

Design and Evaluation of a Compact Vibration Isolator for use in Retrofit Telecommunications Fan Unit Applications

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Abstract

Fan vibration has become a significant issue in telecommunications environments due to increased performance and heat of internal components requiring greater airflow and higher speed fans. This thesis investigates fan vibration problems in telecommunications equipment and develops solutions to the problem in a retrofit scenario. A target value for vibration levels was determined by measuring vibration levels in an alternate existing product that exhibited no wear issues over a span of several years. Two successful vibration isolator designs were developed and implemented. The retrofit solution required minimal changes to the legacy design and achieved a large vibration reduction. The ultimate solution required extensive changes to the legacy design and achieved significant vibration reductions, with vibration levels below the target value in most scenarios. Both designs are Patent Pending.

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Acronyms

AH – Company_A High Speed Fan 13000 rpm

AHB – Company_A High Speed Fan 13000 rpm rebalanced

ASIC – Application-Specific Integrated Circuits

BH – Company_B High Speed Fan 12000 rpm

CM – Contract Manufacturer

CZF – Cast Zinc Fan Frame

EDX – Energy-Dispersive X-ray Spectroscopy

FFT – Fast Fourier Transform

GEN1 – Legacy 8000 rpm fan unit (first generation)

GEN1A – Retrofit to first generation fan unit

GEN1B – Ultimate first generation fan unit

GEN2 – Updated higher speed fan unit

GEN2A – Updated higher speed fan unit using retrofit solution

GEN2B – Ultimate updated higher speed fan unit

IC – Integrated Circuit

OM – Optical Micrograph

PCB – Printed Circuit Board

PMF – Plastic Injection Molded Fan Frame

RMS – Root Mean Square

RPM – Revolutions Per Minute

SEI – Secondary Electron Image

SEM – Scanning Electron Microscope

Glossary

Application-Specific Integrated Circuit (ASIC) – “an integrated circuit designed to perform and specific task [1].”

Beat Frequency – when multiple dynamic excitation sources are operating at similar frequencies. This allows for the waveforms to add on top of one another, creating periodic peaks and valleys in the vibration vs. time plot [2].

Energy-Dispersive X-ray Spectroscopy (EDX) – which bombards the sample with an X-ray and measures the X-rays emitted from the sample as electrons are displaced by the incident X-ray. The amount of energy emitted is characteristic of certain elements and the count of the incoming X-rays of specific energy is plotted with energy emitted (KeV) along the x-axis and count along the y-axis [3].

Fan – An axial fan typically consists of a housing which houses the venturi and a rotor which houses the fan blade.

Fan Unit – a field replaceable pluggable unit that cools a telecom shelf. It incorporates a sheet metal chassis, printed circuit boards (PCBs), a latching mechanism, a fan or fans, and a connector interface with the shelf that provides power and data logic.

Fast Fourier Transform (FFT) – a computational discrete Fourier algorithm which reduces the number of computations necessary to solve the Fourier transform. Converts plots in the time domain to the frequency domain [4].

Fretting corrosion – a localized pattern of oxidization damage which results from electrical contacts undergoing cyclic, small amplitude relative motion [5]–[7].

Fritting – electrical contact breakdown at locations of oxide films [8].

Integrated Circuit (IC) – any subset of electrical components including resistors, capacitors, transistors, etc. integrated into a small package, typically a silicon chip [9].

Optical Micrograph (OM) – “an image acquired by light illumination using a system of magnifying lenses [10].”

Printed Circuit Board (PCB) – a non-conductive board used to mechanically support electrical components and their electrical connections or traces. Layers of conductive and non-conductive material are used to create circuits and form connections. The more complex a circuit, the more layers are required [11].

Root Mean Square (RMS) – the square root of the mean of n values x_i^2 [12].

Scanning Electron Microscope (SEM) – a microscope that uses a focused beam of high energy electrons to bombard the surface of a solid sample and then collect a variety of signals to produce an image [13].

Secondary Electron Image (SEI) – the most common type of micrograph generated using an SEM. SEI shows high detail images of the surface of a specimen with a high depth of field so that all surfaces of the specimen appear focused in the micrograph [13].

Signal integrity – the cleanliness of an electronic signal. A signal with high integrity will appear as close to the ideal waveform as possible without any noise, cross-talk, or signal degradation present [14].

Telecommunications Industry – creates and supports products that deliver and route telecommunications data such as: local phone, long-distance phone, wireless phone, data (internet, etc.), and private line [15].

Vibration – generally related to the oscillating motion of mechanical elastic systems and the forces associated with that. Systems are linear or non-linear. This thesis focuses on non-linear behaviour [16].

Wipe – travel distance or electrical engagement of one electrical contact with its mating half during mating and un-mating of connector halves [17].

Chapter 1 Introduction

1.1 The Problem

Ciena is a telecommunications company with approximately 5000 employees, headquartered in Maryland, but with a significant presence in Ottawa, Ontario for research and design purposes. Ciena manufactures telecommunications equipment in the form of shelves and circuit packs which contain printed circuit boards and optical components required to transmit and switch data and internet traffic.

Ciena has a telecommunications shelf product that is in production and deployed at customer sites worldwide. The shelf product uses cooling fan units to reduce temperatures of critical components during normal operation. In the past, the performance requirements of the components in shelves were lower, and the fans required to cool them therefore ran at slower speeds. Increasing shelf performance over the past decade has resulted in components that operate at higher temperatures, which in turn require additional airflow to be cooled properly. This implies that higher speed fans are required.

An excessive vibration in these higher speed fan units is creating fretting corrosion wear on their connector interface between the fan unit and the shelf [18]. This is causing alarms to be raised in the shelf's software indicating a communication problem with the fan unit and the fan units' speed to be set to maximum. This results in further damage to the shelf and interferes with customer operations.

1.2 Thesis Overview

The goal of this thesis is to develop and evaluate a retrofit solution to reduce the excessive vibration levels in the fan unit exhibiting fretting corrosion and vibration problems (legacy fan unit). This implies that the vibration reduction solution must fit within the existing envelope of the fan unit and the existing fan unit slot in the shelf. The clearances between the fan and the fan unit, as well as the fan unit and the shelf are minimal, which greatly complicates the problem, limits the potential solutions and also eliminates the possibility of using conventional vibration isolators.

To complicate the problem further, the shelf is scheduled to be upgraded in order to increase its performance capabilities. This will make it operate at even more elevated temperatures and require greater airflow volumes to cool its critical components. This in turn will require a fan that operates at higher speeds, thus greatly exacerbating the vibration issue since vibration imbalance forces increase with the square of the fan speed [19].

It is also important to note that the shape and size of the fan unit cannot be appreciably altered, and only within the physical constraints of the existing system since this is a mature, deployed product. The fans internal to the fan unit also must maintain the same physical dimensions due to airflow requirements as well as to stay within industry standard fan sizes.

The specific goals of this thesis are to:

1. Develop a criterion for acceptable levels of vibration for the legacy fan unit
2. Design and evaluate a retrofit vibration reduction solution for the legacy fan unit that can be quickly and easily implemented for fan units that are currently in operation.
3. Develop an ultimate vibration reduction solution to be used for the legacy fan unit and an updated higher speed fan unit that achieves the largest vibration reduction possible within the given design envelope.

In this thesis, the testing and the resulting design insights will be presented chronologically, culminating in the final design and results. All work presented in this thesis is solely that of the author and peer reviewed by a co-worker mentor, unless otherwise explicitly stated.

1.3 Contributions of the Thesis

The main contributions of this thesis are as follows:

1. Acceptable vibration level threshold values were determined by evaluating vibration levels of an alternate existing product with no known wear issues.
2. A retrofit vibration isolation solution to greatly reduce the vibration levels of the legacy fan unit as well as the higher speed upgraded fan unit was designed, evaluated and implemented. This design requires minimal changes to the existing legacy design and requires no fan modifications. This design is Patent Pending.

3. An ultimate vibration isolation solution to significantly reduce the vibration levels of both fan units to below the threshold value in most operating scenarios was designed, evaluated and implemented. This design requires extensive changes to the legacy design as well as custom fans and isolators. This design is also Patent Pending.

Chapter 2 Hardware Review

In this chapter, relevant literature is reviewed and summarized in order to provide necessary technical background information with regards to fretting corrosion of telecommunications connectors and types of fan vibration isolation designs. A summary of each type of vibration isolation design including advantages and disadvantages is also presented for reference.

2.1 Fretting Corrosion in Mating Connectors

Electrical connections at connector interfaces must be inherently stable with low contact resistance, ideally for duration of the life of a telecom product regardless of any environmental factors [5]–[7].

Gold and high-gold alloys are the most suitable and reliable contact materials for such an application since they do not form insulating oxides, have high conductivity, durability, and solder-ability, and can be easily applied through electroplating processes [5]–[7].

Mating electronic connectors that are subject to vibration, mechanical shock, or thermal stresses tend to experience increased contact resistance over time due to fretting corrosion. For the telecom products under consideration in this work, the mode of damage that is most critical is vibration-caused fretting corrosion of gold plated connector contacts. Typically, reliable signal integrity is achieved with a contact resistance of a few milliohms or less [5]–[7].

Fretting corrosion is one of many scenarios which ultimately degrades signal integrity and results in higher contact resistance. Other causes of signal degradation include oxidation, stress relaxation, differential thermal expansion, galvanic corrosion, and formation of intermetallic compounds [5]–[7].

Fretting corrosion occurs in gold plated contacts when the gold layer is mechanically worn away allowing for oxides of the base metals to form which act as insulators and increase the contact resistance. An example of fretting corrosion damage as a function of cycles and frequency of vibration which has been shown to occur in practice can be seen in Figure 2.1 [5]–[7].

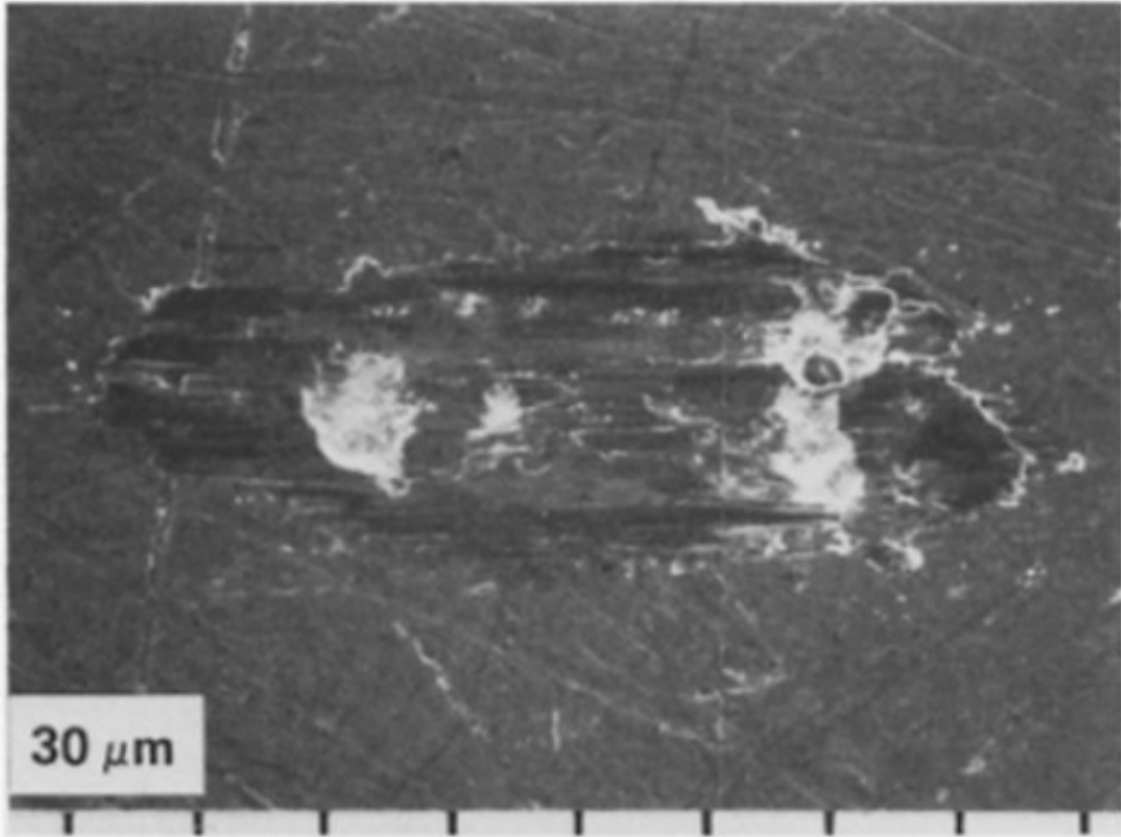


Figure 2.1: Fretting Corrosion of a Mating Contact (Solid Gold Rider in Contact with a 0.05 μm Thick Co-Au Plating on Copper) After 100,000 Cycles [5]

Studies have validated the information in this section experimentally by testing a contact “plate” and “rider” to simulate a connector contact [5].

2.1.1 Fretting Corrosion Process & Damage

Fretting corrosion creates a localized pattern of damage which results from electrical contacts undergoing cyclic, small amplitude relative motion [5]–[7].

The contact material as well as the vibration frequency and amplitude all affect the resultant fretting corrosion, which is typically quantified using contact resistance. Figure 2.2 shows a plot that compares the number of vibration cycles, their frequency and materials, and the resultant variation in contact resistance. In Figure 2.2, the black data points represent copper on copper contact and the white data points represent solid gold on Co-Au plated copper. This figure clearly shows the benefit of using gold as opposed to copper contacts [5]–[7].

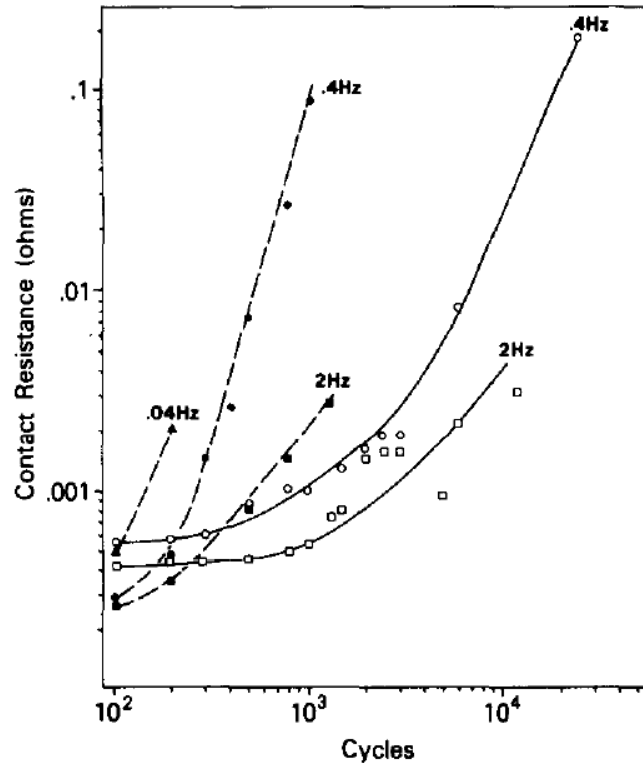


Figure 2.2: Severity of Fretting Corrosion (Contact Resistance) vs. Cycles and frequency of vibration. Black data points represent copper on copper contact. White data points represent solid gold on Co-Au plated copper [5]

The process of fretting corrosion is better understood on the microscopic level and by taking into consideration that no two surfaces are purely planar – there is always a level of roughness present at the microscopic scale. As a consequence, contact between two halves of a connector occurs at high points of each surface, and air gaps remain in the valleys [5]–[7].

The mechanism of fretting corrosion and the parameters that affect it have been studied extensively and are well known [5]–[7]. The parameters which affect fretting corrosion include:

1. **Vibration frequency:** lower frequencies are more damaging since freshly exposed metallic surfaces are exposed to corrosive elements for longer times, allowing oxides and films to grow in size between wipe cycles.
2. **Wipe distance:** is the length of the pin on the male connector that is engaged with the mating receptacle on the female connector. Increasing wipe distance (to a certain extent) reduces connector life since longer wipes expose more worn metal contact area per cycles of fretting. This results in more corrosive product formation per cycle.

3. **Normal load:** it has been shown experimentally that higher normal load at the contact increases the life of the connector where there is a stable, low contact resistance situation [5]–[7]. Normal load is defined as the force between mating connector halves, perpendicular to the connector axis, as shown in Figure 2.3.

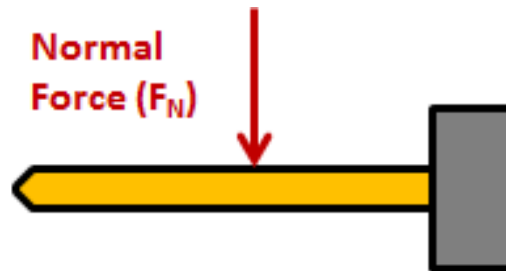


Figure 2.3: Connector Normal Force Diagram

4. **Electrical load:** higher electrical loads can result in frittling, which is an electrical contact breakdown at locations of oxide films and which inhibits the formation of oxide films [8].
5. **Underplate, substrate, and plating:** base materials of the connectors can be protected from damage and oxidation by protective substrates applied beneath a connector plating. Ideally a hard nickel substrate placed between the softer base metal and softer surface film (typically gold) should be used.
6. **Lubricants:** lubricants protect the contact and reduce contact resistance by reducing the wear rate, dispersing frictional particles, and shielding the contact surfaces from the surrounding air.
7. **Friction Coefficient:** will vary throughout the life of the connector and is related to the total number of wear cycles experienced.



Figure 2.4: Stages of Fretting Corrosion [5]

A connector that undergoes the fretting corrosion process of damage in a typical telecom or office environment goes through three stages as shown in Figure 2.4. The first stage involves initial connector wear when high points or asperities penetrate surface films and is characterized by low contact resistance (Figure 2.4a). The second stage begins at the onset of fretting where wear debris begins to be produced, escapes the high contact points and settles into lower points of the contact (Figure 2.4b-e). Low contact resistance is maintained in the second stage until the wear debris accumulates and forms a layer of insulating oxides (Figure 2.4f). This results in a fluctuation in contact resistance until the layers grow large enough for the contact resistance to increase to a point where electrical contact is lost and the connector fails (Figure 2.4g) [5]–[7].

2.1.2 Theoretical Models

Models exist that attempt to predict the duration of the useful life of a connector that is undergoing fretting wear. Most of these models are highly theoretical and make the assumption that many parameters are known that in practice are difficult to obtain in a field environment [6].

A model that uses microscopic and reactive parameters to attempt to determine the number of fretting cycles T , to failure is given by [6]:

$$T = \frac{ZA_n}{\frac{\gamma - 1}{\gamma} \bar{h}_0 \bar{A}_{exposed}} \quad (1)$$

where Z is the average distance between peak height and valley depth of the connector surface, A_n is the nominal contact area, γ is the ratio of volume of corrosive product to volume of initial reactant material, \bar{h}_0 is the average thickness of the oxide/corrosive layer taken over T fretting cycles, and $\bar{A}_{exposed}$ is the average area of exposed bare metal contact area taken over T fretting cycles [6]. It is clear that most of these variables cannot be obtained outside of a specialized laboratory environment.

2.1.3 Mitigation & Healing Methods

The critical factor in good signal integrity of a connector is metal to metal contact with a low contact resistance. In connectors where good metal to metal contact is no longer present, the goal is to find a way to re-establish this contact. This can be achieved by way of fretting, wipe, and reduction of corrosive agents [6].

Thicker layers of gold on connector contact surfaces are the most effective method of mitigating the effects of fretting corrosion, but this solution is also costly [5].

Contact is also improved through the use of connector lubricants at the mating interface. Lubricants include such substances as liquid polyphenol ether which is applied as a liquid, evaporates and leaves a lubricating film in its place [5].

2.2 Fans and Isolation Designs

2.2.1 External Isolators (work with standard fans)

Many designs exist for fan vibration isolators that are external to the fan, or add on to an existing fan. These can be easily used in new designs where extra space can be allocated, they are also easy to implement and typically less costly. The following section reviews and categorizes existing patented designs that fall into this category [20]–[27].

Base Isolating Pad

A base isolating pad design makes use of a large mounting pad that secures to the mounting surface which is loosely coupled with another mounting surface connected to the fan. The loose coupling acts as a damper and this feature can be comprised of many different types of elements, such as a diaphragm (Figure 2.5) and thick damping pad (Figure 2.6) [20], [24].

A diaphragm design has the benefit of completely sealing off the fan inlet from the fan outlet, removing the possibility of air recirculation. However, it also creates a larger mounting footprint which must be accommodated in the overall design. Figure 2.5 denotes the diaphragm feature with #56 in the isolator cross-section [20].

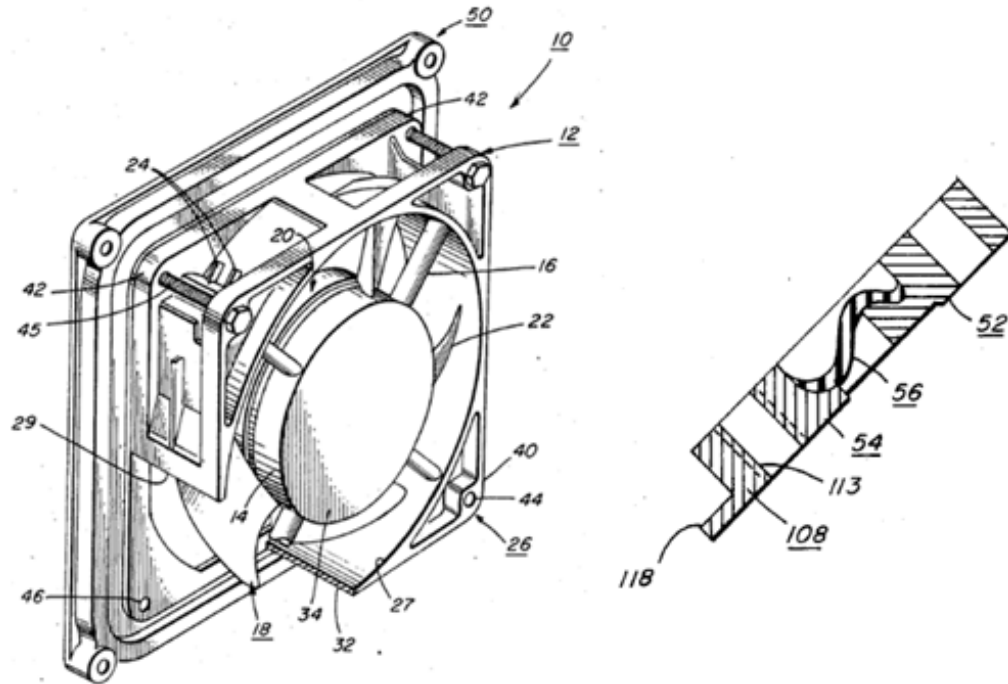


Figure 2.5: Schematic of a Base Mount Isolator Seal Design [20]

A foam core design, as shown in Figure 2.6, allows the isolation to be restricted to the footprint of the fan itself, but adds significant vertical height to the fan assembly. As a benefit, the foam can be chosen from a wide variety of foam and other damping materials that comprise the isolator [24].

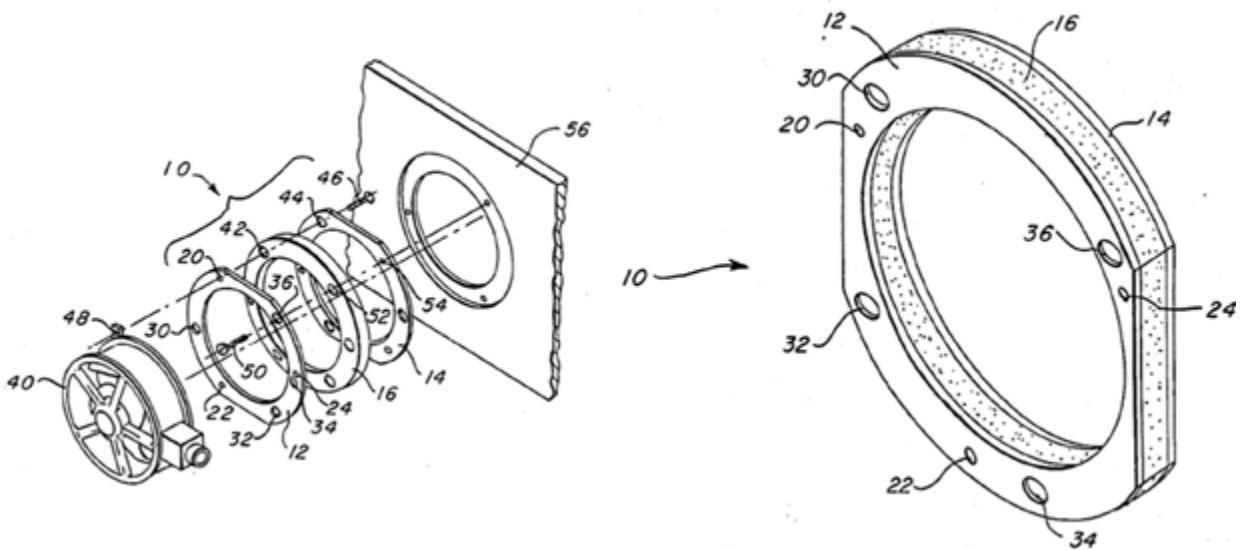


Figure 2.6: Schematic of a Foam Core Isolator Design [24]

Isolator Surrounds Fan

A design where the isolator surrounds the fan attempts to isolate the fan's vibration from the mounting or fixed structure by entirely surrounding it with damping material. This could be considered to be a fully floating configuration since the fan is not directly secured at any point; it is instead encased by the damping material and the fixed support structure as shown in Figure 2.7 [21], [22], [26]–[29].

