtaining consistent failures on the board at a specified vibration level. For more details on vibrational stress related tests refer to Singh’s thesis [6].
Since the design requires engineers to locate the mounting holes on the fixture plate relative to the table grid, engineers are encouraged to be trained with computer aided design (CAD) skills. An instruction manual and 3D model template files are created to guide engineers on customizing the HALT fixture for a given PCB design.

7.4 Short-Run Statistical Process Control

A short-run SPC is introduced as a safe-check to the experiment setup procedure for the HALT process. By monitoring the board’s responses using control charts, assignable causes of variation can be minimized. The check provided by the SPC significantly adds credibility to the report and helps to save potential resources that may ensue if wrong conclusions were made using a faulty setup. The short-run SPC simulated in this project yields promising results in identifying process shifts and a fishbone diagram is drafted to assist the reliability engineers in identifying sources of variation when their results differ between experiments.

The existing proposed SPC involves the setup of 20 sets of 150 consecutively sampled data. Each set takes a total of 2 minutes to run in the HALT chamber. A total of approximately one hour of setting up the trial control limits for a single board design is required as an initial investment. Subsequent monitoring requires at least three consecutive readings of 150 samples each to be plotted onto the control charts before stressing the DUT. Thus, the proposed sampling frequency is to sample the three readings before starting a vibration stress profile. There are only two stress profiles that require vibration and they are the vibration step and combined step profiles.

The operators can speed up the setup process by reducing 20 sets of data for the control limits to 10 sets. Once again, the decision made will be a compromise between the accuracy of the control limits and the available resources. However, this is not highly recommended because some rules of the Shewhart control charts may not be violated with less sampling and the limits may not be a representative of the process. Similarly, during monitoring, more consecutive readings can be done to increase the charts’ sensitivity to detect violation of the control chart rules more quickly. For example, having five consecutive readings allows opportunity for violating rule 3 in Table 2-2 for a single setup. On the other hand, having only three consecutive readings per setup may require more experiments before an assignable cause results in a violation of the control charts.
Chapter 8. Proposed Fixture Setup Procedure

Figure 8.1 shows a summary on the recommended fixture setup procedure for printed circuit boards. The main takeaway of having the fixture setup procedure is to achieve more consistent and credible HALT experiments. Other documents that support the fixture setup procedure include the standard operating procedures for data acquisition using accelerometers, fixture customization and short-run SPC. These documents are provided to Waters.

PCB Fixture Setup Overview for HALT Testing

- Identification of PCB Boundary Conditions
  - Assembly File: Mounting Standoffs
  - PCB Drawing File: Mounting Hole Locations
- Identification of Mounting Holes
  - Fixture Module CAD File
  - Table Grid CAD File
- Fabrication of Fixture Design
  - Edited Fixture Module CAD File
- Purchasing of Fasteners
  - BOM Requirements for Fixture Design
- Mounting of Fixture
  - SOP for Mounting Fixture Module*
  - Necessary Fasteners and Tools
- Short-Run SPC for Fixture Setup
  - SOP for Short-Run SPC*
  - Adhesive Mount Triaxial Accelerometer
  - Labview Data Acquisition File & Device
  - "Dummy" PCB Board

*Document File

Figure 8-1 PCB fixture setup overview for HALT testing

The standard operating procedure for fixture setup is straightforward. Since the team standardized the fixture plate, reliability engineers have to add mounting holes based off the PCB drawings. Additional fasteners and serrated washers have to be purchased if necessary. Using consistent torque values for securing the standoffs and following the SOP for mounting the fixture module, the fixture setup is completed. The fixture will be setup in the center of the table outlined in Section 4.3. To ensure consistency of readings, a short-run SPC is then conducted to detect and minimize variation in the experiment setup between runs. The adhesively mounted triaxial accelerometer is used as the selected gauge. Photos of the setup should be taken for documentation.
Chapter 9. Future Work and Recommendations

Given resource and time constraints, majority of the experiments provide great insights into the existing capabilities of the HALT system itself more than providing a full proof fixture setup solution. This section suggests the areas of work that Waters can pursue to gain confidence in implementing and integrating the HALT process into her product development process.