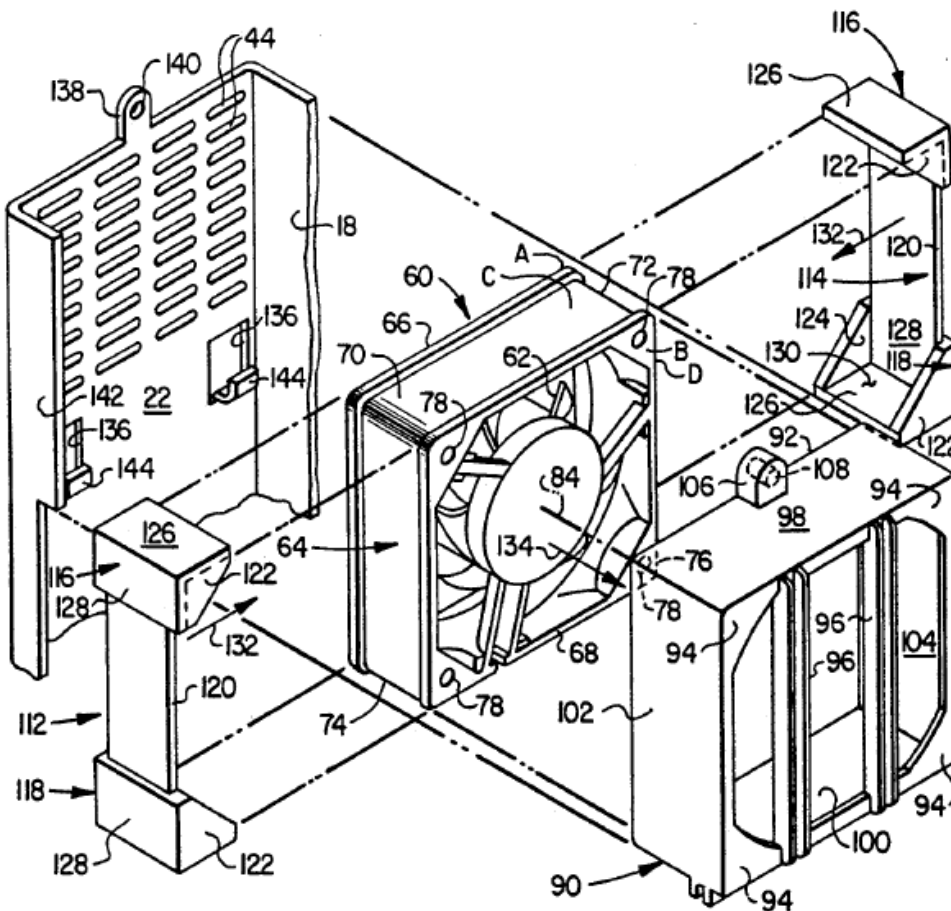


Figure 2.7: Schematic of a Design where the Isolator entirely surrounds fan [21], [22]

A variation of this concept allows for the isolator to only attach to a subset of the fan's surfaces. The concept is the same, however, in that there is no solid connection between the fan and the structure. The structure itself holds the fan and isolator in place. Figure 2.7 shows an example of this configuration [21], [22], [26]–[29].

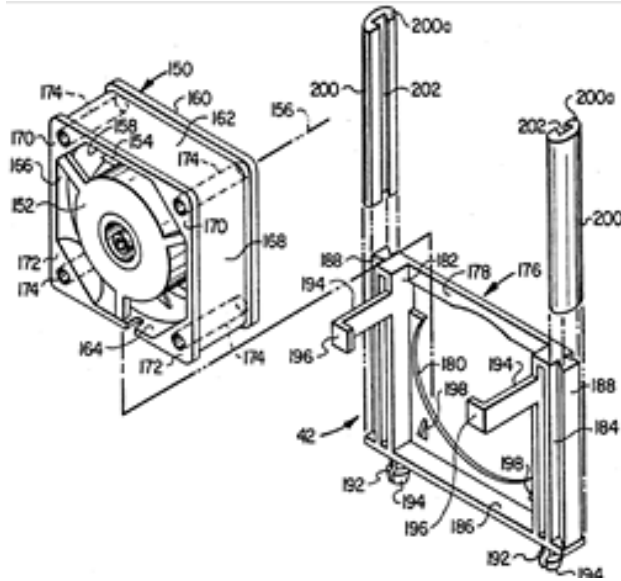


Figure 2.8: Schematic of a Fan encased by partial surrounding isolators [21], [22]

In these designs, the isolator and associated fan mount have a much larger volume envelope than the fan that they isolate.

Various designs exist for the case structure that holds the isolator around the fan. Typical solutions in the industry make use of sheet metal as shown in

Figure 2.8. Alternatively, injection molded pieces can also be used which would potentially be a cheaper solution where a large volume of the product is being sold [21], [22], [26]–[29].

Discrete Fastener-Based Isolators

Designs that are discrete fastener-based isolator systems make use of standard fan mounting holes to damp vibration. Instead of directly using a screw or other secure means of attaching to mounting holes on the four corners of a typical fan, an isolator that secures the fan to the support structure is used instead [23], [25], [30]–[33].

These fasteners typically mount in a hole in the support structure, which is typically a thin material such as sheet metal. A large base retains the isolator fastener in the structure. The base has an extrusion that protrudes into the mounting hole on the fan. Barbs or other retaining features on the fastener secure the fastener to the fan or into an insert that is securely fastened to the fan, as in Figure 2.9 [23], [25], [30]–[33].

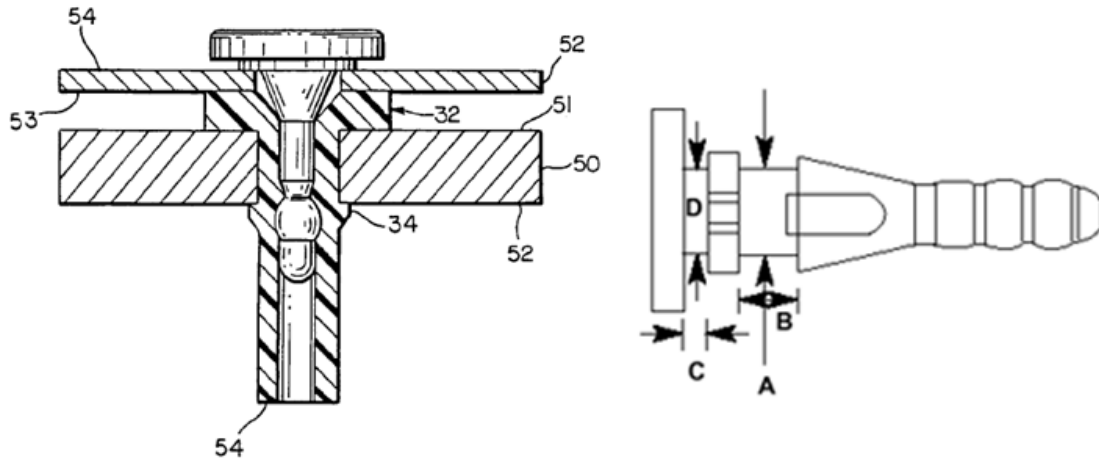


Figure 2.9: Fastener Isolators (Various Types: Left [23] support structure indicated by #52, fan insert by #54, central unnumbered member is the isolator; Right [25] alternate isolator)

The image to the left in Figure 2.9 depicts the support structure as #52, the fan as #50, the fan insert as #34 and the isolator fastener is the central feature that is un-numbered [23], [25], [30]–[33].

A variation on this design uses a plastic frame to which four such isolator fasteners are mounted (Figure 2.10). The plastic frame can be attached directly to the fixed structure or a second stage of damping can be added such as a base isolating pad [20], [23]–[25].

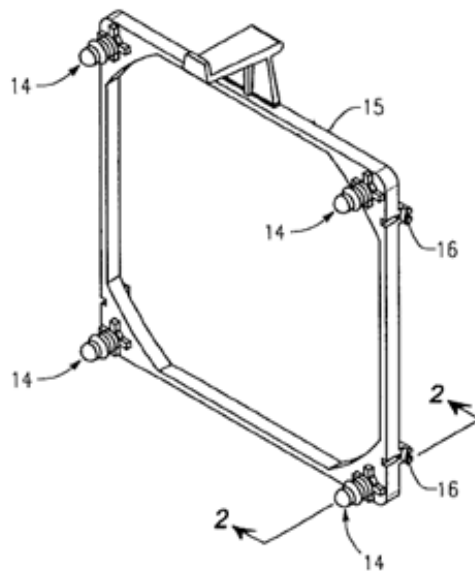


Figure 2.10: Schematic of Fastener Isolators on Frame [30]

Isolator Accessories

Isolator accessories are add-on isolators that create a damped coupling between a traditional fastener such as a screw, the fan mounting hole, and the fixed structure [34].

One such instance of an isolator accessory uses a round isolator disc that is secured around the fan flange at the mounting hole. Typically, the fan is screwed to the fixed structure of the fan unit. This results in compression of the isolator and keeps the fan flange from contacting the fixed structure (Figure 2.11). The downside of this design is that a rigid connection (the fastener) still exists between the fan and the fixed structure [34].

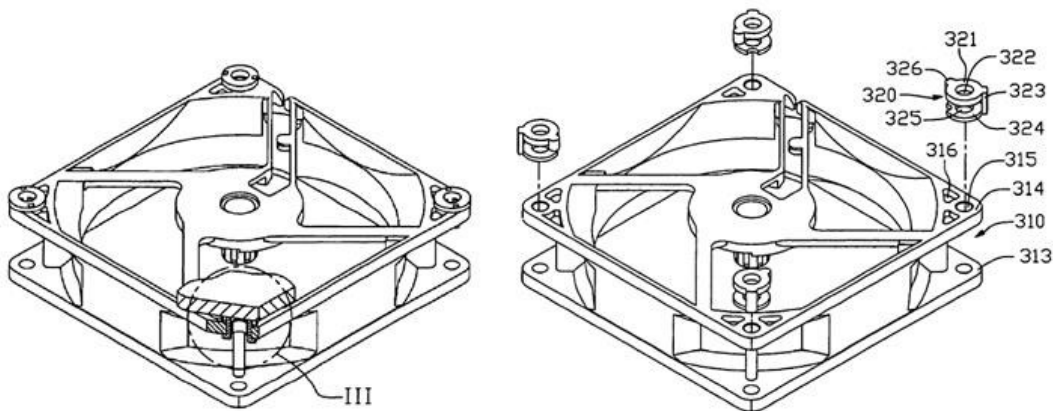


Figure 2.11: Isolator Accessory Schematic Example [34]

Isolated Fan Sandwiched By Structure

Conceptually, isolated fans that are sandwiched by the fixed support structure are very similar to the fans that are surrounded by an isolator. In both cases, the goal is to “float” the fan and prevent any direct contact between the fan and its support structure [35], [36].

The main difference between these two types of isolator:

- Surround isolators are very basic and are essentially solid shapes of isolating material that encase the fan.
- Isolators used in a sandwich configuration can be designed to any desired shape to achieve even greater levels of isolation as well as save on material and space used.

Figure 2.12 shows one such sandwich isolator configuration where the fans are sandwiched by a support structure parallel to the fan's main axis; #13 indicates the bottom support structure and #55 indicates the isolator used in this case. The same concept can be applied to such a configuration that sandwiches a fan perpendicular to its main axis [35], [36].

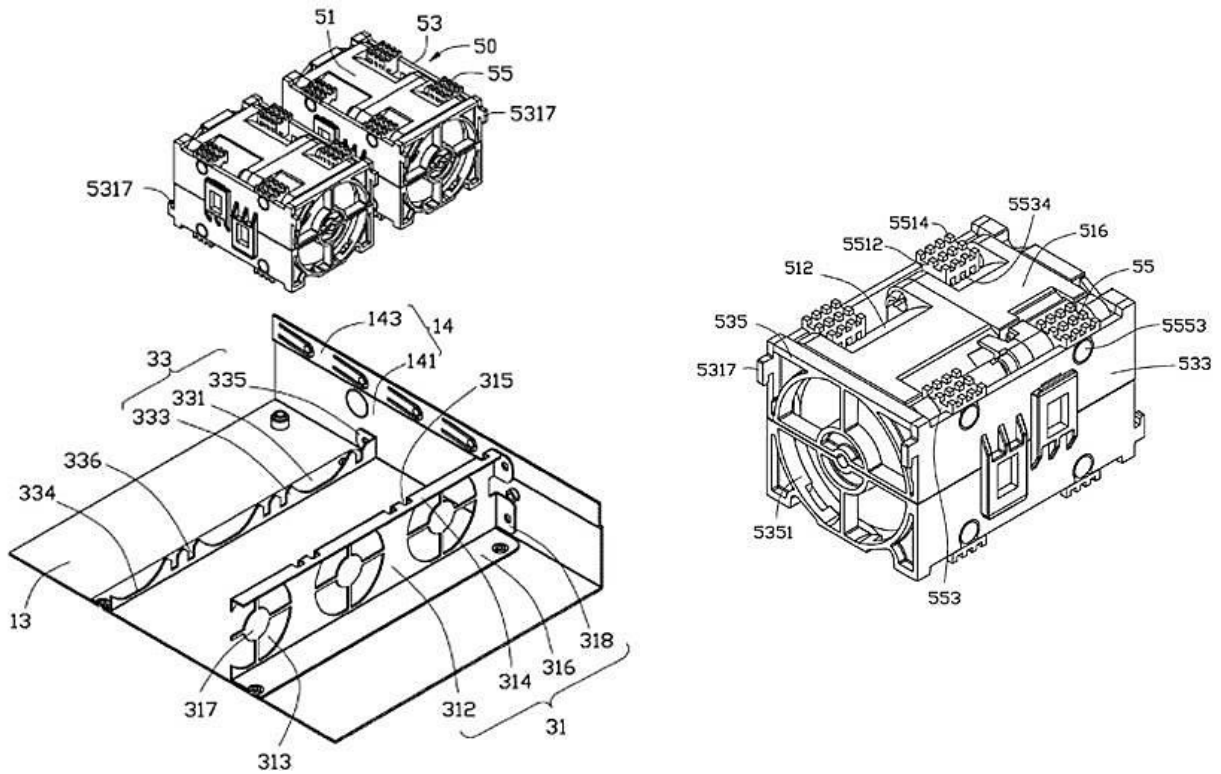


Figure 2.12: Schematic of Isolated Fan Sandwiched by Structure [35], [36]

Isolating Appendages

Isolating appendages are compliant isolator extensions that connect to the fan housing on one end and the fixed structure on the other. They use their length and shape to decouple the fan from the housing by extending beyond the limits of the fan itself as shown in Figure 2.13 [37]–[39]. An extra housing can surround the fans and connect to the appendage as in Figure 2.13, or the appendage can connect directly to the fan itself.

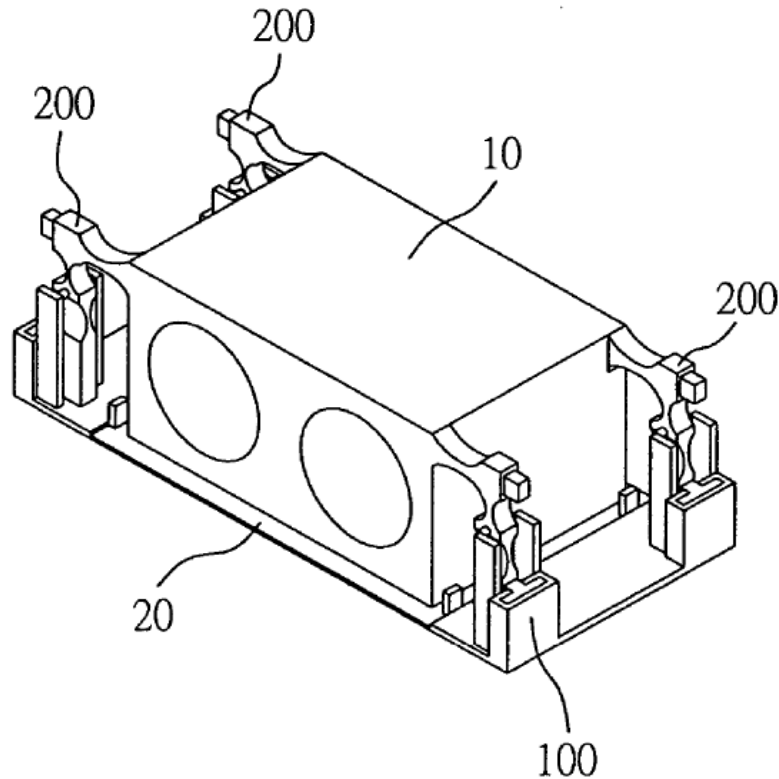


Figure 2.13: Schematic of Isolator Appendages [37]

Various geometries exist, from simple designs that consist of a single appendage oriented in one axis to more complicated designs that have appendages with arms in multiple axes, as shown in Figure 2.13 [37]–[39].

Large vibration reductions can be achieved, but only in an application where large amounts of space exist between the fan and its housing. Such a design solution is not conducive to a retrofit scenario.

Floating Spring

A floating spring design uses either a coil spring or leaf-type spring to isolate the fan from its external housing. These designs are simple to employ, but require additional space between the fan itself and its external housing in order to operate correctly. Figure 2.14 shows two such designs [40], [41].

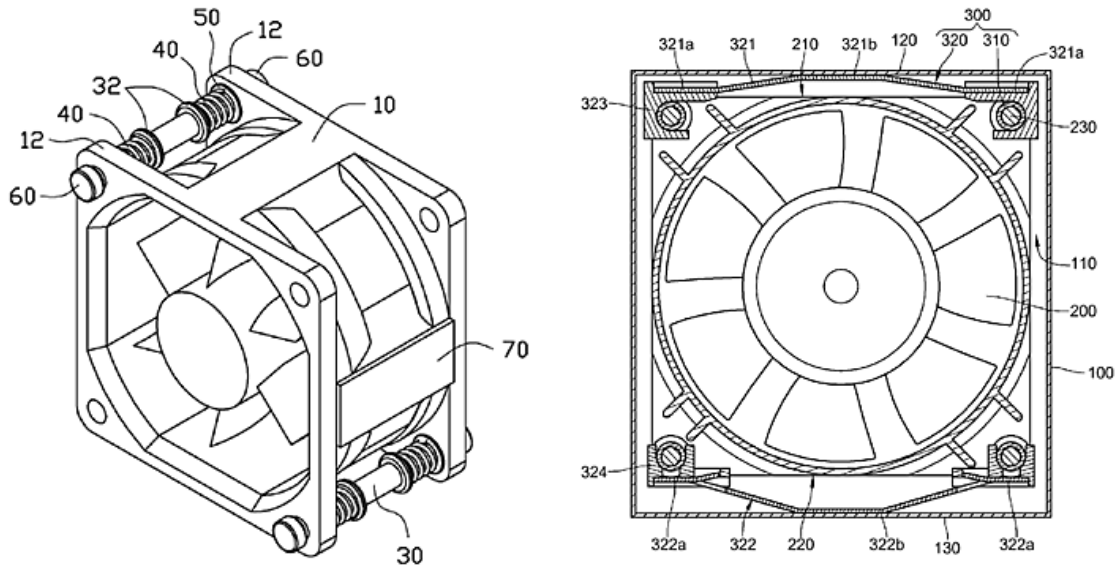


Figure 2.14: Schematics of Floating Spring Designs (Left: coil spring ; Right: leaf spring) [40], [41]

2.2.2 Custom Isolators (custom fan required)

Isolator Accessories

Isolator accessories can also be used with custom designed fans if a slot or other such keying feature is added to the mounting holes to facilitate the assembly of different shaped isolator geometries and retention features (Figure 2.15). Such a configuration would typically be less desirable to implement as it would have the same level of vibration isolation as the isolator accessory for the standard fan but with the cost of the custom fan [34].

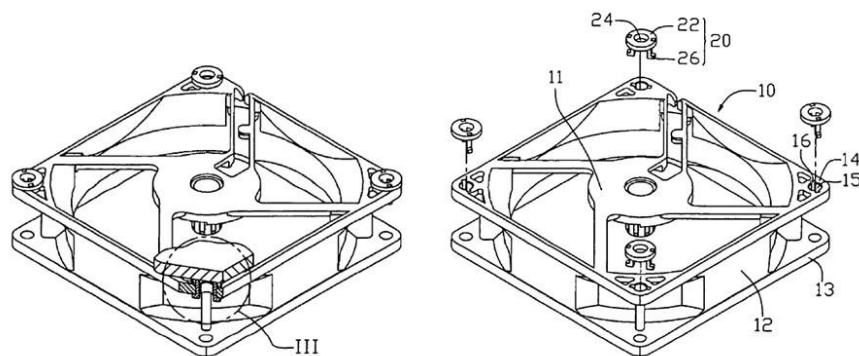


Figure 2.15: Isolator Accessory Custom Fan [34]

Suspended Rotor

A suspended rotor design completely does away with standard fan geometry. It makes use of a non-standard fan housing which serves as a mounting point for vibration isolating members that attach to the rotor assembly. Thus, the rotor assembly is decoupled from the fan housing itself, allowing the fan housing to be directly fixed to the mounting surface. Figure 2.16 shows two such designs [42].

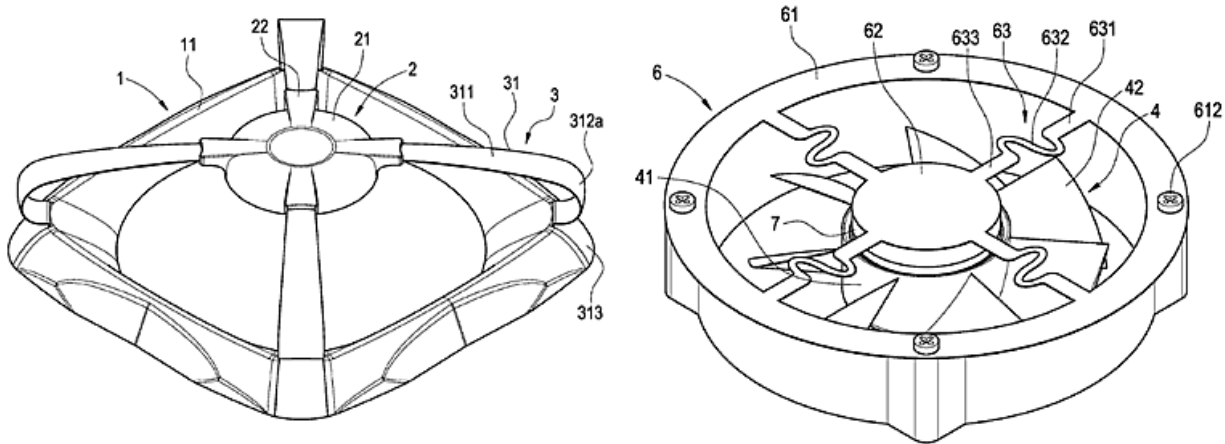


Figure 2.16: Schematic of Custom Fans with Suspended Rotor [42]

These designs are highly customizable for any application. The problem with such a design is that it can only reasonably be developed by a company that only manufactures fans due to its complexity and the multitude of extra design variables that are introduced with such a design [42].

Flange Removal

A flange removal custom fan typically takes a standard fan and removes the outer flanges and replaces them with blocks of isolator material. The isolator blocks fit into the fan by way of tooled grooves or snap features to securely hold them in place. The isolator blocks either have retention features or holes to which they can be mounted to the external housing [43], [44].

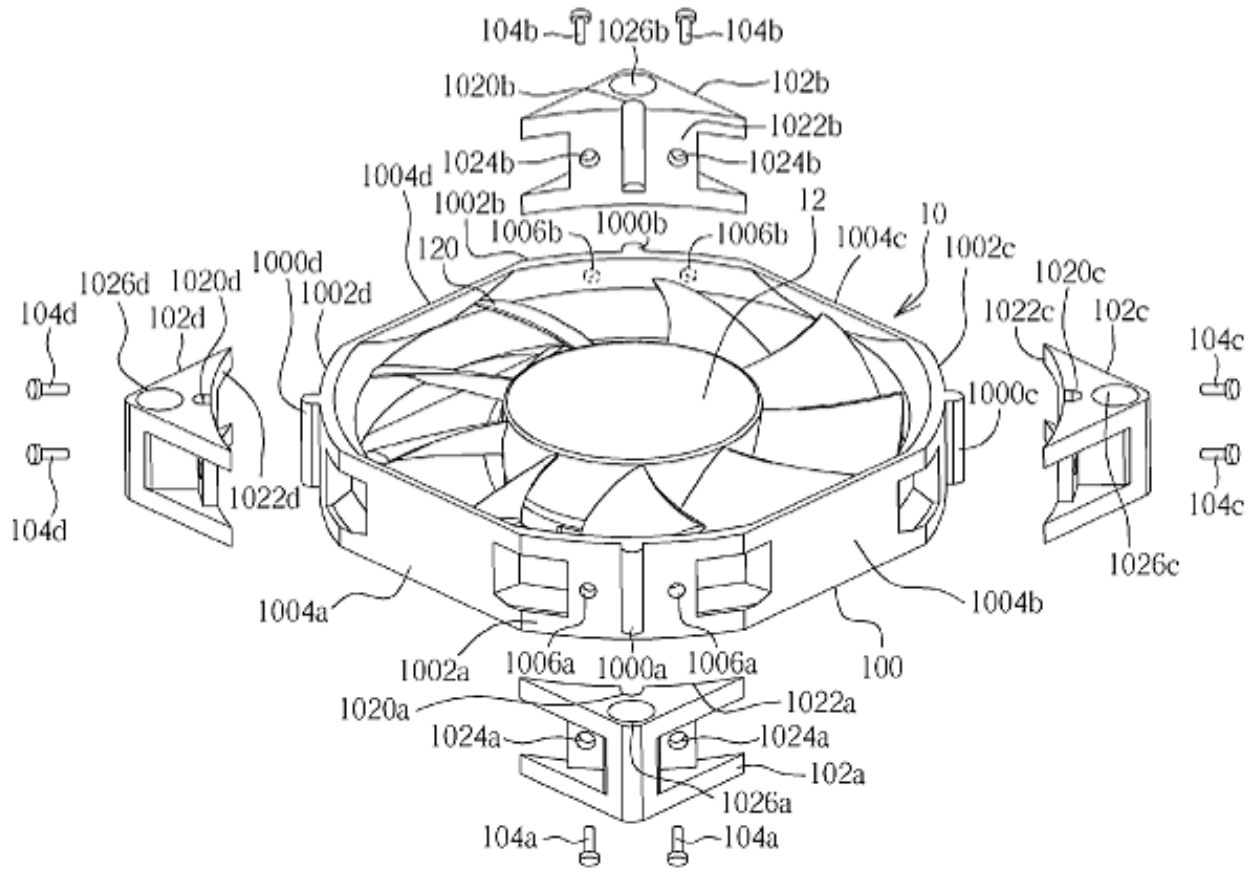


Figure 2.17: Schematic of Custom Fans with Flanges Removed [43], [44]

The benefit of this design is that it can fully fit within the standard fan profile and provide large levels of vibration reduction. The problem with this design is that the isolator blocks fill up the entire volume that would typically exist between standard fan flanges. In some fan unit designs, the empty space between flanges is used for different purposes. Removing this usable space can compromise a design, especially in a retrofit scenario [43], [44].

2.2.3 Summary of Fan Isolation Designs

Table 2.1 below summarizes the different fans and isolator designs found while reviewing the literature.

Table 2.1: Fan Isolator Designs Summary

Design	Fan Type	Advantages	Disadvantages
Base Isolating Pad	Standard	-Seals air inlet completely	-Larger footprint -Larger height
Isolator Surrounds Fan	Standard	-Effective isolation -Isolators encase the fan	-Extra volume required around fan
Discrete Fastener-Based Isolators	Standard	-Small size -Easy to implement	-Base of isolator extends outside of chassis -Limited vibration isolation
Isolator Accessories	Standard	-Small size -Easy to implement	-Require extra vertical space -Limited vibration isolation
Isolated Fan Sandwiched by Structure	Standard	-Simple design -Isolators encase fan	-Enclosure design limits use
Isolating Appendages	Standard	-Effective isolation	-Extra volume required around fan -Complex geometries
Floating Spring	Standard	-Simple design -Easy to implement	-Extra volume required around fan
Isolator Accessories	Custom	-Small size	-Require extra vertical space -Need custom fans
Suspended Rotor	Custom	-Effective isolation	-Need custom fans -Complex geometries
Flange Removal	Custom	-Effective isolation	-Need custom fans -Complex geometries

Chapter 3 Detailed Background & Problem Statement

In this chapter, background information on telecommunications equipment in general as well as information directly related to the first generation fan unit (GEN1) are presented in order to provide a better overview of the scope of the problem. A problem statement is also formally developed for the thesis. Design requirements are laid out and summarized, including design requirements which are yet to be quantified, such as acceptable vibration level.

3.1 Telecommunications Equipment

The telecom equipment analyzed in this thesis is summarized in this section.

3.1.1 Telecom Shelf

The telecom shelf is large format, standing approximately 7 ft tall, and fills a telecom rack, which consists of two vertical members with mounting holes to which the shelf is secured. It is a mirrored configuration with the top of the shelf being a mirror of the bottom. Five fan units are located at the top of the shelf and are installed in an “upright” position. It has line cards (section 3.1.2) positioned below and cooled by this row of fans. Below the line cards are the switch cards which switch data traffic between line cards; this area of the shelf also doubles as the air inlet. The mirror plane exists in the middle of the switch cards, below which are another set of line cards. A second row of five fan units are situated below the line cards and are installed in an “inverted” position. Figure 3.1 shows the shelf and includes the fan unit slot reference numbers.

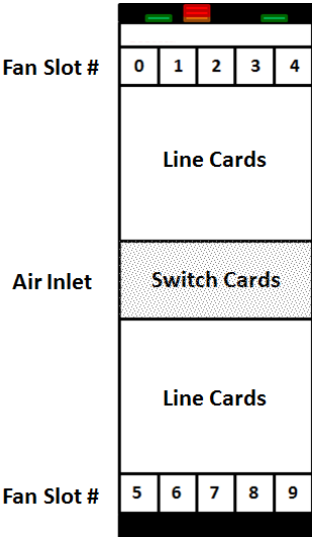


Figure 3.1: Telecom Shelf Configuration

3.1.2 Telecom Line Cards

The line cards used in the telecom shelf are the pieces of equipment that carry the network traffic. They consist of a Printed Circuit Board (PCB) with the following features:

- A row of high speed signal connectors and power connectors that interface with the shelf's backplane PCB.
- A front faceplate with pluggable interfaces for optical fiber and Ethernet cables. Data from the network is routed to and from the line cards through these interfaces.
- Integrated Circuits (ICs) and Application-Specific Integrated Circuits (ASICs – which are ICs designed to perform one very specific, complex function) as well as other electrical components.
- Latches on the faceplate that are used to leverage the card into the shelf and apply force on the mating signal connectors to ensure a solid, reliable contact.

Figure 3.2 shows a general schematic of the above components.

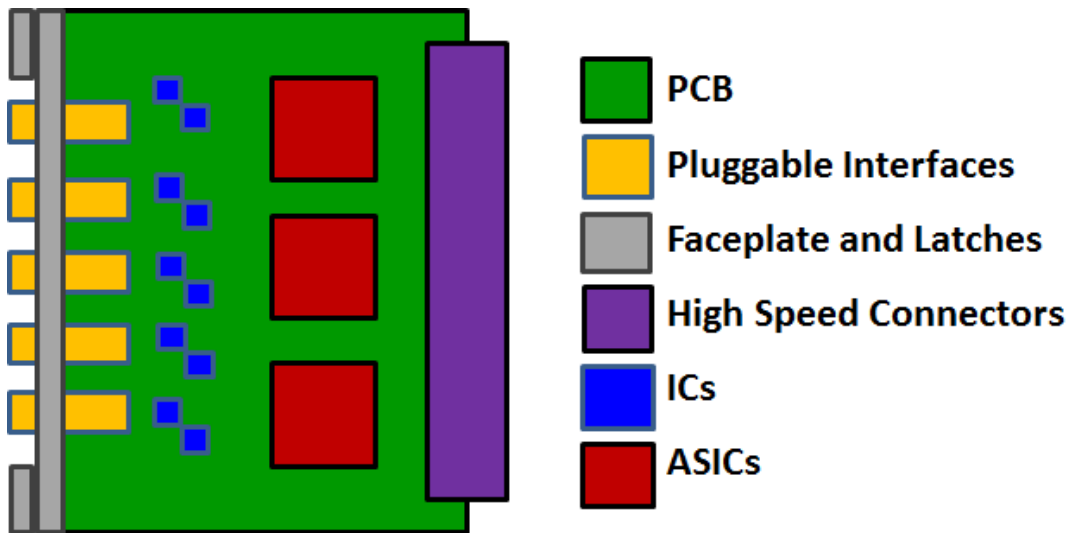


Figure 3.2: Line Card Schematic Block Diagram (Top View)

The line cards are always innovating in order to increase data transfer rates which are in high demand due to higher resolution video, greater volumes of data, and streaming services demanded by the public. As the capabilities of the line cards increase, the number of electrical components on their PCBs also increases. The power of each individual component also increases. As a result, line cards are getting denser with components that output more power.

Greater power components emit more heat, which must be removed from the system in order for the line cards to function and not overheat. Forced convection using air as the fluid medium is typically used, and achieved using cooling fan units.

3.1.3 Cooling Fan Units

Cooling fan units in telecom shelves can be either:

- “Push” systems: fans are placed at the air intake and “push” inlet air across the line cards in order to cool them
- “Pull” systems: fans are located downstream of the line cards and create an area of low pressure on the opposite side of the air inlet. This “pulls” air across the cards, which is more reliable, and provides more uniform cooling.

In either case, increased line card power, means more cooling must be provided. In the case of a system that is being upgraded to accept higher power line cards, more cooling must be achieved using the same form factor fan unit.

The cooling fan unit in question consists of four in-line 92mm axial fans in a sheet metal enclosure with a connector at the rear of the unit which interfaces with the fan power backplane in the shelf. The fan unit is secured to the shelf at the front of the unit with a lever latch, which fastens to the front of the fan to secure it once the fan is inserted into its shelf slot. Figure 3.3 below shows these features in detail. Figure 3.4 shows the fan units mated in the shelf slots in the top row in the upright position and the bottom row in the inverted position.

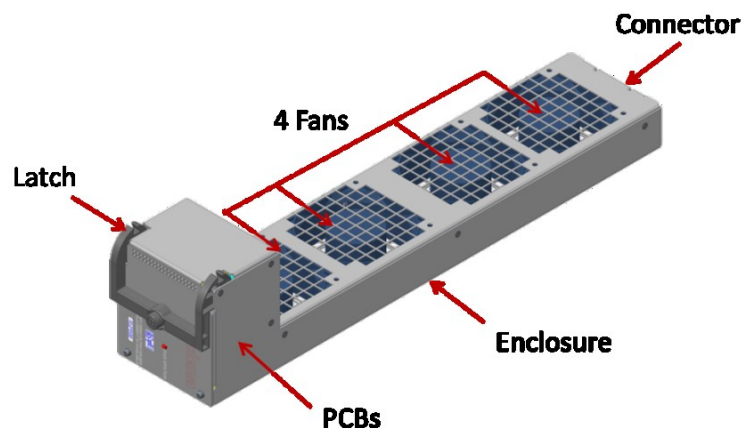


Figure 3.3: GEN1 Fan Unit Components

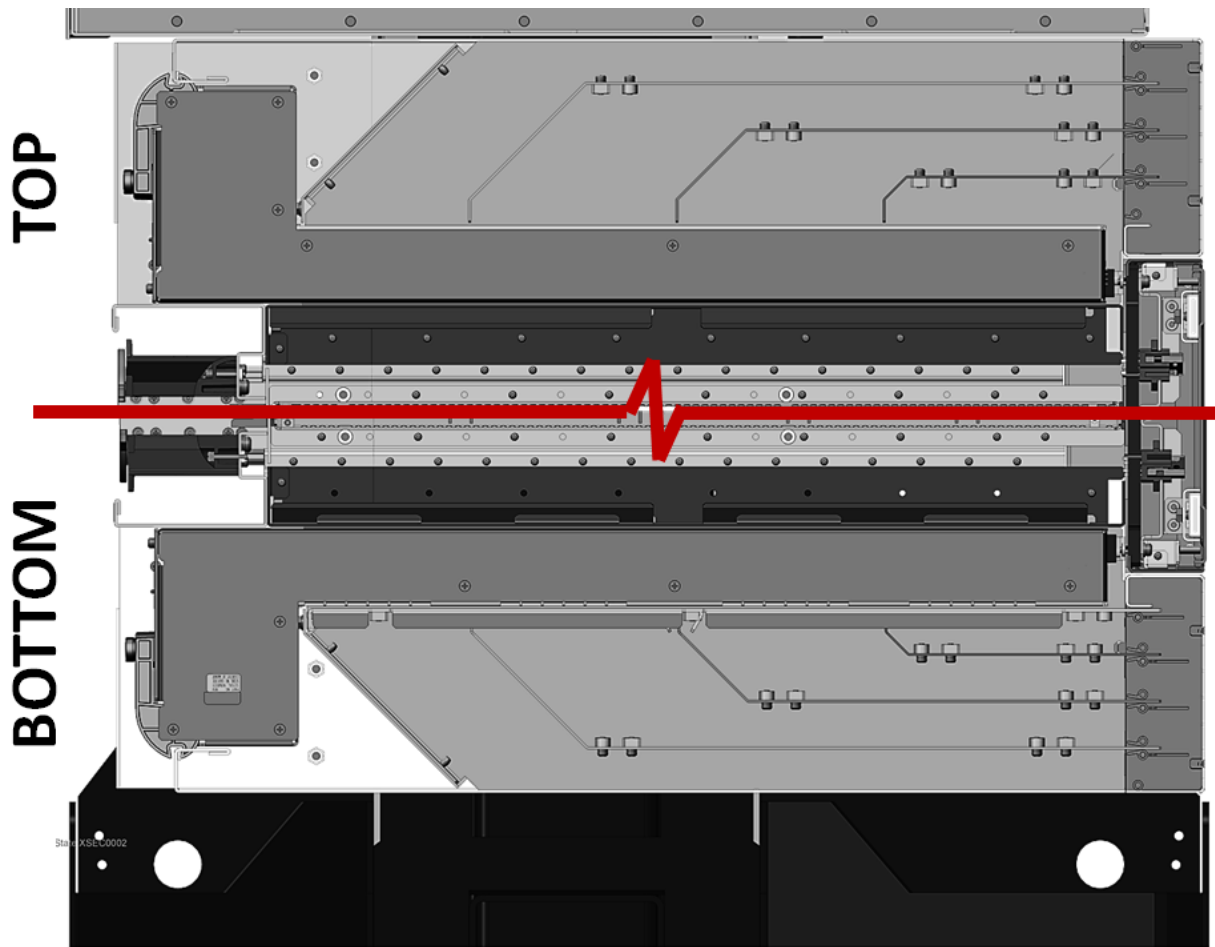


Figure 3.4: Top and Bottom Fan Orientations: Broken Section View

The GEN1 fan unit that was in service at the start of this design process was equipped with 8,000 rpm fans secured to the sheet metal chassis at four corner flanges on the inlet side of the fan using #4 flat head screws. This provided a rigid connection between the fans and the sheet metal chassis. Figure 3.5 shows details of the screwed connection.

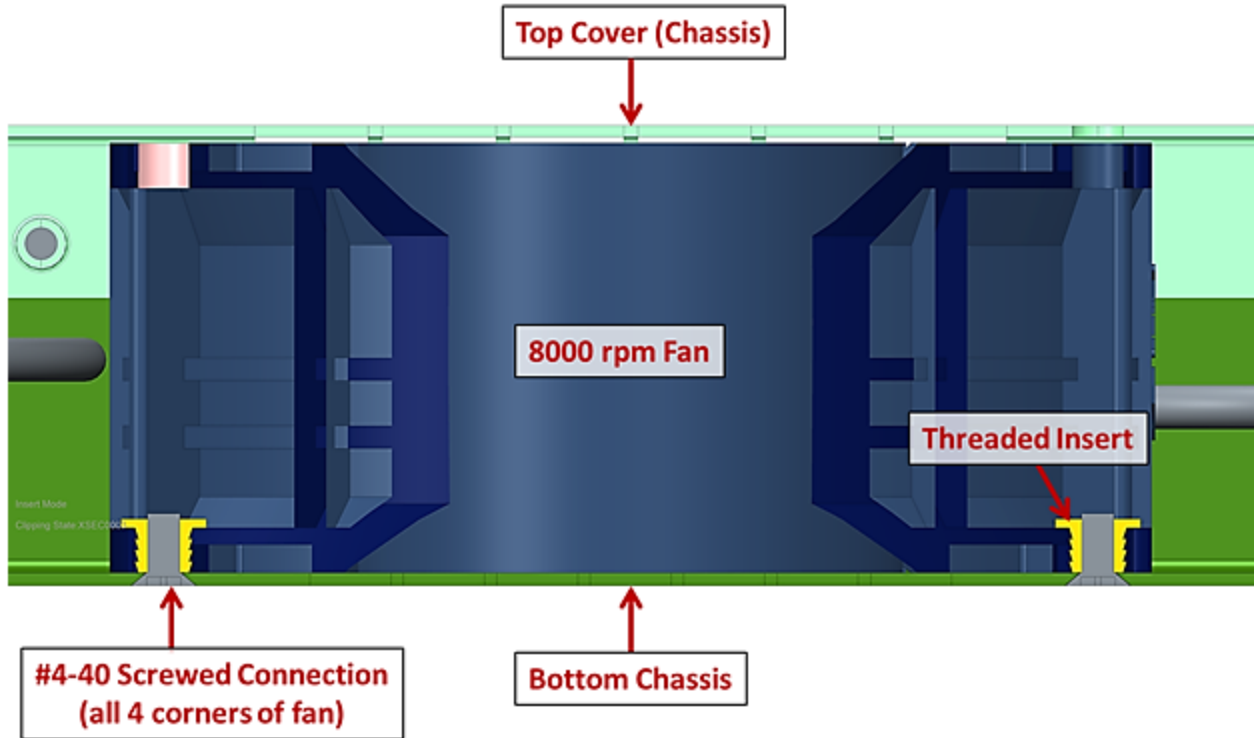


Figure 3.5: GEN1 Fan Unit Screwed Connection: Section View

The fan connector on the fan unit consists of four power blades, two pairs located on either side of a 3x4 array of signal pins as shown in Figure 3.6.

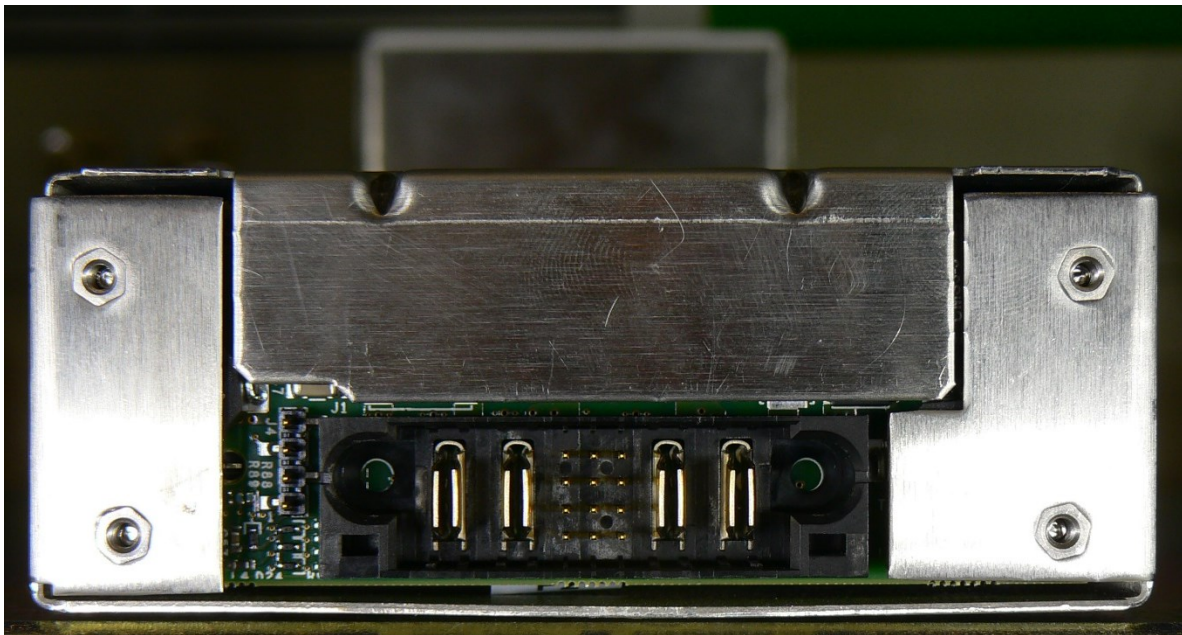


Figure 3.6: Fan Unit Connector Detail

3.2 Design Requirements

3.2.1 Background

In mid-2013, internal reports from test labs based in the USA as well as Ottawa, ON showed that shelves were losing communication with their fan units. When this happens:

- the fans show a red LED on their front faceplate status indicator
- the fans accelerate to maximum speed (8,000 rpm)
- the fans can no longer be controlled by the standard open loop controller by the user command console

Initially, this was thought to be a potential mechanical tolerance loop issue, where if the shelf components were sufficiently manufactured out of tolerance or at an extreme end of the tolerance limits, the fan connector would no longer engage with the mating connector on the backplane. This would result in no connector wipe. A tolerance analysis (see Appendix D) was conducted in order to eliminate this possible cause.

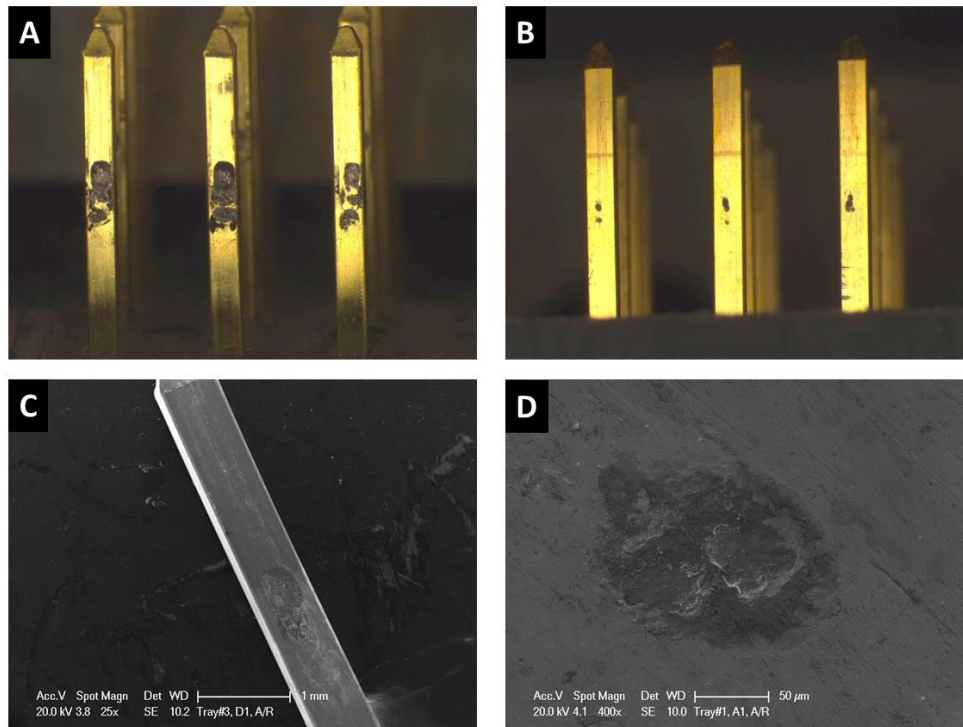


Figure 3.7: Optical and SEM Micrographs of Fretting Corrosion Initial Samples; A: Fan Tray #1 OM (mag. & scale unspecified); B: Fan Tray #2 OM (mag. & scale unspecified); C: Fan Tray #1 SEM SEI 20 keV, 25x; D: Fan Tray #2 SEM SEI 20 keV, 400x

It was subsequently found that the fan connector was developing patches of fretting corrosion on the signal pins that send communications between the fan and the shelf, which was hypothesized to be a result of excessive fan vibration. This theory was confirmed by the connector vendor as well as our internal interconnect subject matter expert. Figure 3.7 shows the initial images acquired from two initial known bad fans analyzed as supplied by the connector vendor.

The mating female connectors on the shelf's power backplane make contact with the fan pins using two oval-shaped contacts located on either side of each fan signal pin. This is the point which contacts the fan pin and creates the fretting corrosion marks seen above.

As a second point of validation, the chemical composition of the base metals of the connector contacts as well as the worn sections was performed. This was done by way of energy-dispersive X-ray spectroscopy (EDX). The plots generated show the characteristic energy given off by each element present due to an incident X-ray bombardment.

EDX was conducted by colleagues at the Ciena Ottawa Microscopy Lab on the:

- female signal pin contact from the backplane connector
- male signal pin from the fan connector
- female power blade contact from the backplane connector
- male power blade contact from the fan connector

Figure 3.8 shows the SEI micrograph of the female signal pin contact from the backplane connector indicating the sampled regions. Figure 3.9 shows the chemical composition of the fretted contact region and Figure 3.10 shows the chemical composition of the undamaged base metal of the connector.