1. Regular Maintenance of the HALT Chamber

Waters should schedule an appointment with a maintenance engineer from Cincinnati Sub-Zero (CNZ) to evaluate the condition of the HALT chamber. The current HALT chamber has been running for over 600 hours without any maintenance. According to the chamber manual, for every 100 hours of use, the air system of the chamber has to be checked for clogged filters and lubrication. For every 500 hours, the vibration system has to be checked. Since Waters did not record the air pressure during its first installation, there is no reference point for Waters to determine whether the vibrators are still performing adequately. Once the maintenance is scheduled, Waters can retest the vibrational response of the plate to the input settings based on the experiment described in this thesis to detect any reduction in variation at higher G\text{rms} values. Waters should check for any biasness in the high frequencies.

2. Physically Review Industry Best Practices and Test Chambers

As identified in Section 7.2.2, it will be good if Waters can engage a reputable third party vendor in the HALT industry, for example Qualmark Corporation, to evaluate the existing fixture setup and the high frequency response of Waters’ HALT chambers. By physically understanding industry best practices in fixture design and technology, it helps to affirm the literature identified in this thesis and highlight any other industry best practices that are unavailable in literature.

3. Skills Training on Dynamics Testing & Analysis

Reliability engineers are familiar with analyzing failures due to thermal stresses. However, they have limited expertise to conduct modal analysis and be confident in making conclusions due to vibrational failures. Modal analysis is a complex but important subject for reliability testing. A
good start to enhance the capabilities of the HALT team is to equip engineers with the knowledge to conduct basic simulation in CAD to identify the mode shapes and resonant frequencies of the PCBs. The R&D Group has 3D models of PCB assemblies which can be readily analyzed. Through this analysis, the HALT team can be more aware on points of maximum deflection or surface strains so that they can efficiently deduce the regions of potential failures. These points are also the locations to place the accelerometers. Design improvements can also be made more efficient if one knows how the devices would react to corresponding stresses. Training will help to speed up the HALT process and have more meaningful deductions.

4. Modular Fixture Optimization & Design for Testability (DFT)

Although the new fixture design is superior to previous fixtures in meeting the design criteria listed in Section 5.1, the versatility of the fixture module is not yet optimized. The optimal fixture should have a uniform vibrational response and can extend to an area as large as 4” by 4”. Two phases are proposed to achieve this. In the first phase of the fixture design, the fixtures should be simulated using reputable computer programs for finite element analysis. Examples of such programs are STARDYNE, NASTRAN and ANSYS [62]. The limited resources did not make this possible in this thesis. Through simulations, Waters can attempt to understand how the plate behaves with its area. Once an optimal design is designed and fabricated, conduct a sine sweep test to check for its resonant frequency. Alternatively, it can be mounted to a vibration table with high vibrational uniformity to check for transmissibility. The next phase involves experimentally optimizing the fixture-plate’s area. A design of experiments (DOE) can be conducted with the dimensions of the plate as variables and the total variance metric as the response variable. The objective is to maximize the coverage of the plate while keeping the total variance metric low.

As covered in Section 1.1.4, existing PCBs at Waters do not follow a standardized way to mount their boards on a chassis. As a result, we have to adopt a basic fixture design just to accommodate the different locations and sizes of mounting holes. The larger sizes of Waters’ hardware relative to her PCBs allow more freedom to design the sizes of the PCBs. Hence, some form of standardization for hole-placement can be implemented. If hole-placement and hole-size are standardized, the HALT fixture can be designed around the known constraints. Less variability in the boards meant that the fixture design can be optimized and more resources can be saved.
Appendix A

A-1 Summary of Comparison between Different HALT Profiles

The table below summarizes the stress profiles from the respective HALT guidelines:

<table>
<thead>
<tr>
<th>Stress Cycle</th>
<th>Qualmark HALT Testing Guidelines</th>
<th>GM Worldwide Engineering Standards (GMW8287)</th>
<th>HALT, HASS, AND HASA Explained by Harry W. McLean</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INITIAL CONDITION</strong></td>
<td>20-30°C, 0 Grms</td>
<td>20-30°C, 0 Grms</td>
<td>20°C, 0 Grms</td>
</tr>
<tr>
<td><strong>Rapid Thermal Transitions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Vibration Step Stress</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Combined Stresses</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Phase 1: Cold Step**
- Temperature Step: -10°C
- Ramp Rate: Undefined
- Dwell Time: >10 Min
- Temperature Step: -10 to -20°C
- Ramp Rate: Undefined
- Dwell Time: 5-15 Min
- Temperature Step: -10°C
- Ramp Rate: Undefined
- Dwell Time: 10 Min

**Phase 2: Hot Step**
- Temperature Step: +10°C
- Ramp Rate: Undefined
- Dwell Time: >10 Min
- Temperature Step: +10 to +20°C
- Ramp Rate: Undefined
- Dwell Time: 10 Min

**Final Condition**
20-30°C, 0 Grms

**Initial Condition**
20-30°C, 0 Grms

**Rapid Thermal Transitions**
- Temperature Cycling: [LOL+(<10)*C] to [UOL-(<10)*C]
- Vibration: 0 Grms
- Ramp Rate: Fastest Possible
- Dwell Time: >5 Min
- Min 3 Thermal Cycles

**Final Condition**
20-30°C, 0 Grms

**Initial Condition**
20-30°C, 0 Grms

**Vibration Step Stress**
- Temperature Step: <30Grms
- Dwell Time: 10 Min
- 'Tickle' Vibration: Drop to 5 +/- 3 Grms after dwell & resume stepping

**Final Condition**
20-30°C, 0 Grms

**Initial Condition**
20-30°C, 0 Grms

**Combined Stresses**
- Temperature Step: (Vibration DL)/(>3)
- Dwell Time: One Thermal Cycle (i.e. "2 X Thermal Dwell Time"
- 'Tickle' Vibration: Drop to 5 +/- 3 Grms after dwell & resume stepping

**Final Condition**
20-30°C, 0 Grms

**Initial Condition**
20-30°C, 0 Grms

**Vibration Step Stress**
- Temperature Step: (Vibration DL)/(>3)
- Dwell Time: One Thermal Cycle (i.e. "2 X Thermal Dwell Time"
- 'Tickle' Vibration: Drop to 5 +/- 3 Grms after dwell & resume stepping

**Final Condition**
20-30°C, 0 Grms

**Initial Condition**
20-30°C, 0 Grms

**Combined Stresses**
- Temperature Step: (Vibration DL)/(>3)
- Dwell Time: One Thermal Cycle (i.e. "2 X Thermal Dwell Time"
- 'Tickle' Vibration: Drop to 5 +/- 3 Grms after dwell & resume stepping

**Final Condition**
20-30°C, 0 Grms

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A-2 Summary of TC-2.5-Panther™ Specifications for Operation & Installation

The table below summarizes the specifications for the TC-2.5-Panther™ as outlined in the product specifications document (correct as of 2007) provided by HALT&HASS Systems Corp. to Waters Corporation. The same chamber had been improved upon by the parent company, CSZ, after a company acquisition in 2011.

TC-2.5-Panther™ Specifications

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp. Range</td>
<td>-100°C to 200°C</td>
<td>Rate of change: &gt;100°C/minute. Higher change rates are optional</td>
</tr>
<tr>
<td>Vibration Table</td>
<td>30” x 30”</td>
<td>Grid Pattern: 28” x 28” – 3/8”-16 UNC on 4 inch centers, metric optional</td>
</tr>
<tr>
<td>Frequency Range</td>
<td>0Hz- 20 KHz</td>
<td></td>
</tr>
<tr>
<td>Vibration System</td>
<td>All Axis</td>
<td>3 translations, 3 rotations</td>
</tr>
<tr>
<td>Vibration Level</td>
<td>&gt;100 Grms, 0-10kHz</td>
<td>Unloaded table with std. vibrators. Higher levels are available</td>
</tr>
<tr>
<td>Dimensions</td>
<td>38” wide X 24” deep X 34” high (Workspace)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>63” wide X 42” deep X 80” high (Outside)</td>
<td></td>
</tr>
<tr>
<td>Chamber Weight</td>
<td>2200 Pounds</td>
<td>The approximate weight is 2500 Pounds</td>
</tr>
</tbody>
</table>

Facility Specifications for TC-2.5 Installation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Power</td>
<td>460 volt/3-phase, 60 Cycle, 75 FLA</td>
</tr>
<tr>
<td>Compressed Air</td>
<td>72 cfm @ 100psi</td>
</tr>
<tr>
<td>Oxygen Sensor</td>
<td>HALT&amp;HASS Systems Corp. recommends installation of an oxygen monitor near the floor, either on the chamber or in the lab if the unit is to be operated in a confined space.</td>
</tr>
<tr>
<td>Noise Level</td>
<td>&lt;68 dBa (measured at 3ft from the chamber @ 50 Grms)</td>
</tr>
<tr>
<td>Liquid Nitrogen</td>
<td>12 gpm @ 20 psi maximum rate during cooling (lasts 3 minutes/cycle)</td>
</tr>
<tr>
<td>Exhaust Plenum</td>
<td>6-inch diameter flange (no muffler required as one is built in)</td>
</tr>
<tr>
<td>Ducting</td>
<td>Six 4” ducts, 3 per side</td>
</tr>
</tbody>
</table>
Appendix B

B-1 TC2.5 Vibration Table

The figure below shows the technical drawing for the vibration table in the HALT Chamber at Waters (TC-2.5-Panther™).
B-2 Technical Drawing of Modular Test Plate

The figure below shows the technical drawing for a modular test plate for 210000308. Initial iterations have only single mounting hole for standoffs to be attached to. However, by combining the various locations of the standoffs into a single plate, we reduced manufacturing costs by 25%.
Appendix C

C-1 Pugh Chart for Existing Fixtures

The table below provides an overview on the team’s evaluation on existing fixtures based on the principles for HALT fixture design outlined in Section 2.3.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>Datum</th>
<th>Fixture 1</th>
<th>Fixture 2</th>
<th>Fixture 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>1</td>
<td>0</td>
<td>+</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Rigid</td>
<td>3</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Small Mounting Area</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Versatility to Waters PCBs</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Quick Setup</td>
<td>1</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Quick PCB Change</td>
<td>1</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Cost</td>
<td>1</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>Distance from Table</td>
<td>2</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Replicates Mounting Condition</td>
<td>2</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>Low Thermal Mass</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Net Score</td>
<td>0</td>
<td>-1</td>
<td>-2</td>
<td>-4</td>
<td></td>
</tr>
</tbody>
</table>

The figure below shows the unsuitability of the clamping fixture (Best option from Pugh chart)
C-2 SOP for Securing Fixture Module to Vibration Table

STANDARD OPERATING PROCEDURE: SECURING & REMOVAL OF FIXTURE MODULE TO VIBRATION TABLE

1. Purpose:

To create a standardized way to secure and remove the HALT printed circuit board (PCB) Fixture Module on the vibration table and minimize variations arising from operators.

2. Scope:

This document is an instruction for the operator to secure and remove HALT PCB Fixture Module on the vibration table. By following this document, the operator will be able to consistently secure the HALT PCB Fixture Modules necessary for HALT testing for PCBs.

3. Terms and Definition:

3.1. DUT- Device under test

4. Equipment:

4.1. Operators must prepare the following tools:

1. Armstrong® Tools Dial Torque Wrench- 3/8”  x1
2. Drive Socket- 3/8” to 3/16” Hex Drive  x1
3. Allen Key- 3/16” Drive  x1
4. HALT PCB Fixture Module (Prepared)  xY
5. Nord-Lock® Washers- 3/8”  x4Y
6. Low-Profile Socket Head Cap Screw- 3/8”-16  x4Y
7. Dummy PCB Board (DUT)  x1

4.2. Setup the Torque Wrench by installing the Drive Socket into the Armstrong® Tools Dial Torque Wrench and adjust the blue dial on the Torque Wrench to 23 foot pounds.
5. **Procedure (Securing):**

5.1. Remove any foreign items on the vibration table (e.g. Fraying fibers from the insulating mat on the vibration table, debris from previous experiments etc.) and clean the base of the HALT PCB Fixture Modules using the appropriate solvents.