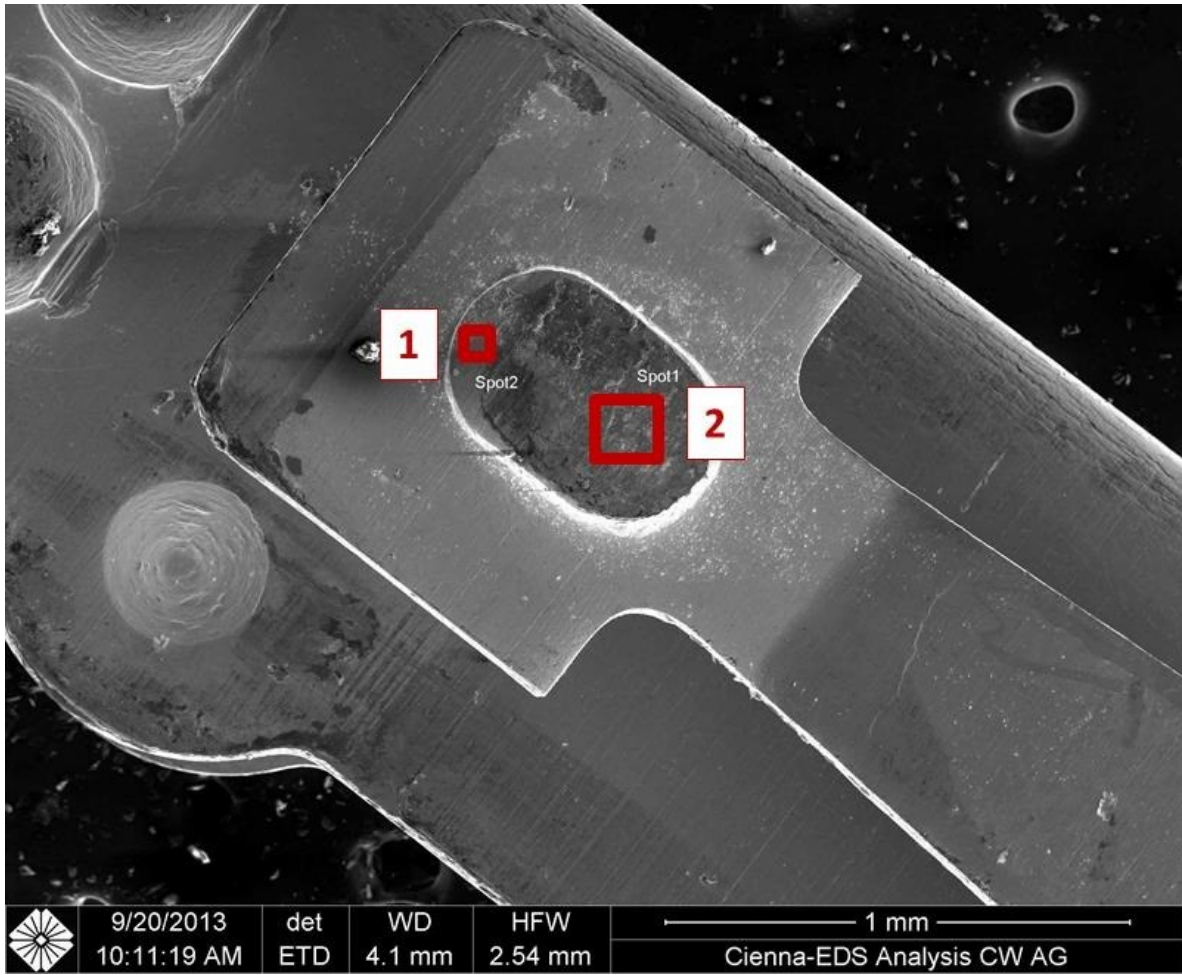


Figure 3.8: SEM SEI Backplane Female Signal Pin Contact. EDX Locations Indicated; #1: Unworn Contact Region; #2: Worn Contact Region

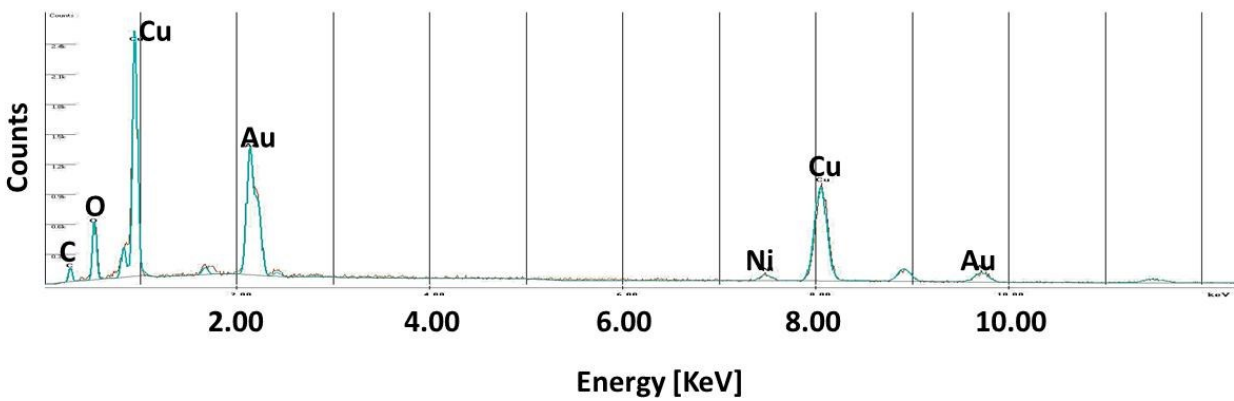


Figure 3.9: SEM EDX of Loc. #2 Worn Region of the Backplane Female Signal Pin Contact

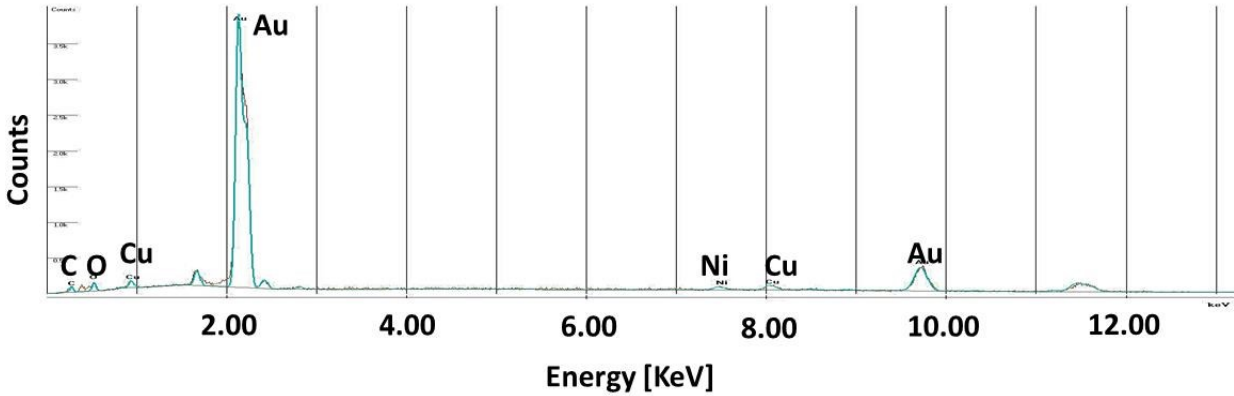


Figure 3.10: SEM EDX of Loc. #2 Unworn Region of the Backplane Female Signal Pin Contact

The differences between the worn and unworn regions are clear. The unworn region shows primarily gold with trace amounts of copper, nickel, oxygen, and carbon. The worn region shows primarily copper (the base material of the contact), with a smaller amount of gold and oxygen, and trace amounts of nickel and carbon. The other contacts and tested locations show similar characteristics with varying amounts of the secondary elements and other primary elements such as palladium on the power blades (see Appendix C). These results imply that fretting corrosion is the cause of the signal loss.

To determine if this vibration-induced fretting corrosion were an isolated, or a systematic problem, all the fans units in shelves in the software and test labs in the Ottawa facility were inspected. An optical microscope was used for inspection to look for fretting corrosion, or any signs of the onset of fretting corrosion. It was found that 96% of the sample size of 78 fan units showed signs of fretting corrosion or onset of fretting corrosion (see Table 13.1 Appendix E). This demonstrated that the problem was systematic. Additional reports from customer sites further confirmed the observations.

3.2.2 Design Requirements

Prior to the problem discovery above, the line cards of the affected system were also increasing in power such that greater heat transfer would be required to cool them (section 3.1.2). Thermal analysis conducted by Ciena’s thermal engineers (using *Flotherm*) determined that in order to use the line card powers proposed, a second generation fan unit (GEN 2) with greater airflow characteristics and thus heat-removing capacity was required.

The fans chosen to replace the GEN1 8,000 rpm fans were the same form factor but with a maximum speed of 13,000 rpm. The 13,000 rpm GEN 2 fan chosen had the same form factor as the 8,000 rpm fan at 92 mm x 92 mm x 38 mm. Since a vibration problem was already present, this complicated the solution, since the vibration levels would be expected to increase to the square of the rotation speed, the imbalance force $F_{Imbalance}$ is given by:

$$F_{Imbalance} = I_m r \omega^2 \quad (2)$$

where I_m is the mass of the imbalance, r is the radius of the imbalance mass from the axis of rotation, and ω is the rotational speed of the fan [rad/s] [19].

Because the GEN1 fan unit is already deployed at customer sites and the GEN 2 fan units will be deployed in a system upgrade scenario only, two fan units must be designed:

- GEN1:
 - 8000rpm fans
 - All existing internal PCBs and general architecture must remain unchanged
 - Sheet metal of the chassis may be altered but not fundamentally changed
 - Fans are not to be changed or modified in any way
 - Must fit within the current fan unit slot in the shelf
- GEN2:
 - Higher speed fans to meet increased airflow requirements
 - Entire internal architecture to be redesigned from scratch
 - Sheet metal of the chassis may be altered but not fundamentally changed (more flexibility than for GEN1)
 - Fans can be modified if needed
 - Must fit within the current fan unit slot in the shelf

These fan units must have a lower level of vibration such as to prevent fretting corrosion.

GEN1 Envelope and Clearances

The GEN1 has the following critical dimensions as outlined in Figure 3.11.

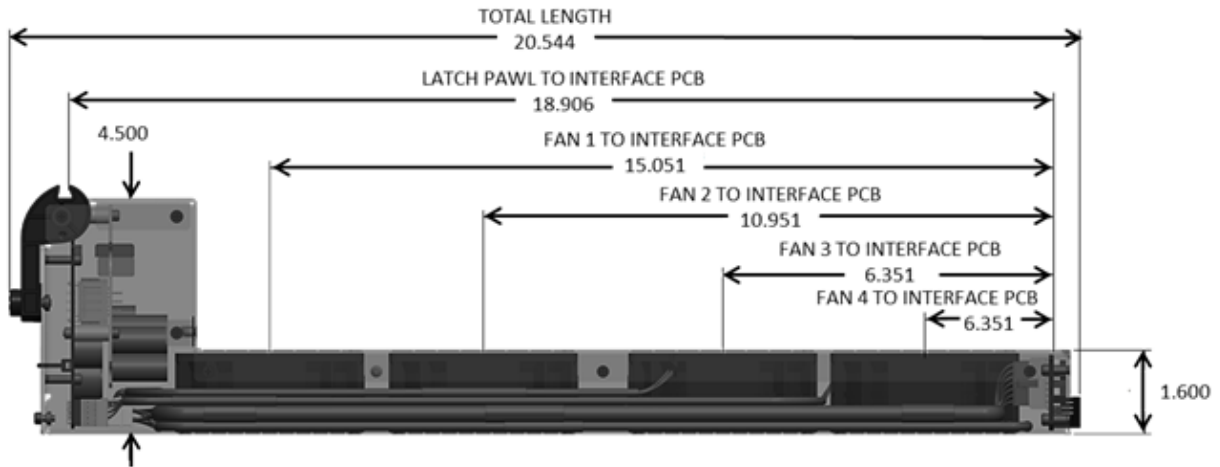


Figure 3.11: GEN1 Critical Dimensions (side) [inches]

Not pictured in the above image is fan width, which is given as 4.124 in. The general dimensions outlined here must be adhered, but they do have some freedom to change based upon the current clearance between the fan unit and the shelf mating slot. Making use of this additional space may be necessary during the design process in order to increase the number of available vibration reduction solutions.

The clearances between the shelf and the GEN1 in its fully mated state are given in Figure 3.12.

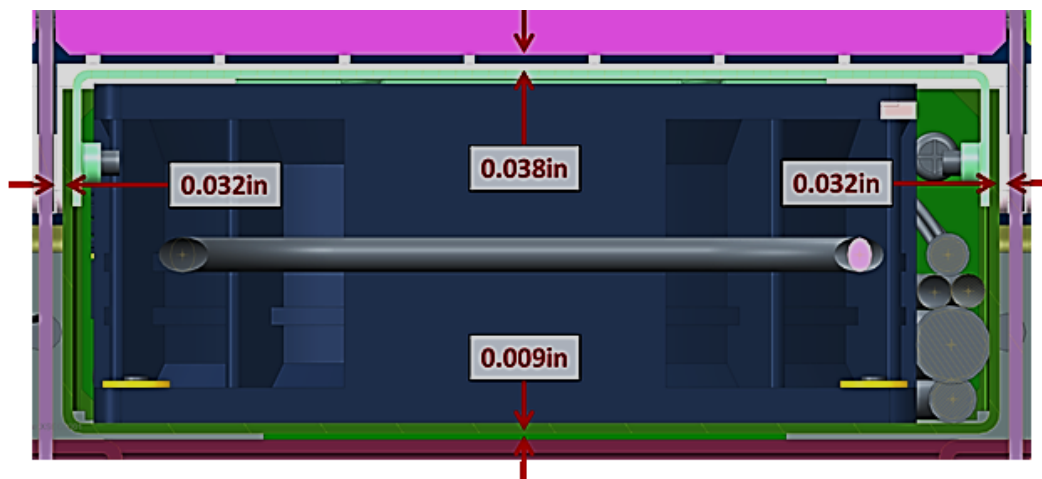


Figure 3.12: GEN1 to Shelf Clearances

Another important dimension relating to the GEN1 is the PCB spacing, the amount of connector “wipe” and distance to connector “crash” that exists. Figure 3.13 below shows a simplified block diagram of the fan connector mating with the backplane connector (the image is a side view, oriented in the same plane as in Figure 3.11. The terms are as defined below:

- **PCB spacing:** the distance between the inside faces of the mating PCBs
- **Nominal connector wipe:** the distance from the tip of the mating pin to the centre of the female contact points of the mating connector
- **Distance to connector crash:** the distance between the mating surfaces of the connectors. A crash situation occurs when this distance is zero, and the connectors are mated to their maximum insertion.

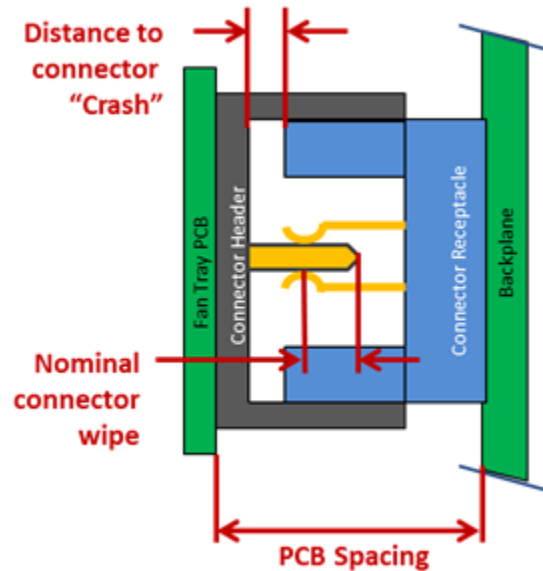


Figure 3.13: Signal connector block diagram defining connector wipe and connector crash

The connector manufacturer specifies the optimal mating position for their connectors typically in a crash scenario. The manufacturer specified nominal wipe and PCB spacing are given in Table 3.1 below along with the actual spacing that exists in the design with the GEN1.

Table 3.1: Connector wipe and PCB spacing GEN1 vs. connector manufacturer

	PCB Spacing (in)	Nominal Wipe (in)
Connector Manufacturer	0.675 ±0.009	0.152
GEN1	0.745	0.070

In the current design, only about half of the nominal wipe available is being used.

UL-94 Flammability Standard

Flammability standards are important in telecom equipment. The industry standard for materials used in telecom is UL-94. The important test is UL-94-V where the material must achieve a V0 rating (the most stringent in the test) [45], [46].

Specifically, the UL-94-V test evaluates burning, dripping, and afterglow times of a test sample that is subject to repeated flame application [45], [46]. Afterglow is the smouldering combustion still present on a material after a flame is removed [47].

Any material of off the shelf (OTS) parts must specify what flammability standard they adhere to, and provide documentation to certify that.

For reference, the test performed to achieve a UL-94-V0 rating is as follows [45], [46]:

1. Pre-treatment of sample:
 - a. 2 days / 23 °C / 50% relative humidity
 - b. 7 days / 70 °C / hot air oven
2. Apply flame with 20 mm high Tirill burner flame for two 10s intervals, where the second flame is applied once the specimen extinguishes from the first application or immediately if sample does not ignite.
3. The test sample must meet the following requirements:

Table 3.2: UL-94-V0 Flammability Test Performance Requirements [45], [46]

Burning time after flame application (s)	≤10 s
Total burning time (s) (10 flame applications)	≤50 s
Burning and afterglow times of specimens after second flame application (s)	≤30 s
Dripping of burning specimens (ignition of cotton batting)	NO
Specimens completely burned	NO

Telcordia GR-63-CORE 4.6 Acoustic Noise

Telcordia is an entity that creates standards pertaining to the telecommunications industry. The main standard that pertains to mechanical design is *Telcordia General Requirements (GR) 63-CORE NEBS Requirements: Physical Protection* [48]. This document gives the minimum “spatial and environmental criteria” for all telecom equipment used in most central offices (CO) and other telecom equipment deployment spaces [48].

The main section that pertains to the current fan redesign is section *4.6 Acoustic Noise* [48]. This section standardizes the acceptable noise level of a piece of telecom equipment as it exists under its standard operating conditions (see Table 3.3 as cited directly from the *GR-63-CORE*), and not the worst case [48]. The worst case should be documented and provided in the certification, but no limit is set for this noise level.

Table 3.3: Telcordia GR-63-CORE 4.6 Acoustical Noise Emissions Limits [48]

Environmental Description	Declared Sound Power Level $L_{WA,d}$ (dB)	Temperature* (°C)
Equipment to be Located in Telecommunications Room (attended)	78	27
Equipment to be Located in Telecommunications Room (unattended)	83	27
Equipment to be Located in Power Room	83	27

These levels must be taken into consideration during design but the vibration reduction is the primary concern. Passing *GR-63-CORE 4.6* is more of a concern after the product has been developed and reaches regulatory testing.

OSHA 29 CFR Part 1910.95 Occupational Noise Exposure

The *US Federal Government Occupational Safety & Health Administration* has a standard for acoustic noise that is permissible to be exposed to without hearing protection [49]. This is given by *OSHA 29 CFR Part 1910.95 Occupational noise exposure* [49]. This standard is of less concern since it does not provide a hard limit that the design must adhere to [49]. The noise level emitted by the fan units and upgraded shelf can emit greater noise levels than indicated by *1910.95*, this is not a design consideration. It is more important just to be aware of this standard’s existence [49].

Final Design Criteria

The final design criteria are outlined in Table 3.4 below.

Table 3.4: GEN1 & GEN2 General Fan Unit Solution Design Criteria

Design Criteria	Target Value or Associated Standard
Reduce vibration caused by fan rotation to or below “safe” limit	To Be Determined
Required Fan Dimensions {Quantity}	92x92x38 mm {4}
Materials used must meet industry specified flammability rating	UL-94-V0
Decrease fan unit noise level as much as possible	Telcordia GR-63-CORE 4.6 OSHA 29 CFR Part 1910.95
Keep same fan unit form factor (solution must fit within current constraints taking manufacturing tolerance into consideration)	N/A
Cost to be reduced only if performance is not sacrificed	No Limit
Ensure fan unit is safe to handle and operate	N/A

3.2.3 Research Objectives

The main goal of this thesis is to reduce the vibration level of the fan units to an acceptable level, yet to be determined, to prevent fretting corrosion from occurring. This must be done with the required fan dimensions and UL-94-V0 rated materials. All other design criteria are important, but secondary to the main objectives.

Ultimately, the goal is to prove that the vibration reduced fan units meet or exceed the target vibration value and to prove that fretting corrosion will no longer occur. These goals may not be entirely achievable, but all efforts will be made to attempt to do so.

Chapter 4 Experimental Methods

This chapter outlines the experimental methods used during the design and testing of the fan units. All relevant equipment employed, including manufacturers and models, is detailed and schematics are provided where required. The methods described in this section describe fundamentally how the vibration tests were conducted and how data was acquired and processed.

4.1 Fan Vibration Data Acquisition

The goal of the vibration testing data acquisition is to measure the vibration levels in three axes at the fan unit connector, or another reference surface in the case of individual fan testing. The output obtained as data is acceleration and time, which is output in a spreadsheet format for each data point or test conducted. This data can then be post processed in order to obtain certain desired results.

4.1.1 Materials and Methods

The equipment required to conduct vibration tests on fan units is detailed below.

- Data Acquisition Unit: *Measurement Computing USB-1608GX*
- 3-Axis Accelerometer: *Ciena* custom PCBA using *Analog ADXL 325 ±5 g* Accelerometer Chip (Figure 4.1 and Figure 4.2). This will be used to measure vibration levels on the fan connector. This was designed by a colleague.
- *3M* Adhesive Transfer Tape #*9485PC*
- Fan or Fan Unit(s)
- Test Fixture:
 - Telecom shelf
 - Benchtop test fixture (designed by colleague mentor)
- Flathead screwdriver #0
- Philips head screwdriver #1
- Scissors
- Laptop with the following software:
 - *Matlab R2012a* or higher (32 bit only)
 - *MCCDAQ* Software and related drivers

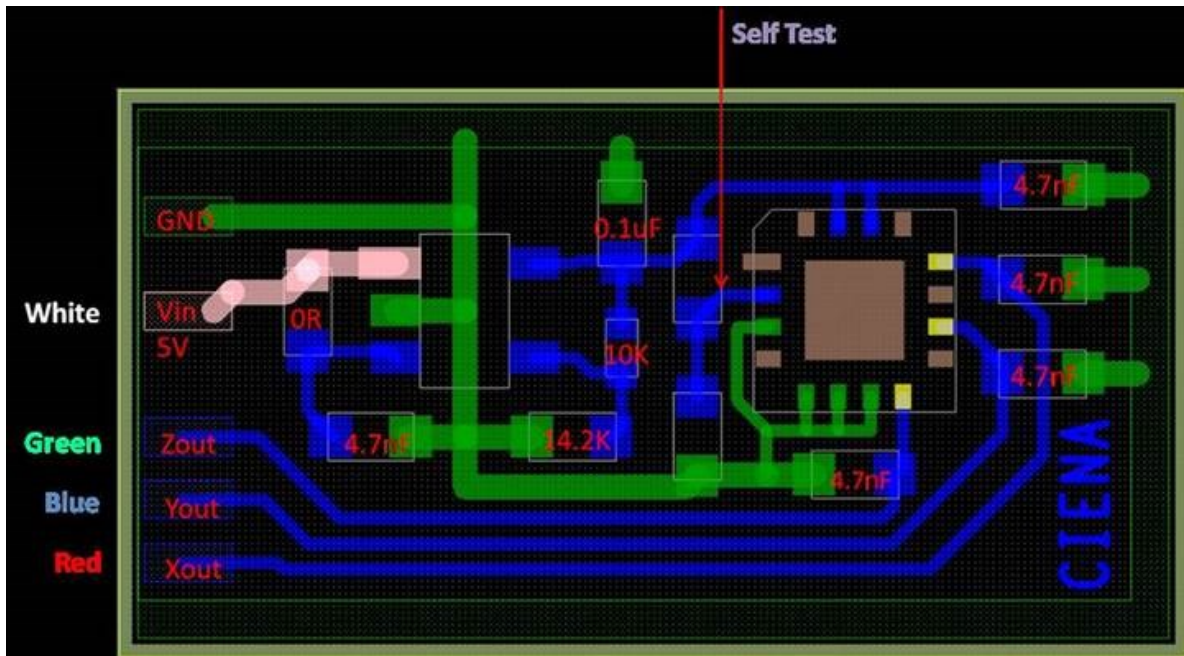


Figure 4.1: 3-Axis Accelerometer Schematic (Top View)

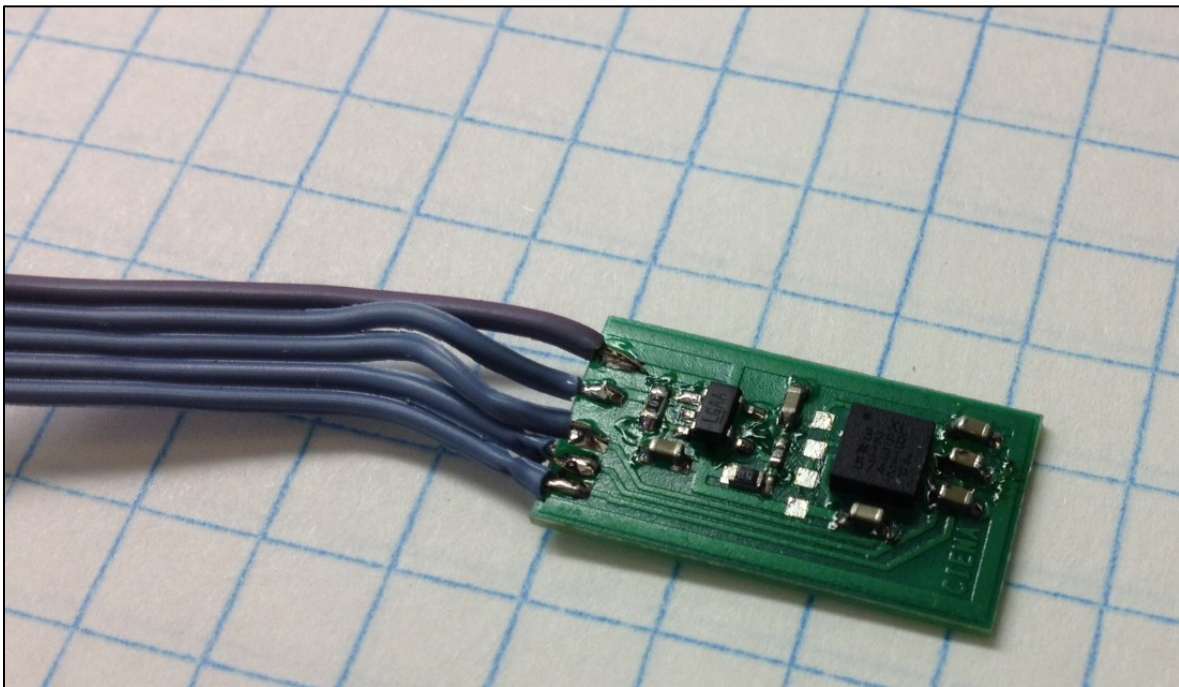


Figure 4.2: 3-Axis Accelerometer

4.1.2 Test Procedure for Data Acquisition

This section will give a general overview of the steps performed to acquire raw vibration data. The detailed step-by-step test procedure for acquiring data is outlined in detail in Appendix A. The first step with any test was to decide upon the test conditions and the variables to be tested, and the fan speeds at which to test. Once this was determined and the fan or fan unit configured based on the decided conditions, it was then instrumented by adhering the accelerometer to the fan connector shroud of a fan unit (Figure 4.3), or the top of the test jig (Figure 4.4) if an individual fan test were to be performed. The accelerometer was wired to a data acquisition box connected to a computer running *Matlab*.

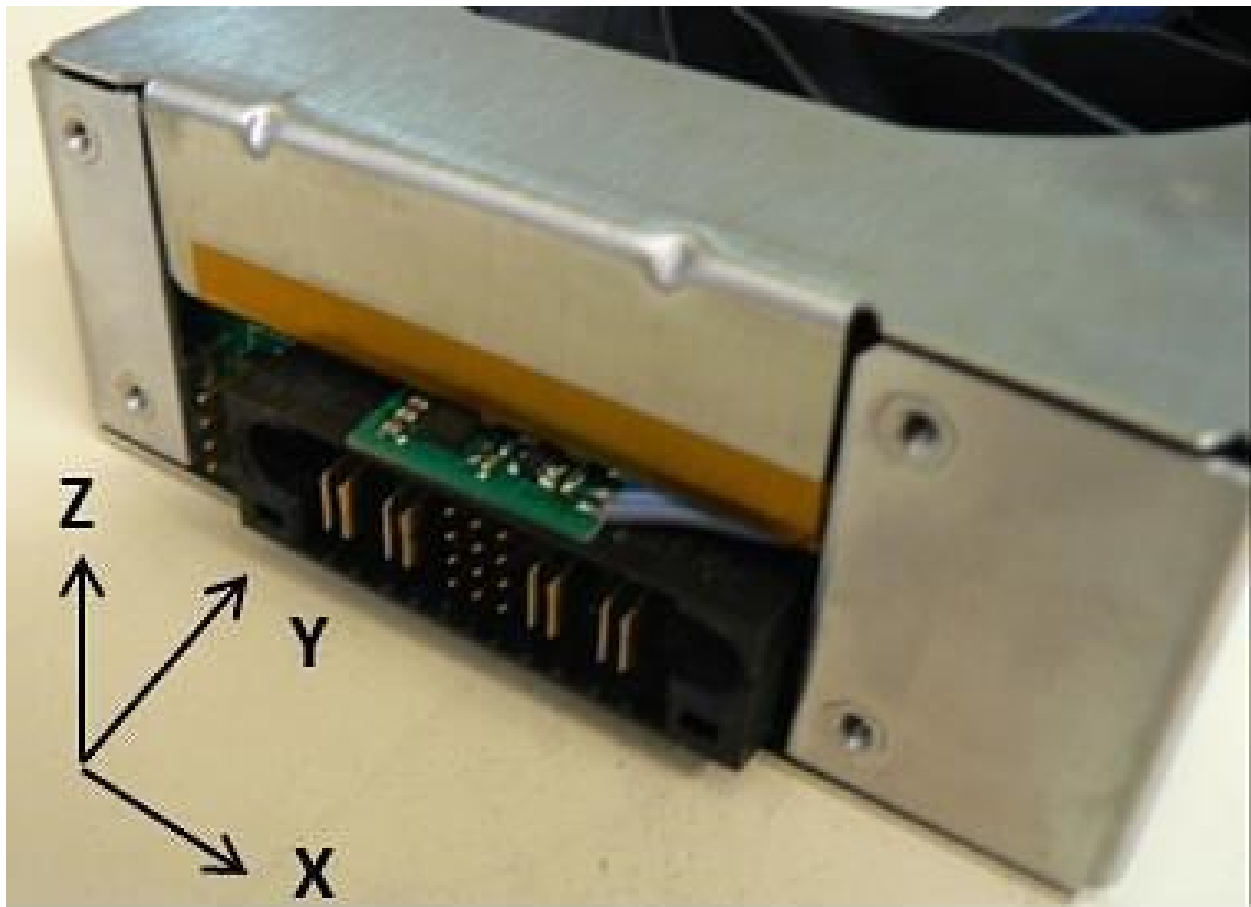


Figure 4.3: Accelerometer Placement on Fan Connector Shroud

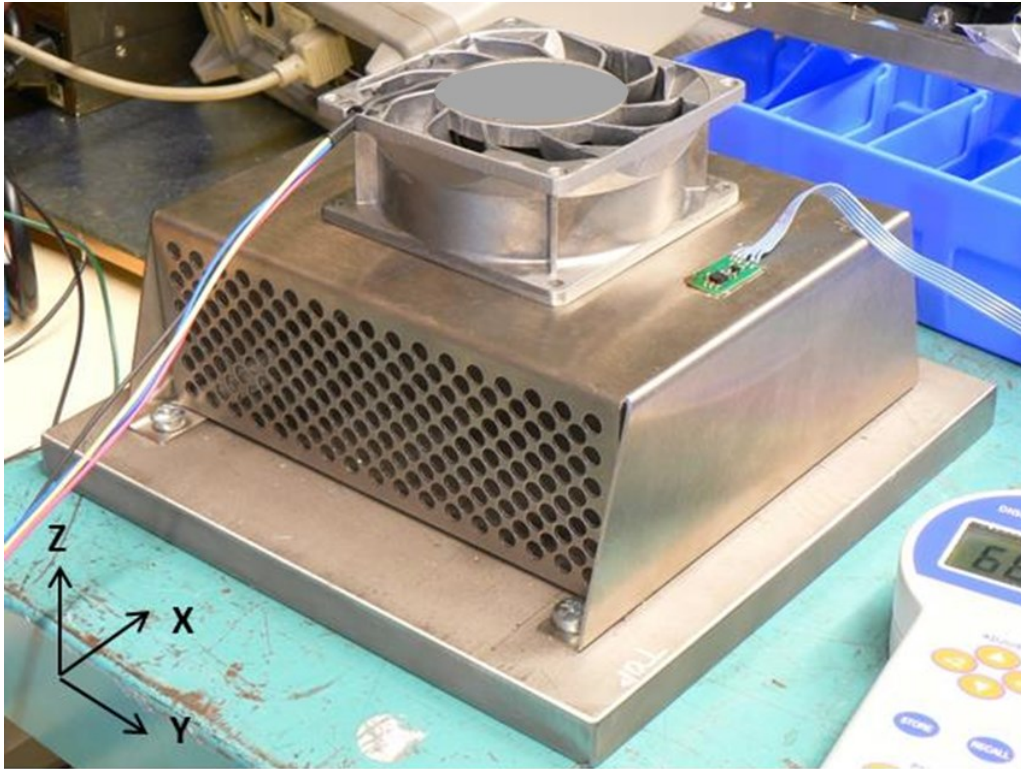


Figure 4.4: Single Fan Test Jig with Accelerometer Attached

The fan or fan unit was then set to the first speed to be tested. Once the fan(s) reached the desired speed, the speed was verified using software if in the shelf, or a stroboscope if testing an individual fan. A *Matlab* script was then run to acquire the vibration data at a rate of 8333 Hz for 20 s. The raw data was output to a spreadsheet, the columns with vibration data in millivolts for each axis (converted to ‘g’ using accelerometer conversion factor later in post-processing) and the other for time in seconds.

This process was repeated at each desired speed and for each desired variable test condition. Data was then catalogued for post-processing.

4.1.3 Vibration Results

The raw data spreadsheet files were batch post-processed using a *Matlab* script that would take the raw data and convert it to acceleration ‘g’, plot the acceleration vs. time data for each axis, produce an FFT for each axis, and output the RMS vibration value for each axis. Typical output data were presented as shown in Figure 4.5 (for simplicity, the X-Axis only is shown).

Filename: Accelerometer
Sample Frequency: 8333 Hz
X Acceleration: 0.148965 g RMS
Y Acceleration: 0.195493 g RMS
Z Acceleration: 0.111572 g RMS

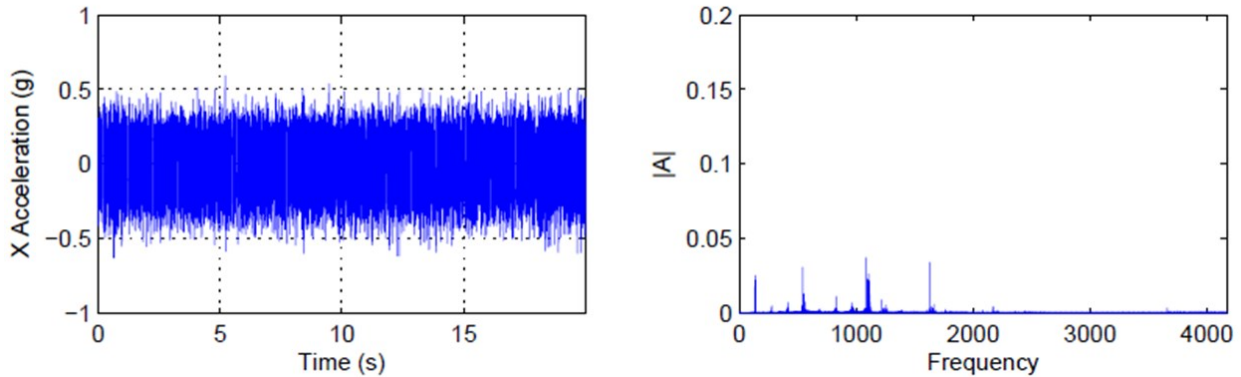
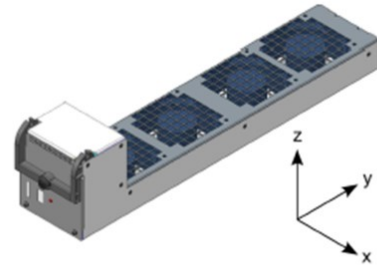


Figure 4.5: Vibration Results Post-Processing Data Format (X-Axis)

The RMS vibration data were the main indicator used as an indicator for the overall vibration level. Each RMS value for a certain speed and test condition would be used as a single point on an RPM vs. RMS acceleration (g) plot. This type of plot will be used most frequently in the rest of the thesis to present data and compare vibration levels of fans and fan units in different configurations. These plots will be presented separately for all three axes of the accelerometer.

4.2 Determining an Acceptable Vibration Level

The most significant unknown at the start of the design process was how much vibration was currently present in the shelf and what level of vibration would result in no fretting corrosion. Determining the “acceptable” level of vibration was a critical question, and not an easy one to solve.

The path chosen to do so was to find another more mature product line with a similar size shelf, with a similar size fan unit and similar fan connector system had no known history of fretting corrosion problems. Many shelves exist in the software labs that have been set up and operated continuously for several years delivering similar service to that of a customer site.

The system chosen was in service since its delivery to the software lab at Ciena Ottawa in 2008-2009, and had two fan units each with four 120mm fans (Figure 4.6). The fans had been running constantly for this period of time at nominal ambient temperature. Via OM, it was determined that no fretting corrosion was found on the fan units as shown in Figure 4.7.

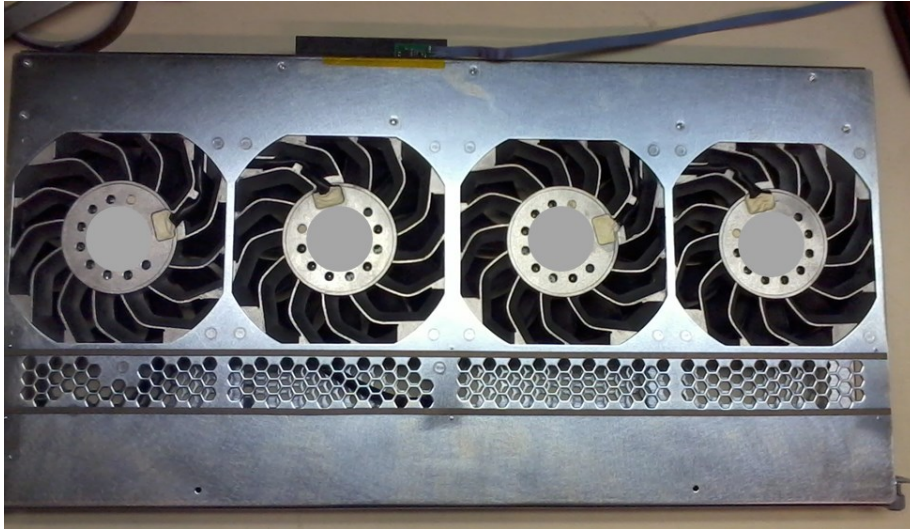


Figure 4.6: Long service life, unworn fan unit from alternate shelf product

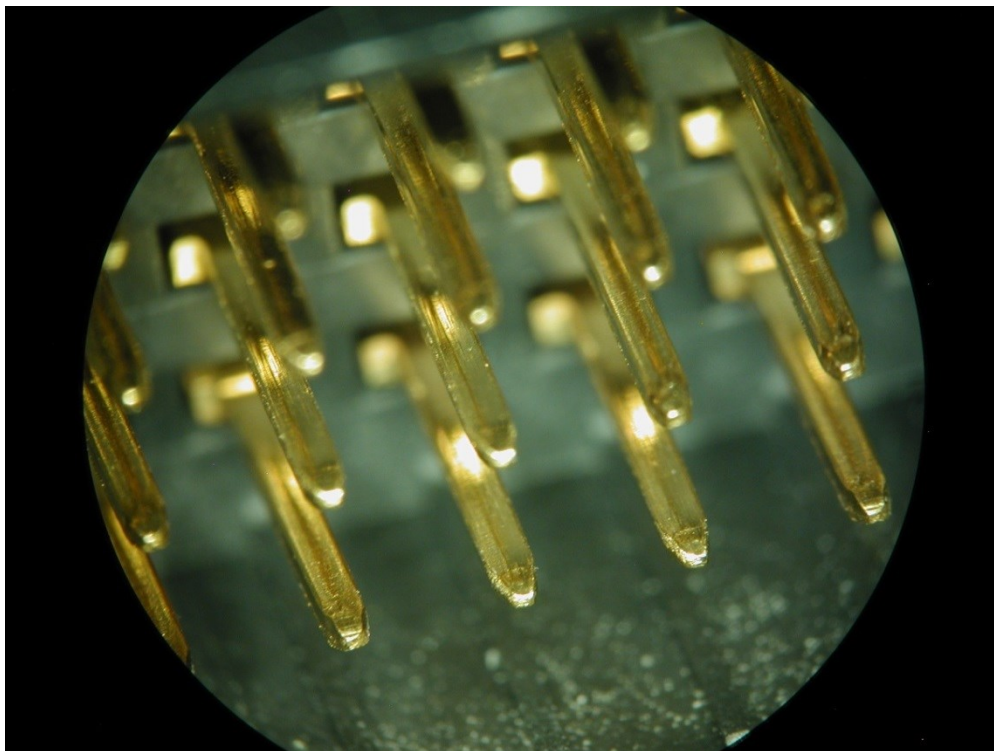


Figure 4.7: Long service life, unworn fan unit from alternate shelf product connector detail

Vibration tests were conducted on the unworn fan unit from the alternate shelf product in order to determine an estimate for an “acceptable” level of vibration. This would serve as a reasonable target vibration level for the fan unit to be redesigned. Accelerometers were placed on the connector shroud as shown in Figure 4.8.



Figure 4.8: Accelerometer placement on long service life, unworn fan unit

Various scenarios were tested on the long service life fan unit including:

1. Test *in-situ* in shelf as it had been operating (3600 rpm, standard for 27 °C ambient temperature) since it was installed in 2008-2009 [T_{amb}]
2. With one fan unit removed, which causes the other fans to run up to maximum speed (7200 rpm) [**max**]
3. Each of the above scenarios with the fan units unfastened from the shelf [T_{amb} **unscrew, max unscrew**]

Fan axes used for this text are shown in Figure 4.9.

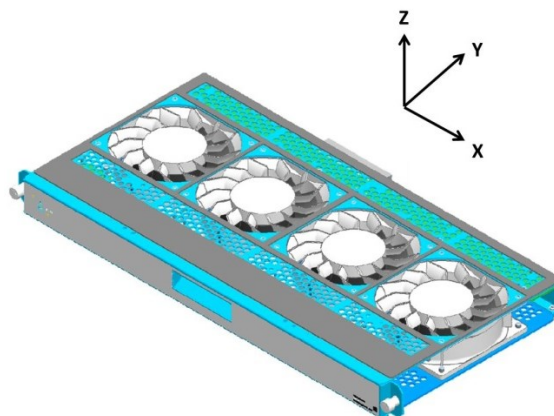


Figure 4.9: Accelerometer Axes for long service life, unworn fan unit

The results obtained are shown in Figure 4.10. The X-axis, Y-axis, and Z-axis results are shown, as well as a “Total” which represents the scalar value of the resultant average RMS vibration vector given by the vibration levels in all three axes.

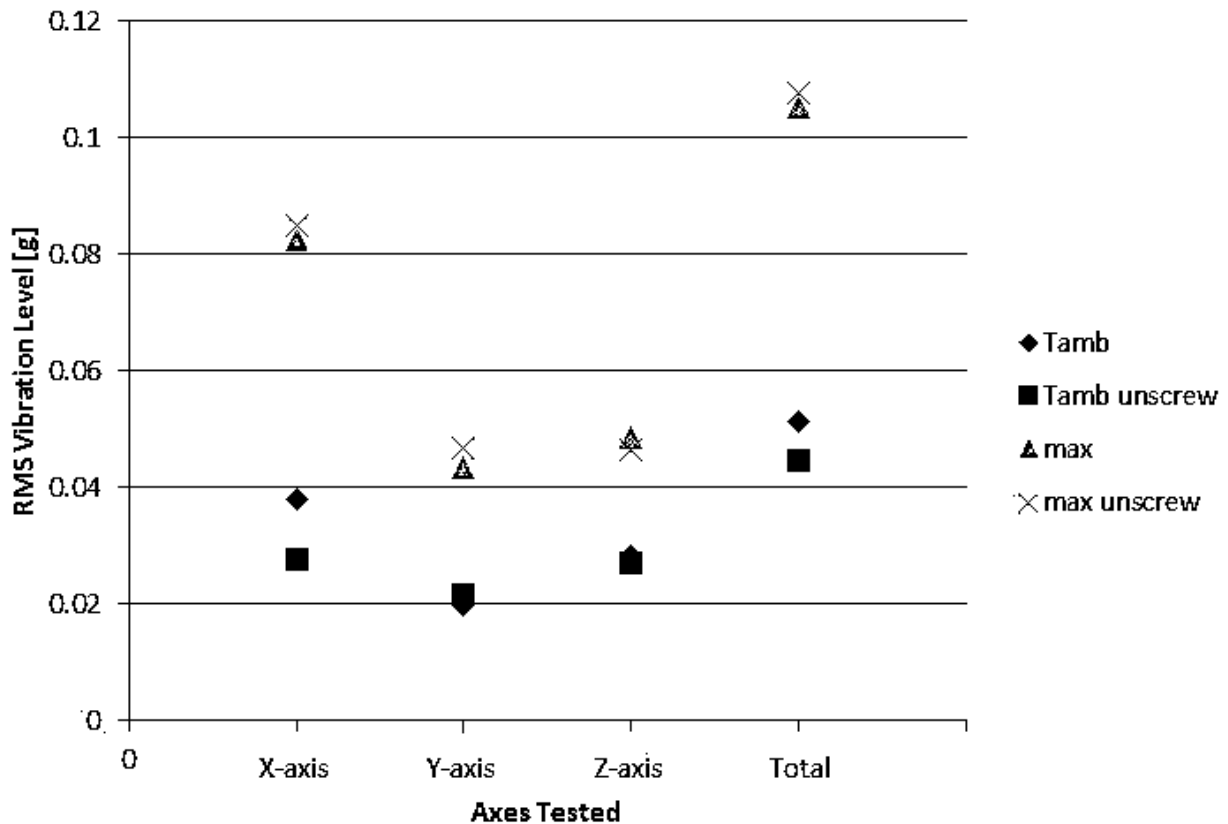


Figure 4.10: RMS Vibration levels of long service life, unworn fan unit from alternate shelf product. T_{amb}: atmospheric temperature conditions. T_{amb unscrew}: atmospheric temperature conditions with fan unit unscrewed from shelf. Max: maximum RPM. Max unscrew: maximum RPM with fan unit unscrewed from shelf

The worst case scenario described in the above figure pertains to the total RMS value when a fan unit is unseated, causing the unit in question to go to maximum rpm. This case relates to a maximum RMS vibration level of 0.1 g. This is the target value used as a maximum threshold for vibration since it was the most reliable known acceptable vibration level on a similar fan unit and connector style to date.

It is acceptable to use this 0.1 g RMS value obtained on an entirely different design from an entirely different system because:

1. The number of fans and fan speeds used in both designs is similar
2. The connector is of the same family with the same power and signal contact geometry
3. The measured value of 0.1g RMS was obtained on the connector shroud, and is the effect of the vibration in the fan unit system on the connector itself. The fan unit as a system and its specific geometry has an impact on the vibration level, but how and why the vibrations are transmitted from the fan unit system to the connector is irrelevant. This is why the 0.1 g RMS value can be transferred as a target vibration value from the alternate product fan unit to the current fan unit under consideration. For the purposes of fretting corrosion, the magnitude of vibration matters and not its connecting system, so long as the mating connectors are of similar design.

This allows the fan criteria for vibration to be updated, as indicated in Table 4.1.

Table 4.1: Updated Solution Fan Unit Design Criterion

Updated Design Criteria	Target Value
Reduce vibration caused by fan rotation to or below “safe” limit	0.1 g RMS

Chapter 5 Generation 1 Design Progression & Solution

This chapter presents the bulk of the research and design work conducted. This section begins by determining an acceptable vibration level based upon data collected from another shelf product. Vibration levels of the legacy fan unit are then determined and potential interim vibration solutions proposed and tested.

5.1 Preliminary GEN1 Vibration Testing

With a target value for maximum vibration determined, initial shelf level vibration testing was conducted on the GEN1. This would provide information on the current performance gap between the GEN1 and the desired performance.

To reduce the number of variables in the vibration testing process, the fan unit slots in the shelf used for this round of vibration testing were limited to slot #2 (upright fan unit) and slot #7 (inverted fan unit). Additionally, since the synchronization of the accelerometer axes channels was impossible to determine, they were considered individually, without a resultant scalar acceleration plot. The X-axis and Y-axis are of the greatest interest since these are in the same plane as the fretting corrosion on the connector pins.

The test was conducted in the shelf in the Power Aisle at the Ciena Ottawa Carling site. This shelf will be referred to as “Shelf_A”. A “sweep” of fan speeds was conducted using the shelf software to set fan speed with a Full Fill (FF) of all 10 fans present and operating. The range tested was 2000-8000 rpm at 500 rpm intervals for 20 s per interval. Figure 5.1 shows the results for the GEN1_1 in Slots #2 and #7. Figure 5.2 and Figure 5.3 are the Y-axis and Z-axis plots respectively.

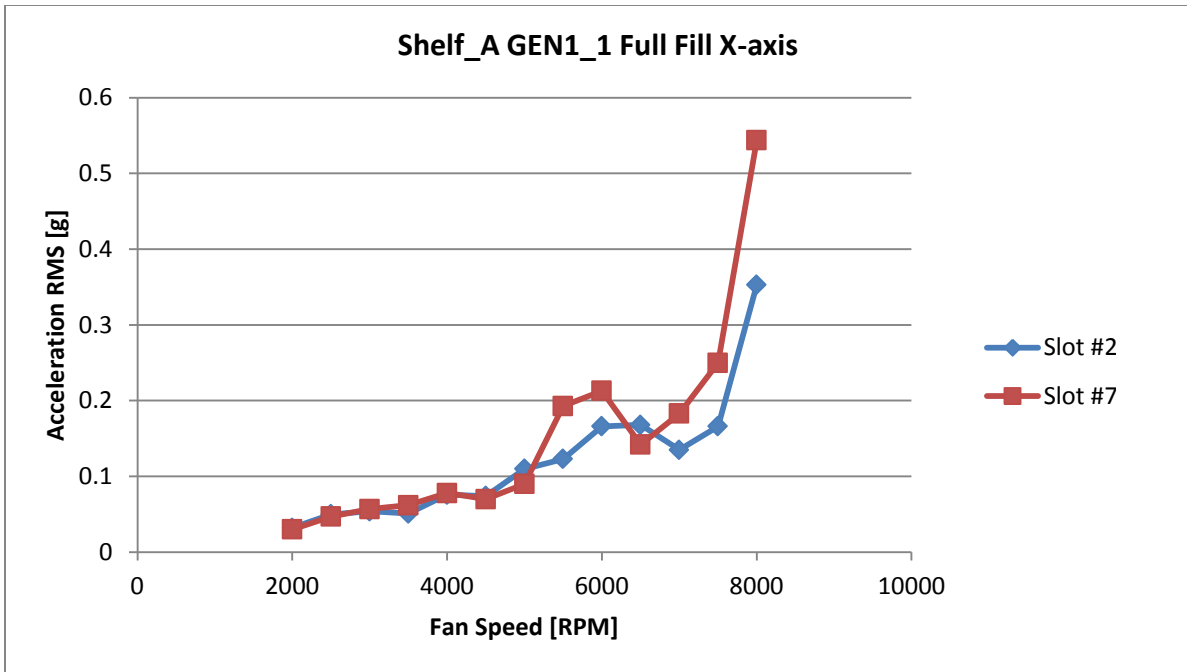


Figure 5.1: Shelf_A GEN1_1 Full Fill Sweep Vibration Test X-Axis

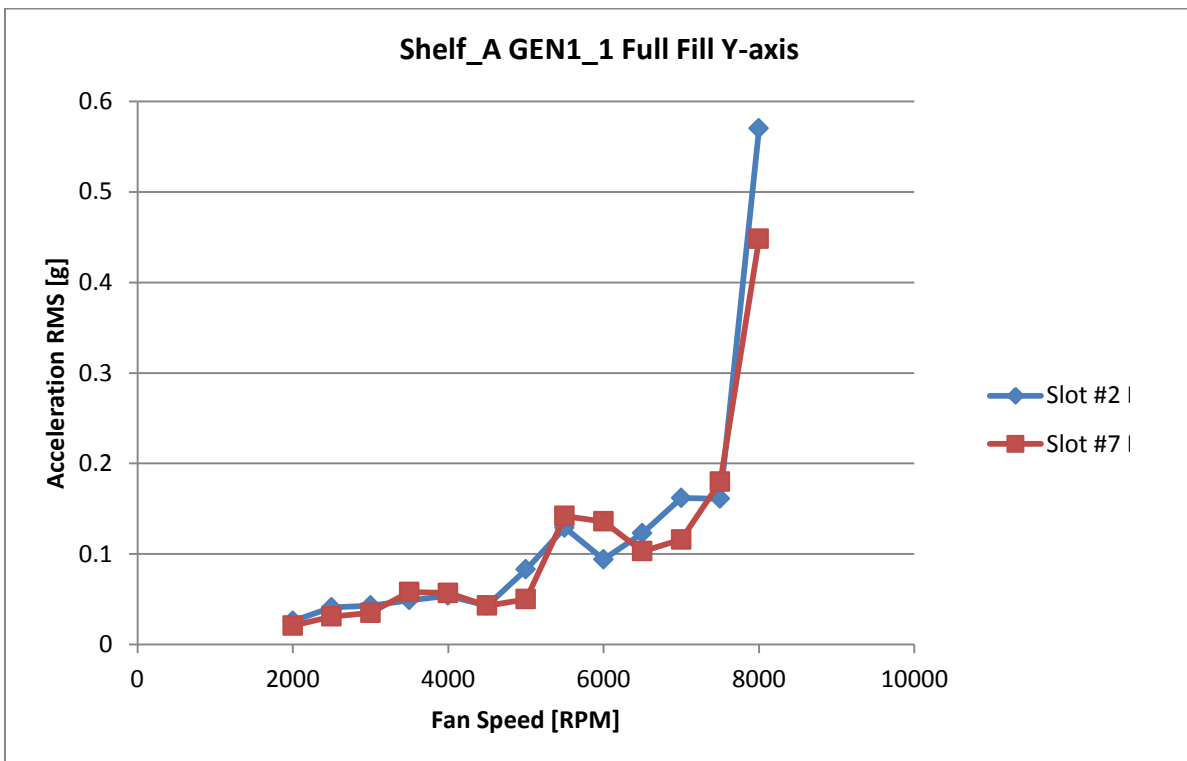


Figure 5.2: Shelf_A GEN1_1 Full Fill Sweep Vibration Test Y-Axis

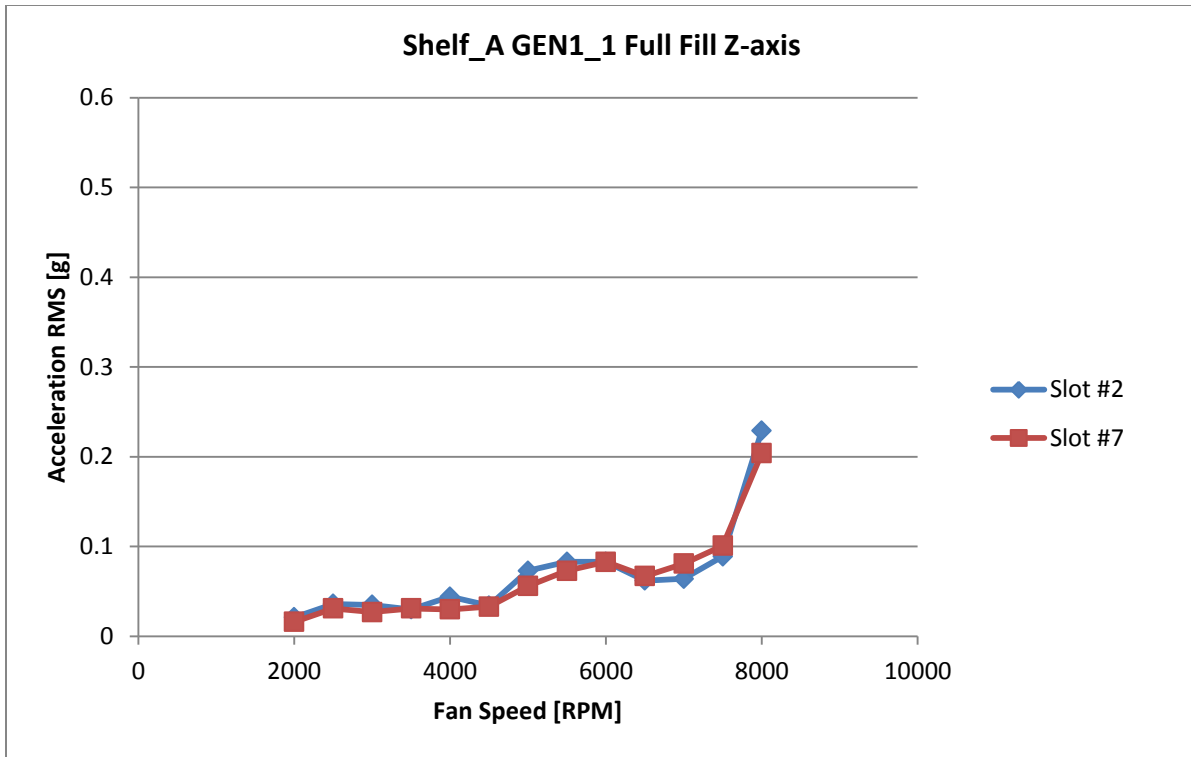


Figure 5.3: Shelf_A GEN1_1 Full Fill Sweep Vibration Test Z-Axis

These plots show that at the maximum fan speed of 8000 rpm, all vibration values exceed the target value of 0.1 g RMS. The curves show exponential behaviour, with a resonance around 5500-6000 rpm where a spike indicates higher RMS vibration levels than would be expected by a standard exponential model. With the exception of the vibration spike which is an anomaly for this design, this behaviour and vibration level is as expected.