5.2. Layout the HALT PCB Fixture Modules at the designated locations on the vibration table.

5.3. Using a dummy PCB board, gently place it over the HALT PCB Fixture Modules to check that the modules are placed in the right locations.

5.4. Insert Nord-Lock® Washers into the 4 recesses on each of the HALT PCB Fixture Modules. Check that each Nord-Lock® Washers come in complementary pairs and the side with most serrations should be facing outwards.

5.5. Place the Low-Profile Socket Head Cap Screw into the 4 recesses on each of the HALT PCB Fixture Modules.

5.6. Secure the Low-Profile Socket Head Cap Screw using the Allen Key with the master hand. Torque the screws until an opposing torque is felt by your hand. Ensure that the Hex Drive is secured snugly to the female end of the Socket Head Cap Screw.
5.7. Fasten the Low-Profile Socket Head Cap Screws using the Armstrong® Tools Dial Torque Wrench. Ensure that the Hex Drive is secured snugly to the female end of the Socket Head Cap Screw.

5.8. Torque the Socket Head Cap Screws using the master hand while having the secondary hand pressing down onto the axis of rotation. Torque the Low-Profile Socket Head Cap Screws to 23 foot pounds.

5.9. Physically and visually check that the setup is completed (e.g. no major creases on the thermal insulating pad and the plates are evenly secured onto the table)

6. Procedure (Removing):

6.1. Untighten the Low-Profile Socket Head Cap Screws using the Armstrong® Tools Dial Torque Wrench. Using the secondary hand pressing down on the axis of rotation, torque the screws in the anticlockwise direction with the master hand. A clicking sound can be heard if the screws are secured properly.

6.2. Once the opposing torque is removed, use the Allen Key to remove the Low-Profile Socket Head Cap Screws

6.3. Remove and store the assembly components accordingly

7. Maintenance:

7.1. Conduct regular checks on the Armstrong® Tools Dial Torque Wrench based on the frequency the Reliability Lab conduct calibrations

7.2. Replace any worn out Low-Profile Socket Head Cap Screws and Drive Socket- 3/8” to 3/16” Hex Drive with new ones. Check BOM for the HALT PCB Fixture Module to retrieve the vendor information.

7.3. Replace Nord-Lock® Washers with new ones if the surface has worn out (visually check and compare with the new washers or clicking sound in 6.1 is consistently absent). Nord-Lock® Washers are experimentally proven to last fastening at least 30 times.
C-3 Accelerometer Decision Tree

The figure below provides a decision tree for Waters Corporation that will help to narrow down the kinds of accelerometers to be used for a HALT experiment. The decision is dependent on the device under test (DUT), temperature and vibrational settings.

Decision Tree: Selecting Accelerometers

Is your DUT Less Massive wrt. to Triaxial Acc.? → More than 1

Is your DUT Small wrt. to Triaxial Acc.? → Number of Degrees of Freedom Required

Only 1 → Is your DUT Less Massive wrt. To Triaxial Acc.?

Is your DUT Small wrt. To Triaxial Acc.?

Yes

Can your DUT function with a hole at the point of interest?

Yes

Vibration Levels

< 40 Grms → Temperature Range

< 30°C → DISCUSSION WITH EXPERIMENT TEAM ON BEST SOLUTION/COMPROMISE

> 30°C → > 40 Grms

> 40 Grms

Discussion with Experiment Team on Best Solution/Compromise

No

Vibration Levels

< 40 Grms → Temperature Range

< 30°C

> 30°C

> 40 Grms

> 40 Grms

> 30°C

< 30°C

Discussion with Experiment Team on Best Solution/Compromise
References