A secondary test was performed in Slot 0 of Shelf_B. The test was conducted with a full fill of GEN1 fan units and two different GEN1 fan units (GEN1_2, GEN1_3) outfitted with an accelerometer each. The test performed was similar to the above test, but also included a second accelerometer mounted behind the mating connector on the backplane of the shelf. Additionally, the data points tested correlated directly with the fan speed vs. temperature look-up table used by the shelf software to set the fan speed (see Appendix A).

The goal of this test was to determine if the vibration levels on the backplane connector were to be factored into data sets as well as to determine the amount of variation in vibration levels between fan units. Figure 5.4 below shows all 3-axes test results for both the GEN1_2 in Slot 0

as well as the corresponding backplane connector. Figure 5.5 below shows all 3-axes test results for both the GEN1_3 in Slot 0 as well as the corresponding backplane connector.

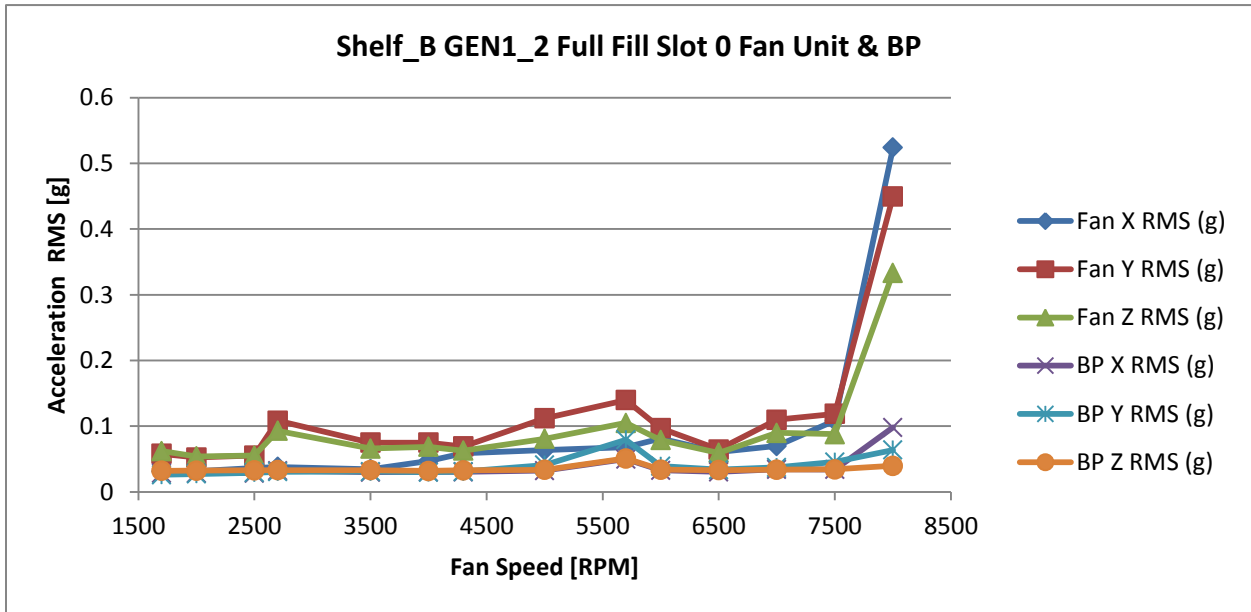


Figure 5.4: Shelf_B GEN1_2 Full Fill Sweep Vibration Test Slot 0 with Backplane (BP) Accelerometer

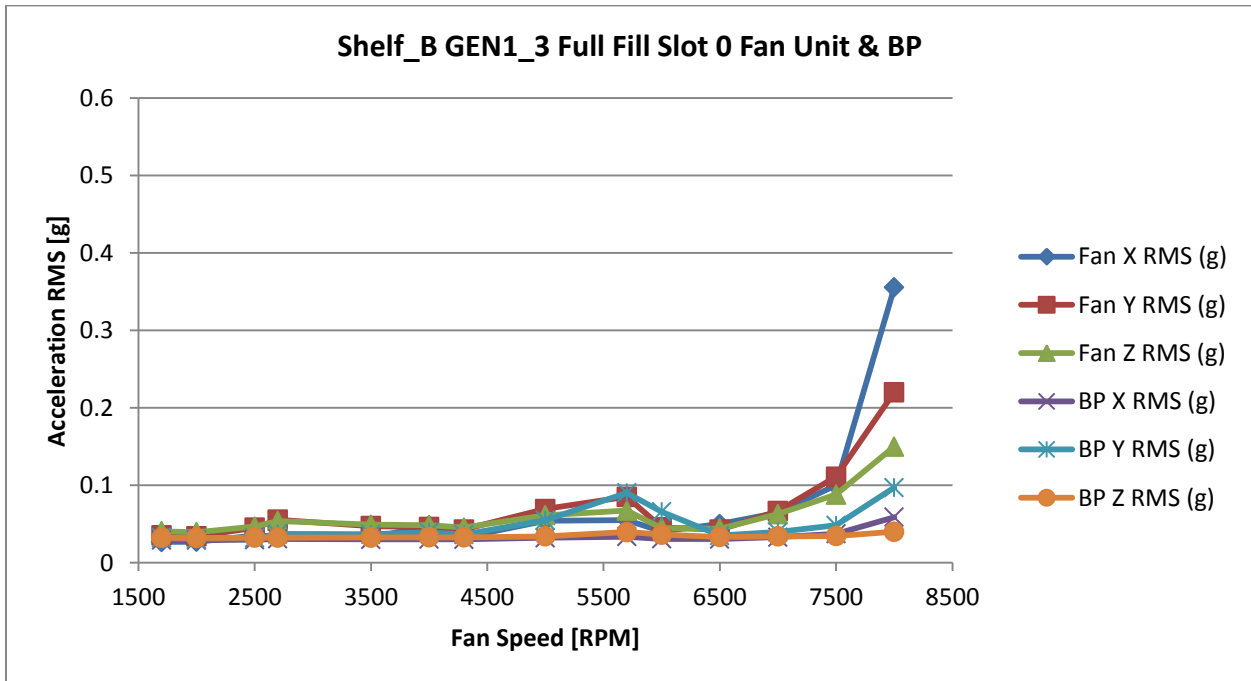


Figure 5.5: Shelf_B GEN1_3 Full Fill Sweep Vibration Test Slot 0 with Backplane (BP) Accelerometer

Figure 5.4 and Figure 5.5 give a few insights into some variables present, especially when compared with Figure 5.1 through Figure 5.3:

1. RMS vibration levels vary from fan unit to fan unit, and likely from fan to fan. Intuitively, this makes sense, as no two fans will be identical.
2. The specification to which the fans are balanced is loose, resulting in the presence of a range of vibration levels for fan units of identical design

This is important for future testing, since serialization and identification of each tested fan unit and fan must be recorded in order to properly track results.

Additionally, these results allow critical testing points to be extracted for future tests of this fan unit where results are needed quickly and a full sweep is not desired. Critical points were selected based upon the fan speed lookup table (Table 6.3 in Appendix A) in the software and points of interest determined based upon inspection of the above plots. There critical points for this fan unit are: 2700 rpm, 5700 rpm, and 8000 rpm.

5.2 Preliminary GEN1 Modifications

Sections 4.2 and 5.1 have achieved their goal of outlining the current RMS vibration values for the GEN1 as well as the RMS vibration values sought in order to eliminate the problem.

The next step was to test some preliminary vibration isolation solutions that could be retrofitted to the current GEN1 equipment and shelves available. This was a feasibility test and was meant to be done with solutions that could be mocked up in the lab without the added expense and time of getting new sheet metal made for each design variable to be tested.

Two types of variables for testing existed:

1. Installation variables. Modifications not directly related to fan design.
2. Design variables. Any modifications that can be made to the fan unit design itself.

5.2.1 GEN1 Installation Variables

As mentioned in section 3.2.2, the nominal connector wipe of the GEN1 is not maximized, a nominal gap exists. As a result of this, when a fan unit is installed in the shelf using the latch only, to increase connector wipe it can still be pushed further backwards along the axis of the fan until the front latch pawl contacts the shelf. This distance is equal to the gap between the front latch pawl and the shelf. When the GEN1 is inserted in this manner it is referred to as being “pushed home”.

There are three possible installation scenarios for the GEN1:

1. **Unscrewed:** GEN1 is inserted into the shelf using the latch but the latch screw is left undone. This is suspected to be the most common installation method used in Ciena’s internal labs. Figure 5.6 shows this scenario.

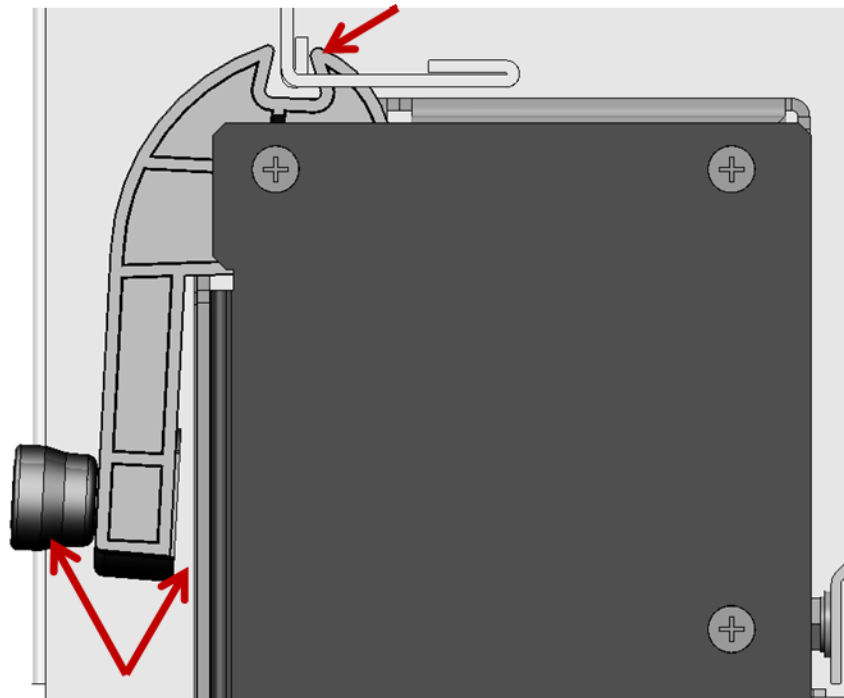


Figure 5.6: Unscrewed Connection

2. **Screwed down latch:** GEN1 is installed in the standard scenario, using the latch to install the fan and the latch screw screwed in to hold the fan unit in place. Figure 5.7 shows this scenario.

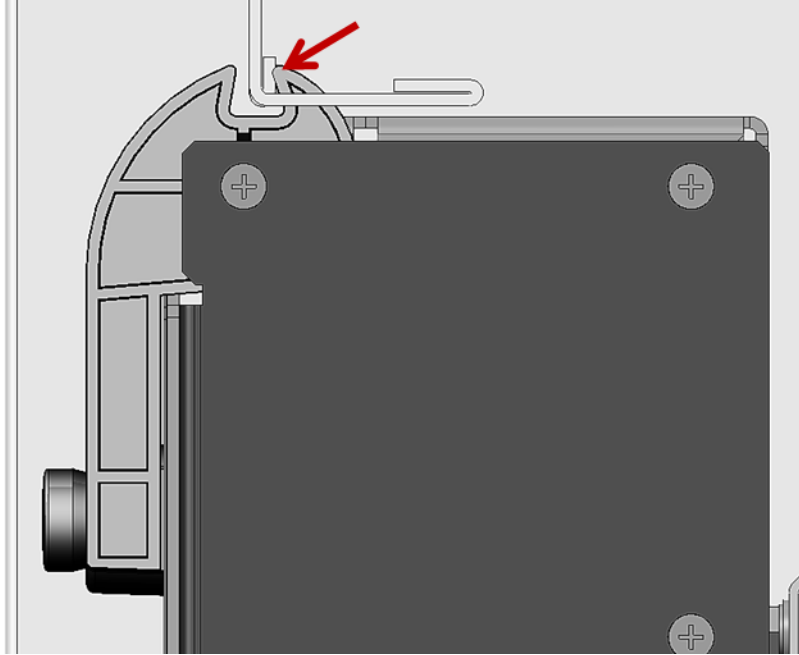


Figure 5.7: Screwed Down Latch Connection

3. **Screwed down latch and pushed home:** GEN1 is installed as in the “screwed down latch” scenario above and then the fan is pushed back as far as possible along the fan axis. Figure 5.8 shows this scenario.

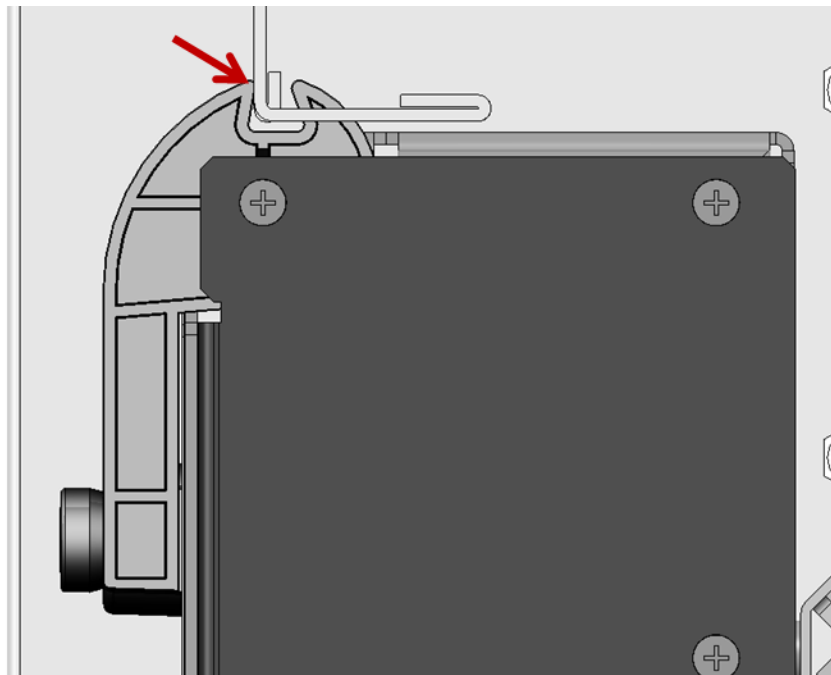


Figure 5.8: Screwed Down Latch and Pushed Home Connection

5.2.2 GEN1 Design Variables

The GEN1 design variables pertain to any changes to the GEN1 fan design. It is hypothesized that the GEN1 design variables have the greatest impact on the RMS vibration values, as this is where a damper can be added to the system in order to decrease the amplitude of vibration force that is transmitted from the imbalanced fan to the fan connector and the rest of the shelf system.

Due to the minimal clearances that exist in the fan and shelf design, as described in section 3.2.2, any typical larger dampers or vibration isolators that would be used in such a scenario cannot be used. A few design options were feasible within the design envelope, which are outlined below:

- **Base isolating pad (die-cut gasket):** unlike the base isolating pad described in section 2.2.1, the thickness of the pad used in the GEN1 had to be minimized in order to fit within the existing sheet metal. The pad was cut in the shape of the contact surface of the inlet side of the fan and adhered to the base sheet metal as shown in Figure 5.9.

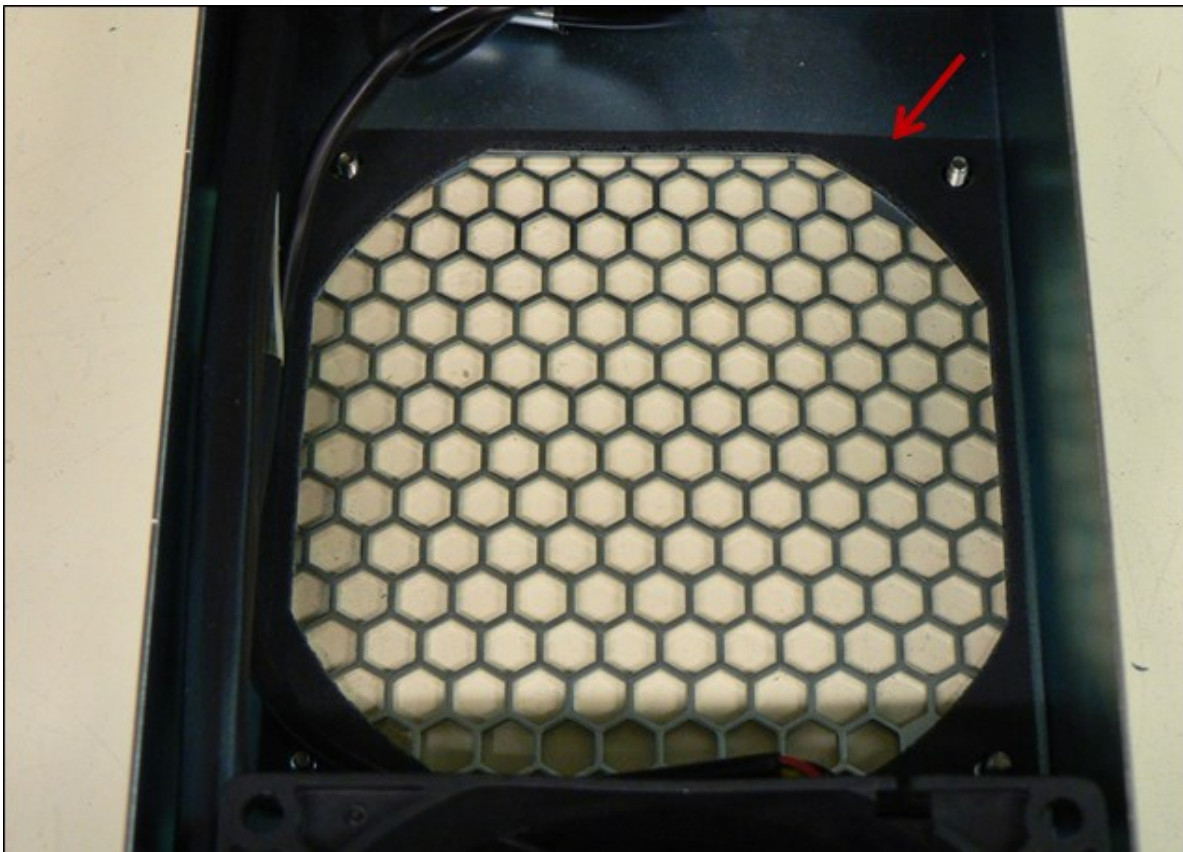


Figure 5.9: GEN1 base isolating pad prototype test

The material selected for the base isolating pad was an open-cell silicon foam sheet material with a low density and low force for deflection. The specific material chosen was *Rogers Bisco BF-1000 extra soft cellular silicone* which has a density of 208 kg/m³ and typical force-deflection of 20.7 kPa [50]. This foam and gasket design was already being used to mitigate vibrations in another product’s fan units. The minimum available thickness of 0.063 in was used, with an expected installed compression of 75% with the fans screwed down.

- **Connector shim (simulate connector crash):** fully mating the connector pairs is their standard installation method. This variable aims to simulate a connector crash present with fully mated connectors which could be achieved by elongating the fan unit.

A 0.082 in rectangular shim was 3D printed in the Ciena Mechanical Lab and placed around the male pins of the fan connector as illustrated in the block diagram of Figure 5.10.

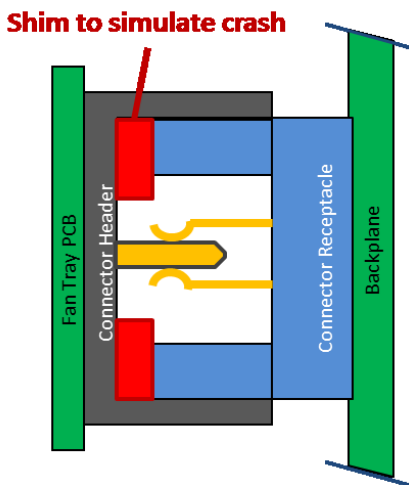


Figure 5.10: Connector block diagram with shim to simulate crash condition

- **Floating fans on isolators:** this variable aims to remove the screwed connection between the fan and the fan unit base in an attempt to decouple or “float” the fans. This was mocked up with the current sheet metal by 3D printing press fit pins that fit into the countersunk screw mounting holes in the fan chassis base. Teflon washers were then

placed over these pins and wire heat shrink adhered to the pin itself.

The pin is meant to locate the fan in the correct position in the chassis, the washer is meant to separate the fan from the sheet metal and also provide a bearing surface with a low coefficient of friction on which the fans can move in the same plane as the fan rotor rotation. Lastly, the heat shrink was to act as the vibration damping material, with a nominal radial gap between the heat shrink and the mounting hole on the fan flange. Figure 5.11 shows a block diagram of this design and Figure 5.12 shows a detailed view of two of the pins in the mock-up prototype.

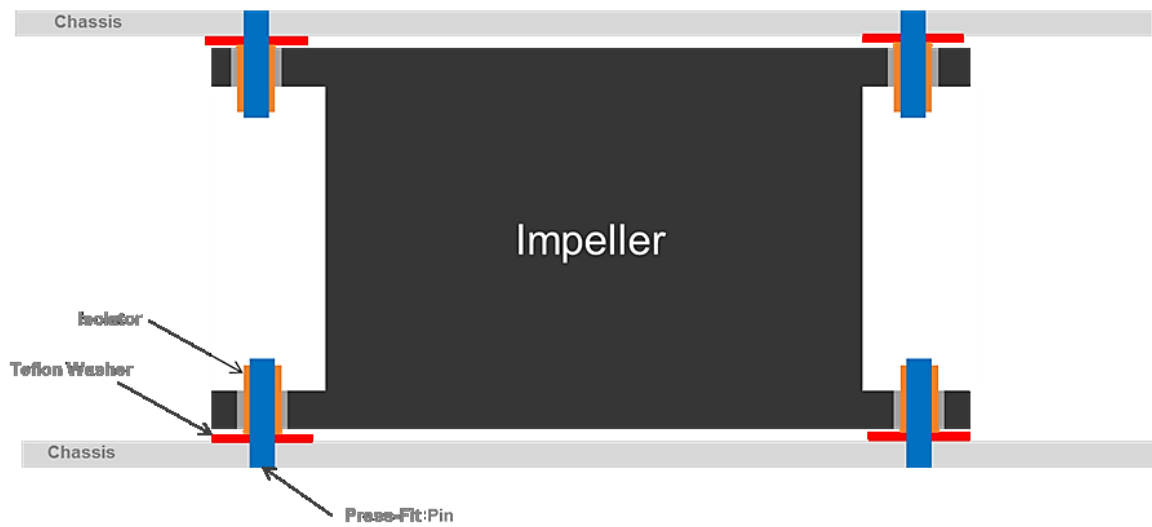


Figure 5.11: Floating isolation design block diagram

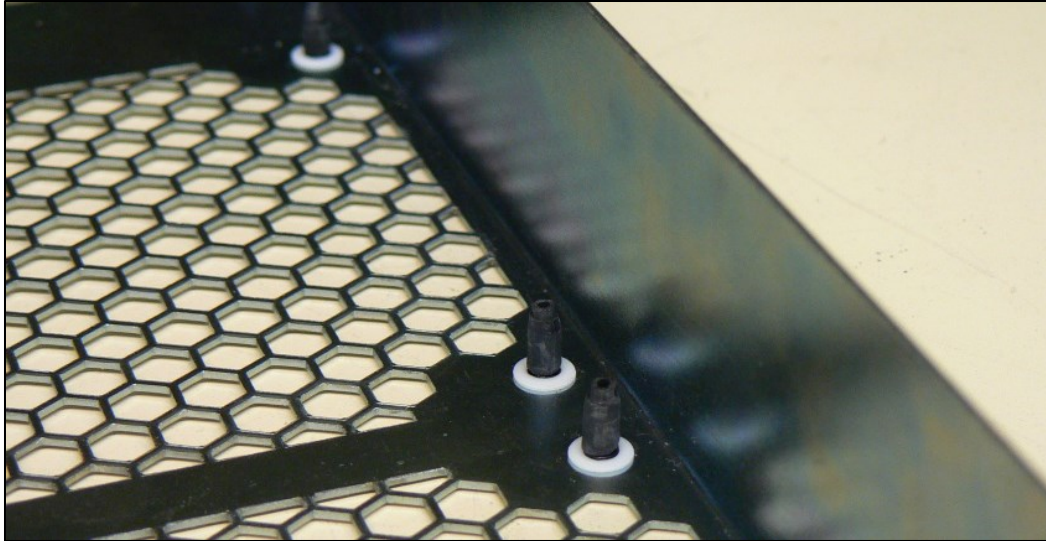


Figure 5.12: Floating isolation design prototype mock-up for test

5.2.3 Preliminary GEN1 Modification Vibration Test and Results

The vibration tests conducted were again performed in Shelf_B in fan slot 4 with GEN1_3.

Fan unit speeds were set to the three speeds determined in section 5.1. It should be noted that although this test is being performed to compare variables, the variables are only being changed on one fan unit in slot 4; all other fan units in the shelf are running at the desired speed, but are configured in their standard un-modified installation orientation with the fan latch screwed down.

Eight different configurations were tested using the six variables mentioned previously: unscrewed, screwed down latch, screwed down latch and pushed home, base isolating pad, floating fan isolators, and connector shim. The eight configurations of these variables are:

1. Screwed down latch (standard install)
2. Screwed down and pushed home
3. Unscrewed latch
4. Die-cut gasket
5. Die-cut gasket and connector shim
6. Connector shim
7. Floating isolator
8. Floating isolator and connector shim

GEN1_3 was modified for each test and variable and re-assembled so that each individual fan was placed in the same location and orientation inside the fan unit.

Data were recorded for all three X-, Y-, and Z-axes of the fan unit in slot 4 as well as the corresponding backplane connector of the shelf. Each speed data point was collected for a single 20 second duration. Figure 5.13 through Figure 5.15 show the data from the fan unit, and Figure 5.16 through Figure 5.18 show the data from the backplane.

Shim results were not obtained for 2700 rpm.

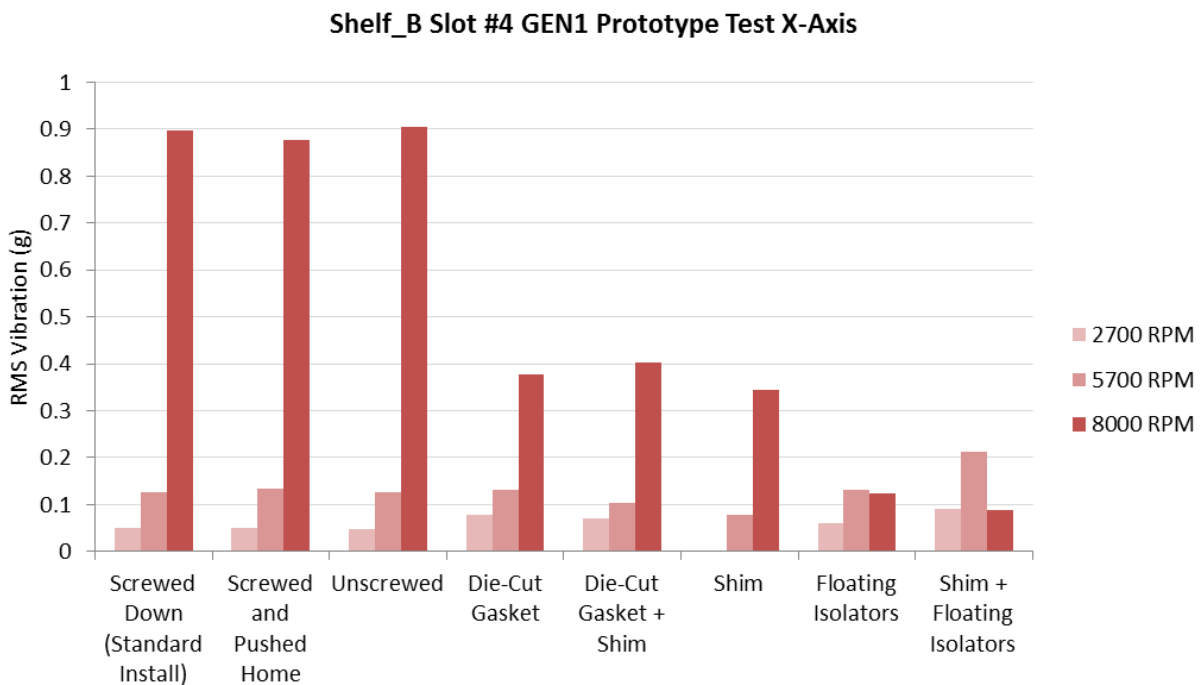


Figure 5.13: Shelf_B Slot #4 GEN1 Prototype Vibration Test X-Axis

Shelf_B Slot #4 GEN1 Prototype Test Y-Axis

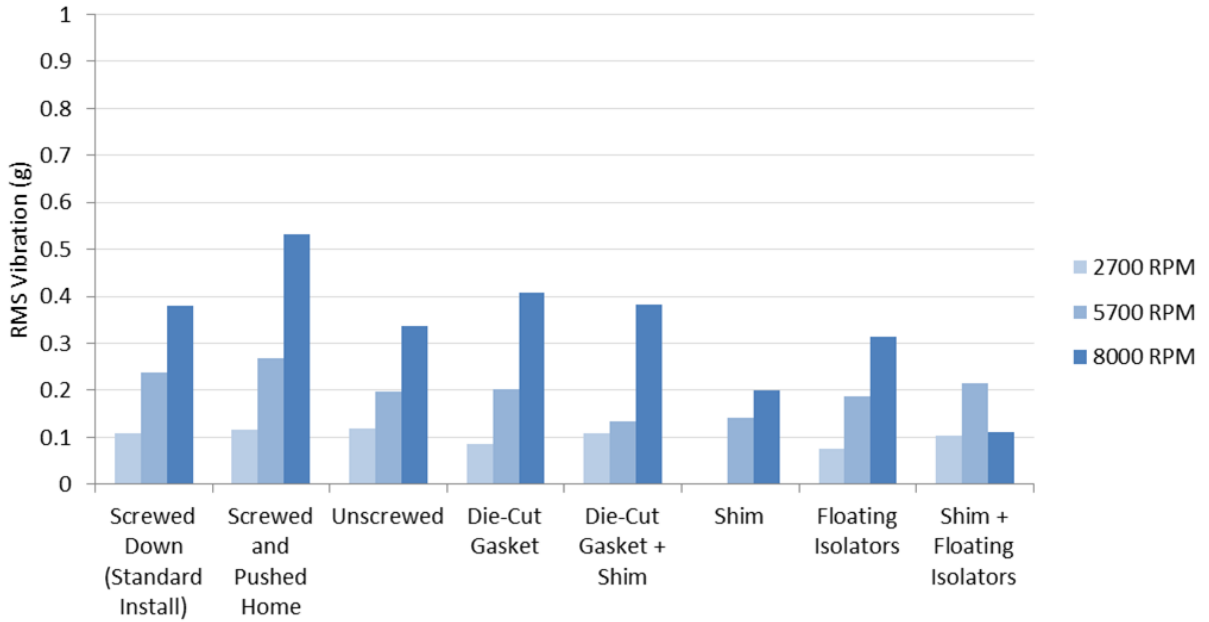


Figure 5.14: Shelf_B Slot #4 GEN1 Prototype Vibration Test Y-Axis

Shelf_B Slot #4 GEN1 Prototype Test Z-Axis

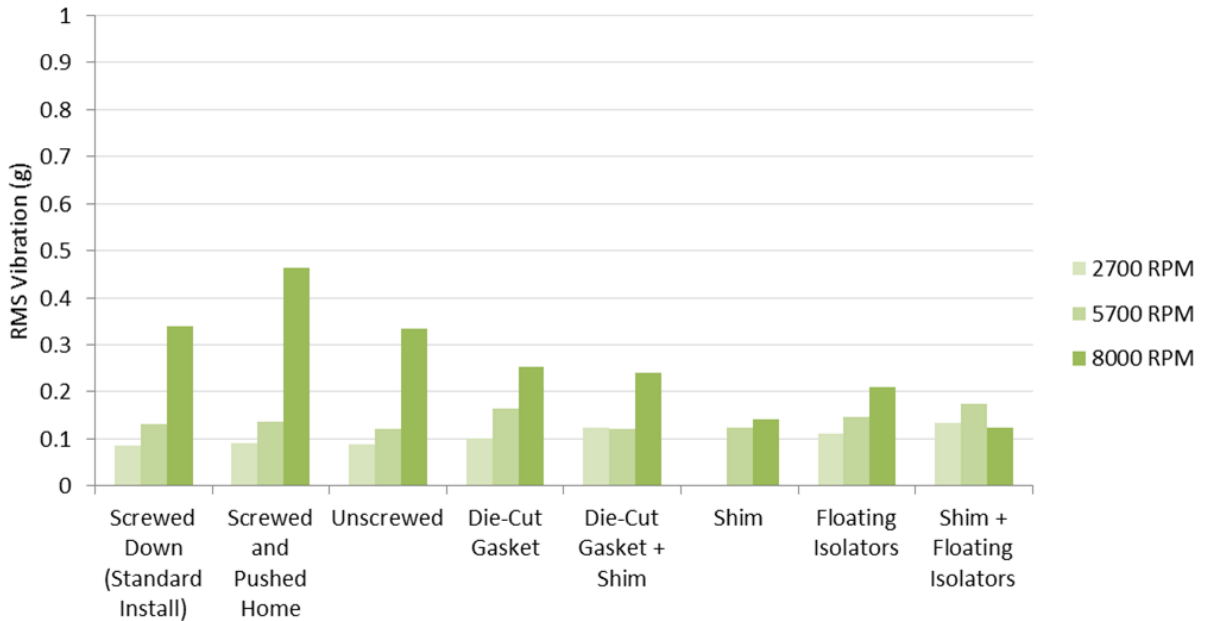


Figure 5.15: Shelf_B Slot #4 GEN1 Prototype Vibration Test Z-Axis

Shelf_B Slot #4 GEN1 Prototype Test Backplane X-Axis

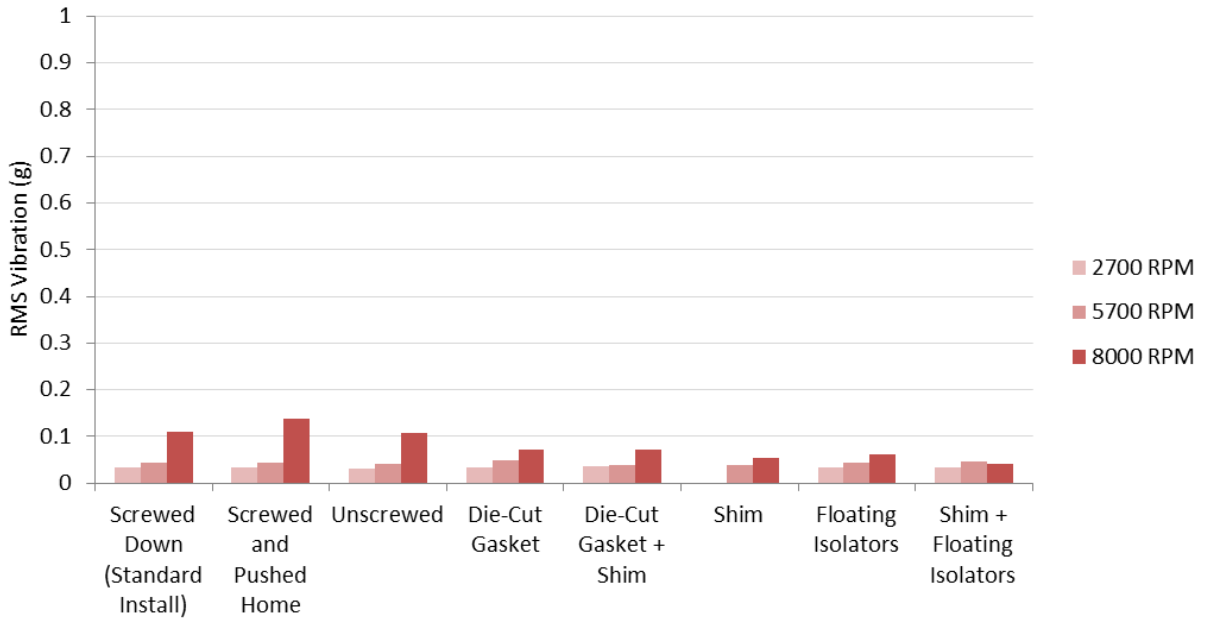


Figure 5.16: Shelf_B Slot #4 GEN1 Prototype Vibration Test Backplane X-Axis

Shelf_B Slot #4 GEN1 Prototype Test Backplane Y-Axis

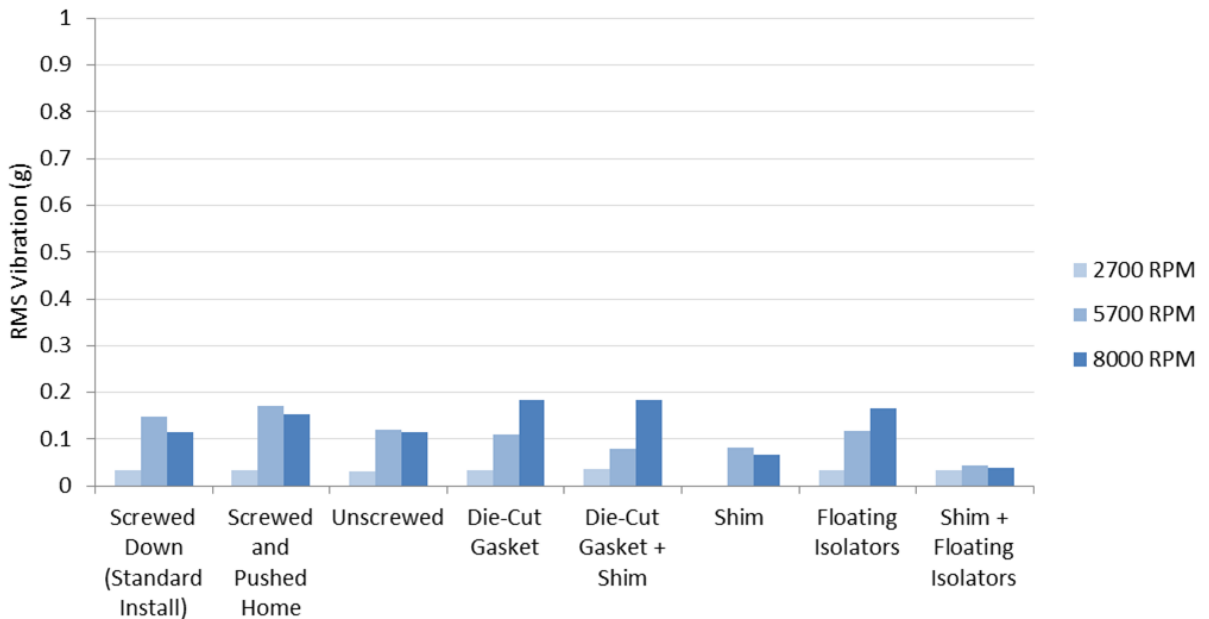


Figure 5.17: Shelf_B Slot #4 GEN1 Prototype Vibration Test Backplane Y-Axis

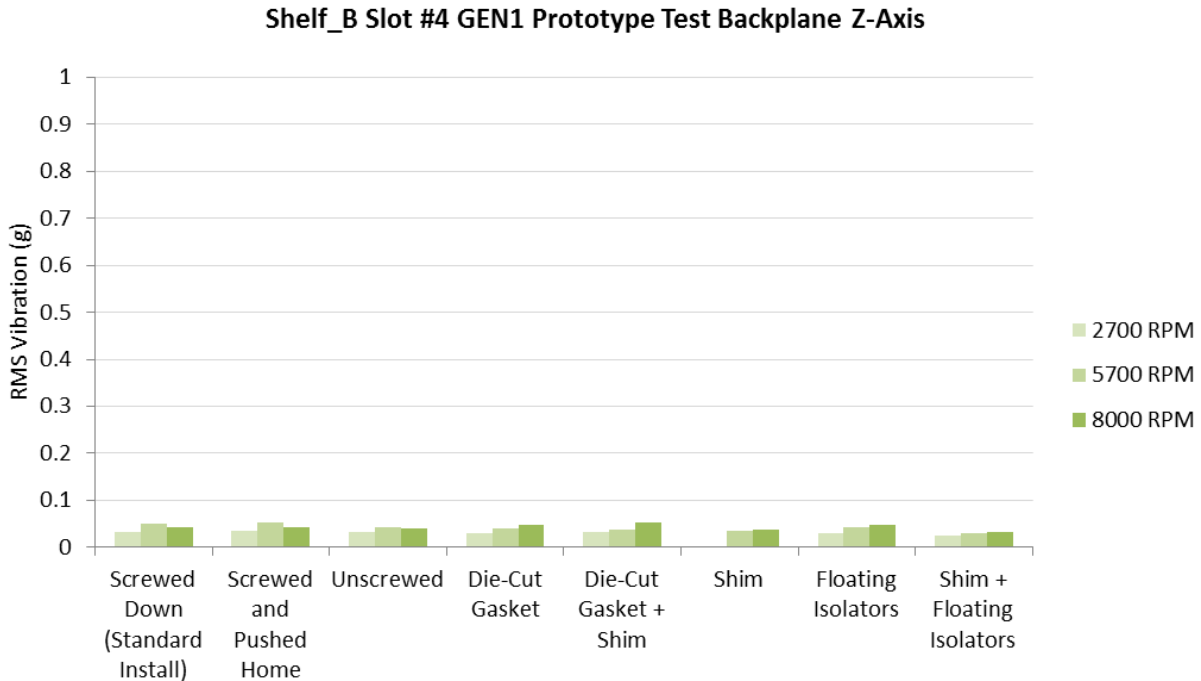


Figure 5.18: Shelf_B Slot #4 GEN1 Prototype Vibration Test Backplane Z-Axis

These results show that the installation variables (“Screwed down”, “Screwed and Pushed Home”, and “Unscrewed”) do not have any significant impact on the RMS vibration levels of the fan unit or the backplane connector. The largest gains in vibration reduction are obtained when using the connector shim and floating isolator in conjunction. The only data point where this does not show the most improvement is at 5700 rpm in the X- and Y-axes of the fan unit, where both the floating isolators and the connector shim individually outperform the combination of the two.

Using the connector shim on the rear PCB of the fan unit produces a similar effect to increasing the overall length, ensuring there is a constant force (provided by the latch) on the connector halves. This produces some reduction in vibration levels, especially at lower speeds.

As a result of this testing, it was decided that a combination of the connector shim and floating isolators would be used to create an initial design prototype for retrofit to the GEN1 fan unit (GEN1A).

5.3 GEN1 Retrofit Solution (GEN1A)

The first, or Alpha, prototype of the GEN1A solution aimed to integrate the connector crash scenario as well as the floating isolator scenario. The benefit of this design is that it is fully compatible with all other components in the GEN1 assembly, so no changes to the internal PCBs are required. The GEN1A fan unit took the LFU design and modified it by:

1. Lengthening the fan unit's base sheet metal and top cover by 0.087 inches in order for the connector crash to occur. A nominal interference of 0.005 inches was also added in order to ensure that crash contact was maintained at all times, even in units at the outer tolerances limits.
2. Replacing the countersunk holes in the fan chassis base used for mounting the fans with 1.5mm diameter push-in stainless steel pins.
3. The top cover which previously did not serve as an attachment point for the fans also had corresponding 1.5 mm diameter push-in stainless steel pins added to it.
4. Teflon washers with a thickness of 0.010 inches were placed over the press fit pins.
5. Cylindrical isolators were installed over the press-fit pin and glued to the base of the pin. The isolators were made of *PORON Microcellular Urethane Foam*. Two different durometers were tested for comparison, *PORON 4701-30-15 (extra soft)*, and *PORON 4701-60-15 (extra firm)* [51], [52]. A durometer comparison of the two materials is shown in Table 5.1 [51], [52].
6. Removing the threaded inserts from the fan flanges. This required a new manufacturer part number and existing fan inventory to be modified by having the inserts drilled out.

Table 5.1: *PORON* Isolators Materials Durometers in Shore "A" and Shore "O" [51], [52]

<i>PORON</i> Material	Durometer (Shore "A")	Durometer (Shore "O")
4701-30-15	30	42
4701-60-15	< 3	< 3

The isolators were glued to the pin using *Loctite 4205*, which is a thermal resistant gel adhesive [53]. This adhesive was chosen because it can withstand heat ageing affects; this

is important for the fan units since they see exhaust air and temperatures up to 90 °C, as determined by Ciena thermal engineers. Figure 5.19 shows the heat ageing curve for *Loctite 4205*.

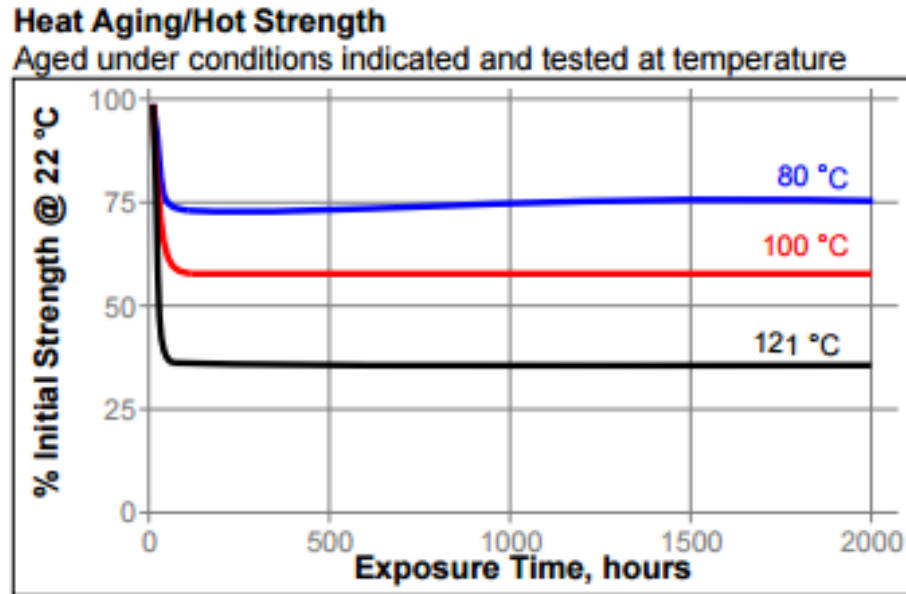


Figure 5.19: Loctite 4205 Heat Ageing vs. Time Curve [53]

The generalized assembly sequence for the vibration isolators used on the GEN1A is shown in Figure 5.20. Figure 5.21 shows a cross-section of the assembly and detailed view of the isolator design. A tolerance analysis (Figure 12.7 and Table 12.7 in Appendix D) was also conducted to determine if any interference would be present in this new design since the clearance gap between the fan unit top and the fan would be reduced by adding in 0.010 inch thick PTFE washers on either side of the fan. The tolerance analysis determined that no issues should be present as long as the parts are made as per the drawings.

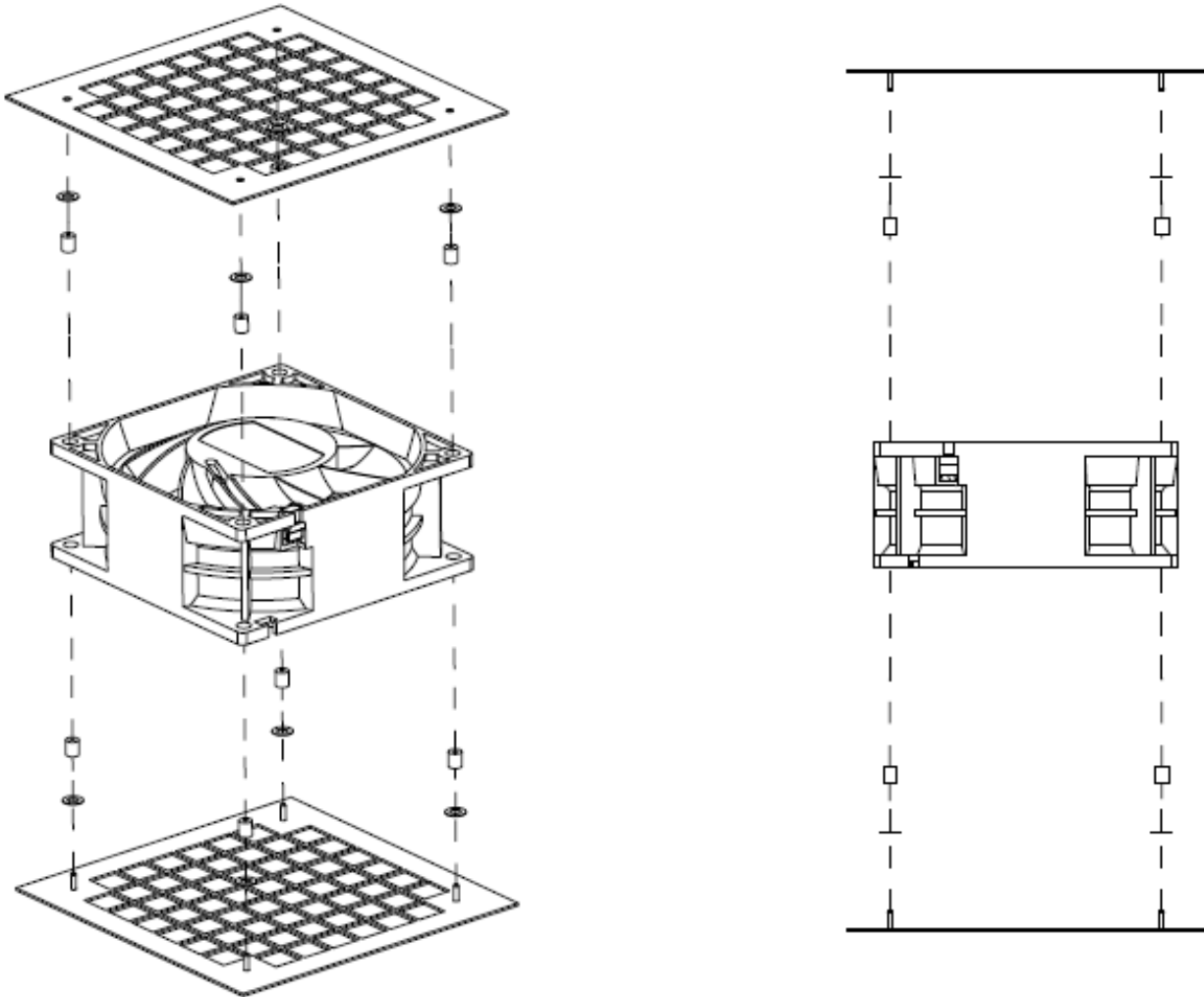


Figure 5.20: Retrofit Vibration Isolator Design Exploded View

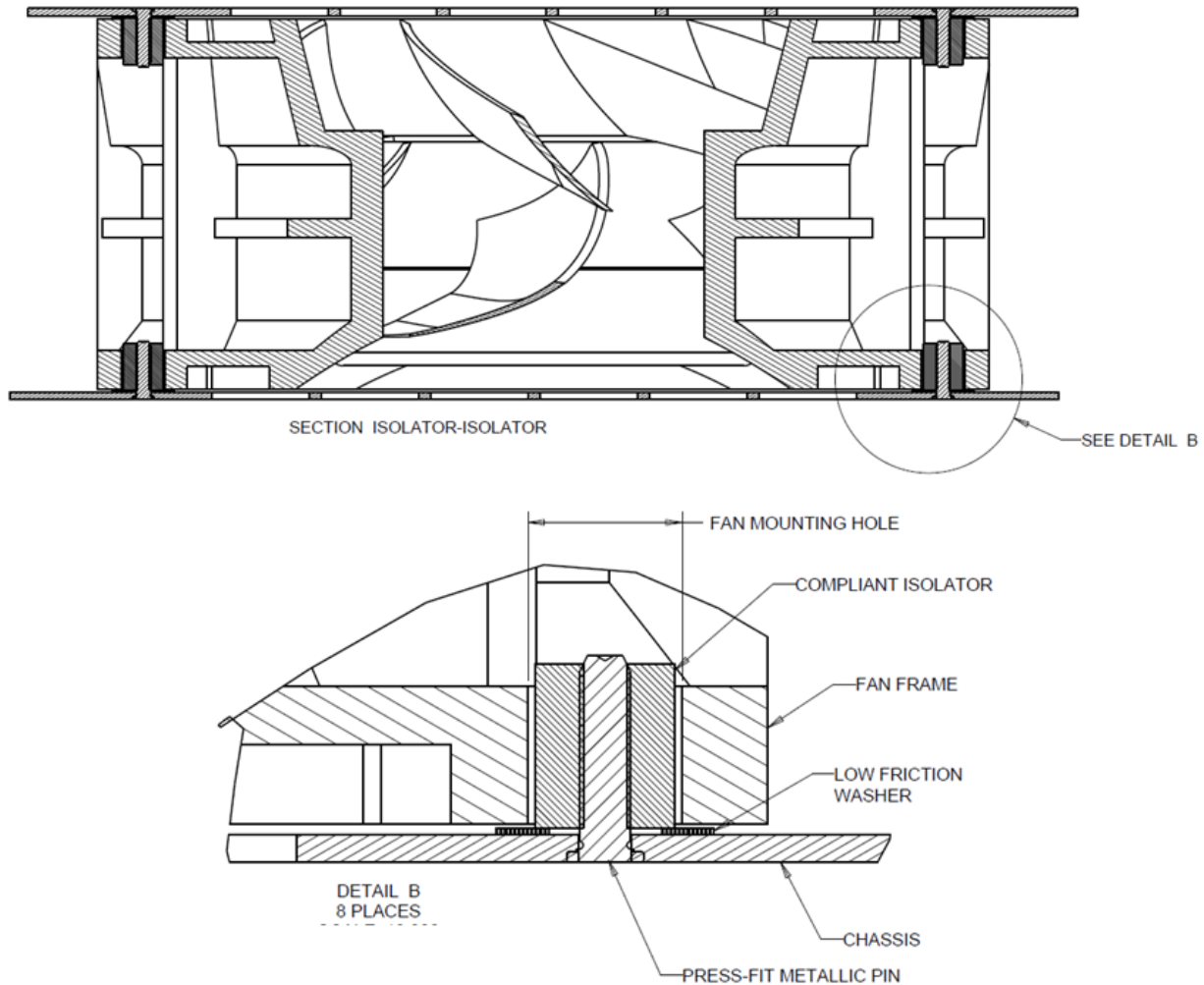


Figure 5.21: Retrofit Vibration Isolator Design Section View

A small nominal radial clearance was left between the isolator and fan mounting hole to aid in assembly, and a nominal radial interference was added between the pin and the isolator to ensure a solid connection once glue was applied. This design is Patent Pending. This design is a research contribution to the overall thesis as it can be used in various other fan unit designs which suffer from similar physical constraints as the fan unit considered in this thesis.

This retrofit isolator design was theorized to be a significant improvement within the design envelope because it eliminates the rigid connection between the fan housing and the chassis. By eliminating the screwed connection and replacing it with a cylindrical damper on a rigid pin with a low friction PTFE washer bearing surface, the fan is able to move relative to the chassis in the X-Y plane. This movement in the X-Y plane occurs primarily where the fan imbalance force

acts, and the isolator acts as a damper to absorb this energy as opposed to directly transmitting it to the chassis. The PTFE washer provides a limited amount of damping in the Z-Axis as opposed to no damping when considering a screwed connection.

The GEN1A design was prototyped by Ciena’s contract manufacturer (CM) and samples were delivered to Ciena Ottawa. The vibration level of the GEN1A was measured in slot #4 of Shelf_B with a FF of fan units. The data was compared to the GEN1 data obtained previously in the unmodified scenario as well as the shim and floating isolator scenario. Only the fan unit in slot #4 varied in design, all other fans remained constant in an unmodified state. Figure 5.22 through Figure 5.24 show the raw vibration plots for each axis of each configuration at 2700 rpm, 5700 rpm, and 8000 rpm respectively.

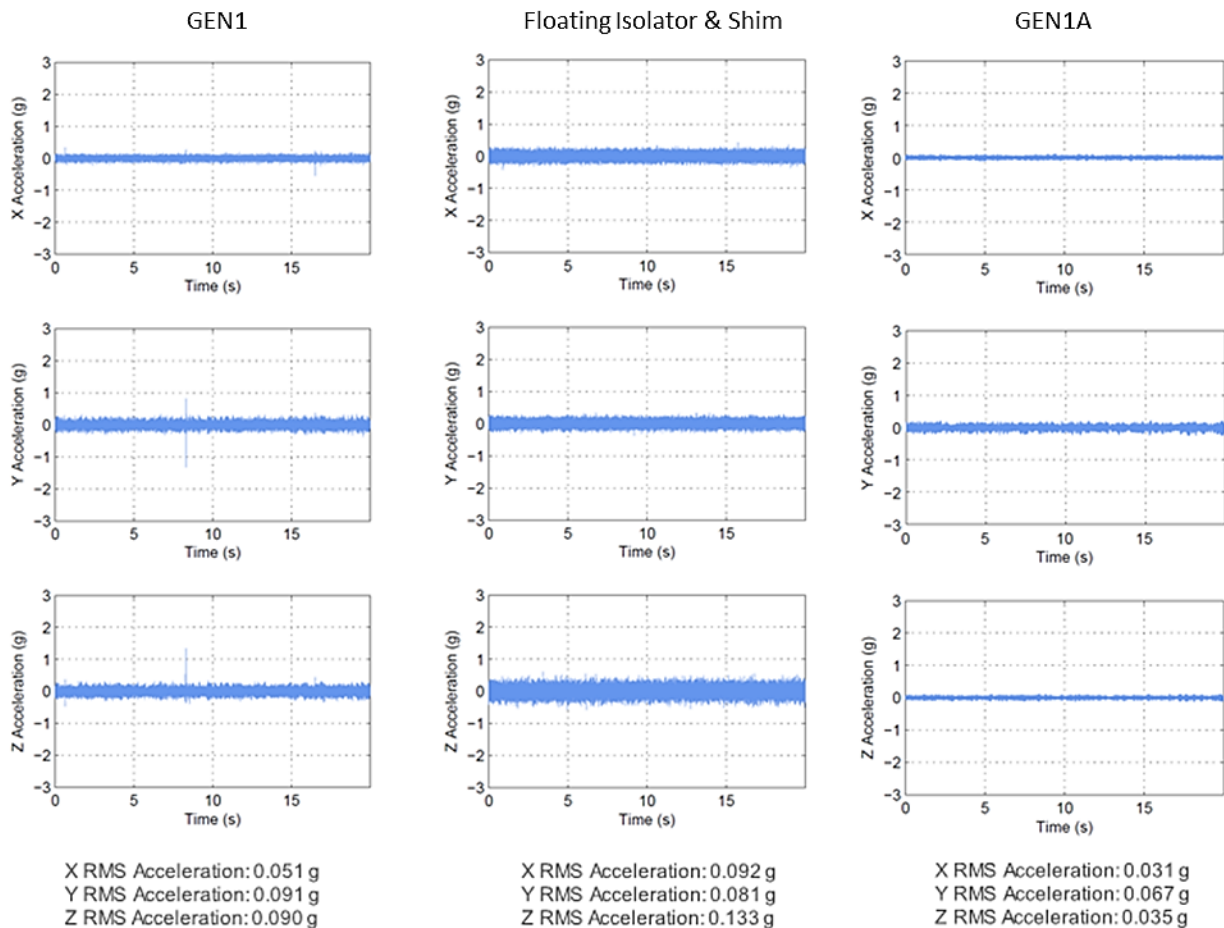


Figure 5.22: GEN1 vs. GEN1A Raw Vibration Data Plots at 2700 rpm

Note that vibration levels at 2700 rpm are much lower than at higher speeds, and are currently below the 0.1 g RMS target value. Despite this, a clear improvement in overall vibration level as well as RMS value can be seen between the GEN1 and GEN1A fans.

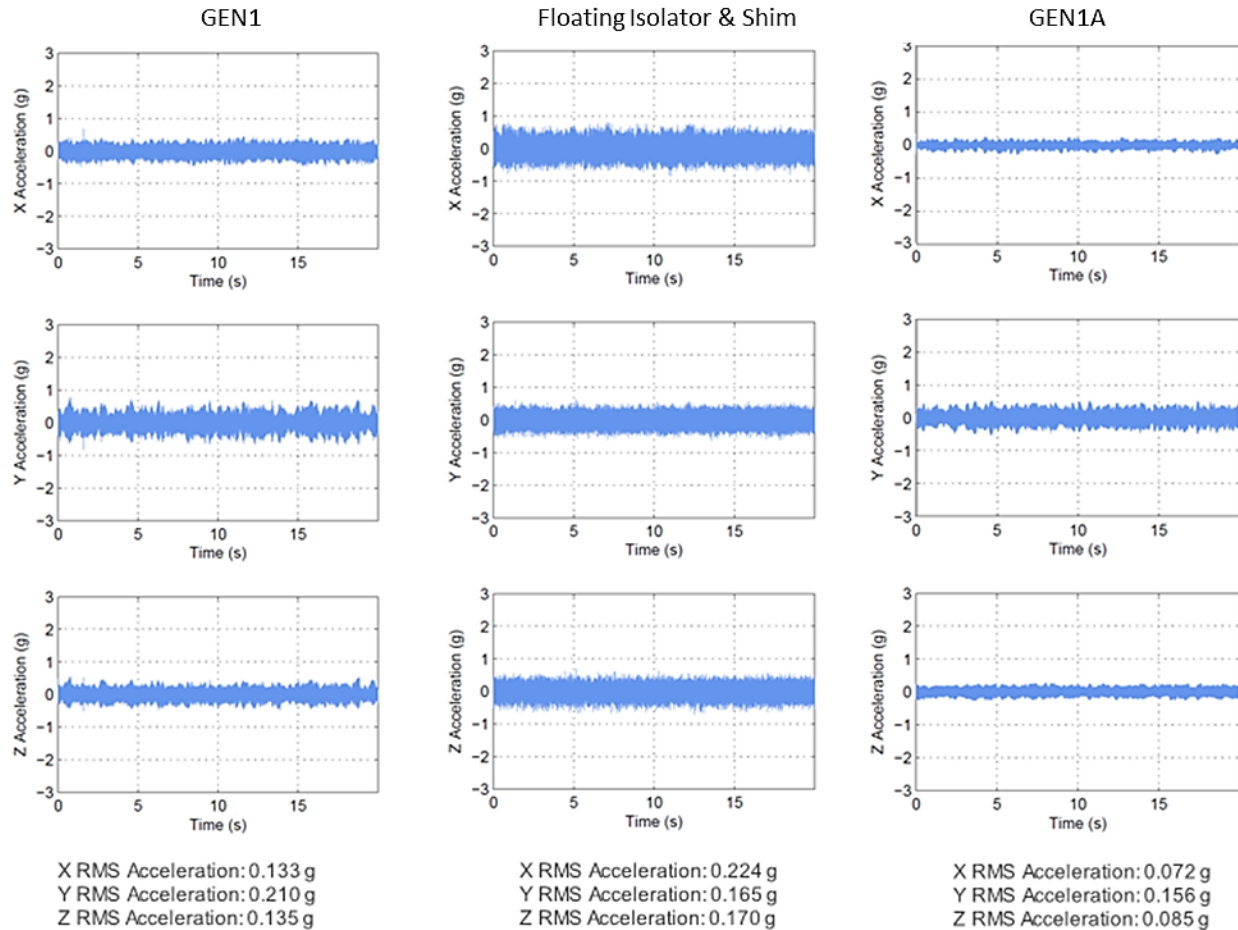


Figure 5.23: GEN1 vs. GEN1A Raw Vibration Data Plots at 5700 rpm

From Figure 5.22 to Figure 5.23 it is clear that the floating isolator and shim mock-up prototype performs worse in the X- and Z-Axis at 2700 rpm and 5700 rpm. However, the GEN1A outperforms the GEN1 in all instances when comparing RMS values by 60% reduction at most (2700 rpm Z-Axis), and 26% reduction at the least (2700rpm Y-Axis).

The GEN1A still exceeds the 0.1g RMS target vibration value determined previously, but the significant gains in vibration reduction for a minimal design change in a retrofit scenario cannot be discounted.

As Figure 5.24 shows for the 8000 rpm data, the floating isolator and shim mock-up prototype exhibits the greatest vibration reduction at higher frequencies. The GEN1A shows even more gains on top of that shown by the floating isolator and shim mock-up prototype. The GEN1 plot at 8000 rpm also shows a beat frequency which has a period of approximately 0.4 Hz. Both prototypes effectively eliminate this frequency and produce a more uniform vibration plot.

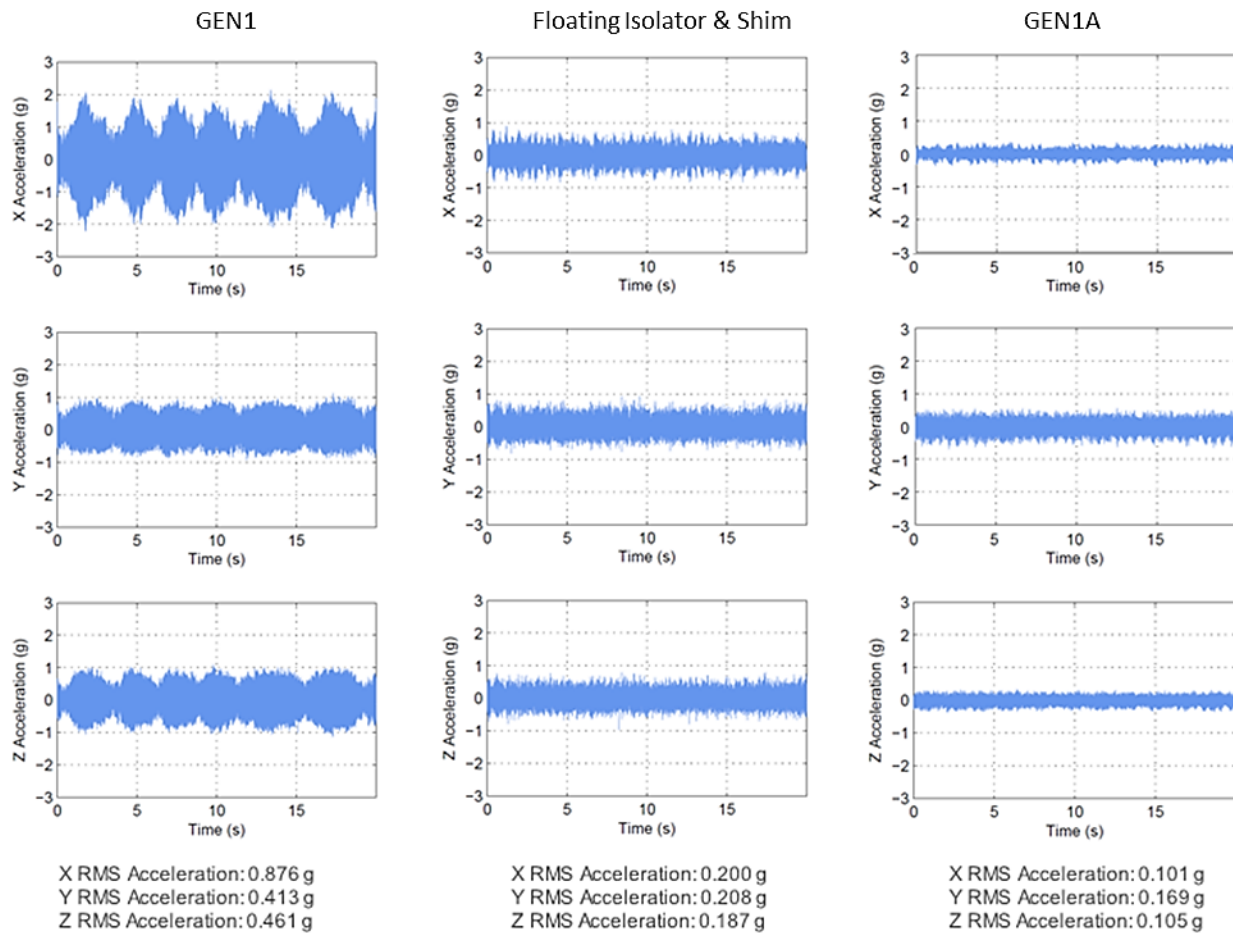


Figure 5.24: GEN1 vs. GEN1A Raw Vibration Data Plots at 8000 rpm

The reduction in RMS vibration level is significant at 8000 rpm when comparing the GEN1 to the GEN1A:

- X-Axis: 88% reduction in RMS values
- Y-Axis: 59% reduction in RMS values
- Z-Axis: 77% reduction in RMS values

After these successful preliminary test results, a more rigorous test was proposed with the same fan units. The proposed test involved performing a FF sweep in Shelf_A with the instrumented fan in slot #2 in the following configurations:

- Stock GEN1
- Stock GEN1 (no power to instrumented fan – used to obtain shelf noise)
- GEN1A (same fans and PCBs as GEN1)
- GEN1A (no power to instrumented fan – used to obtain shelf noise)

Figure 5.25 through Figure 5.26 show the results for the X- and Y-Axis. Figure 5.27 through Figure 5.28 show the results for the X- and Y-Axis with the shelf noise removed. The shelf noise was removed in this instance because only the instrumented fan was modified and the vibrations induced from the stock LFU fans running in the other slots would theoretically make the RMS vibration values artificially high. Z-Axis data were not included in this data set.

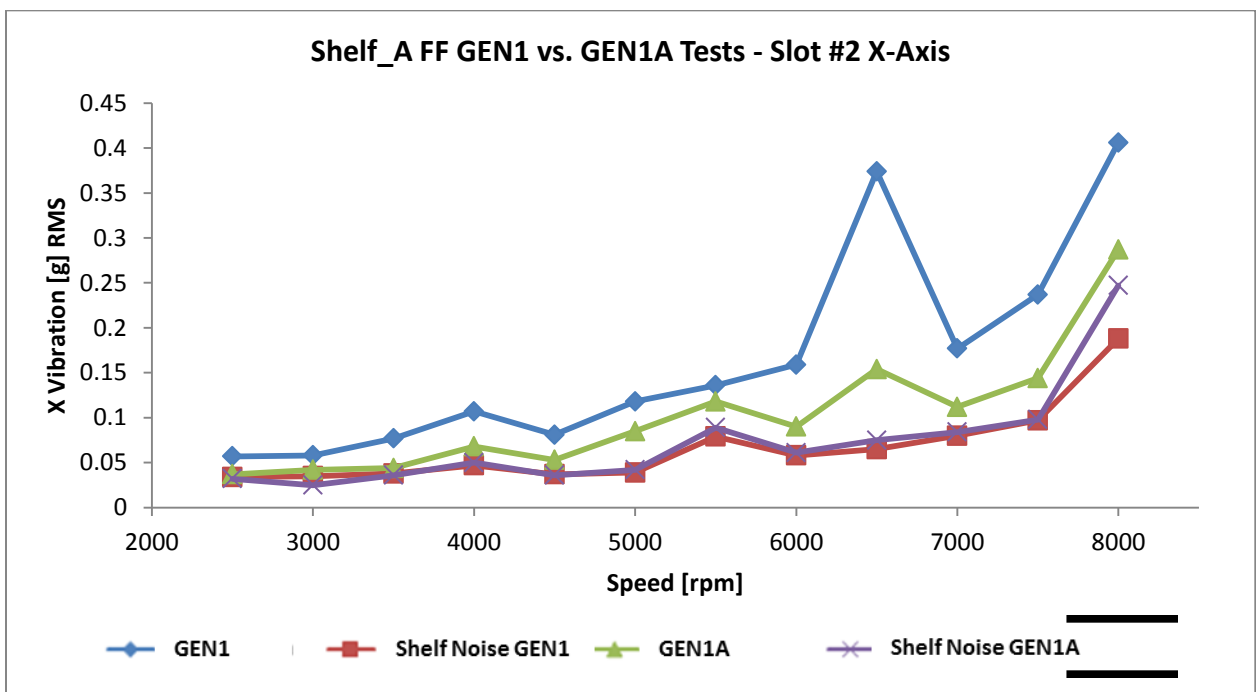


Figure 5.25: Shelf_A Slot #2 GEN1 vs. GEN1A Vibration Test X-Axis

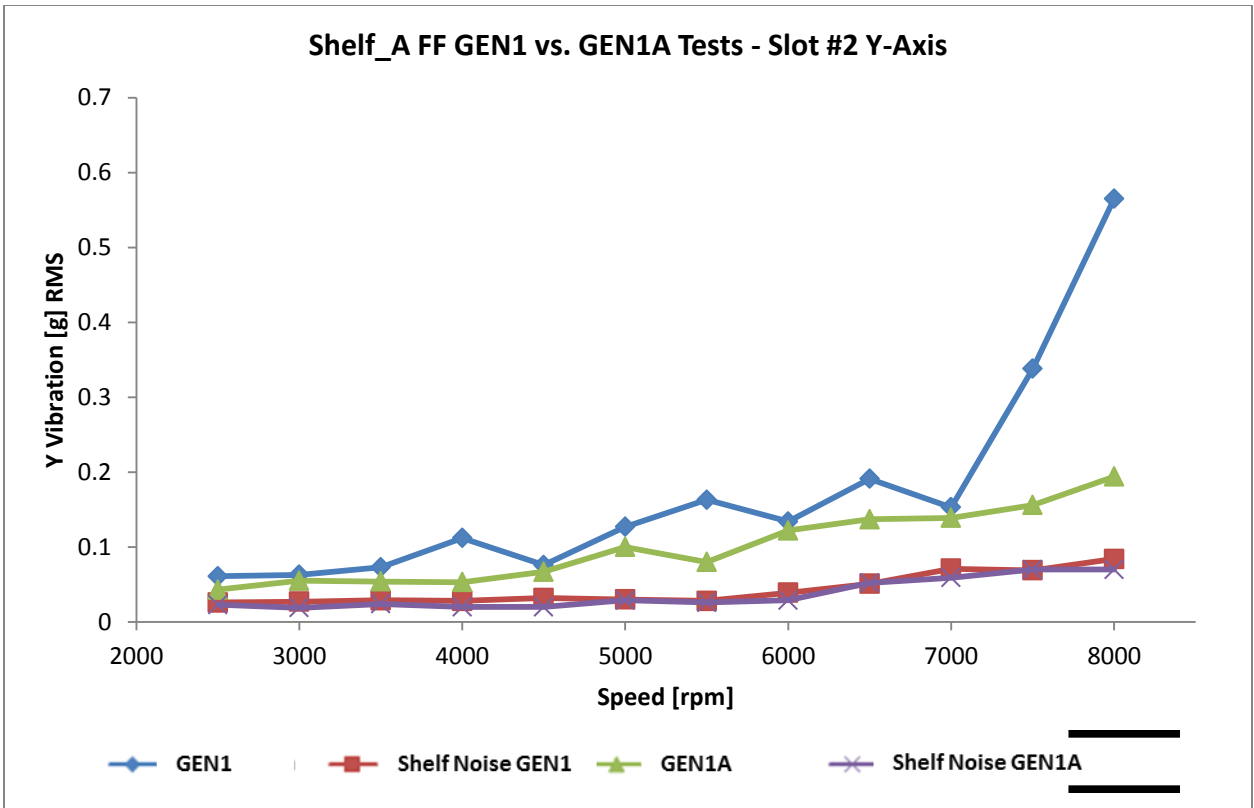


Figure 5.26: Shelf_A Slot #2 GEN1 vs. GEN1A Vibration Test Y-Axis

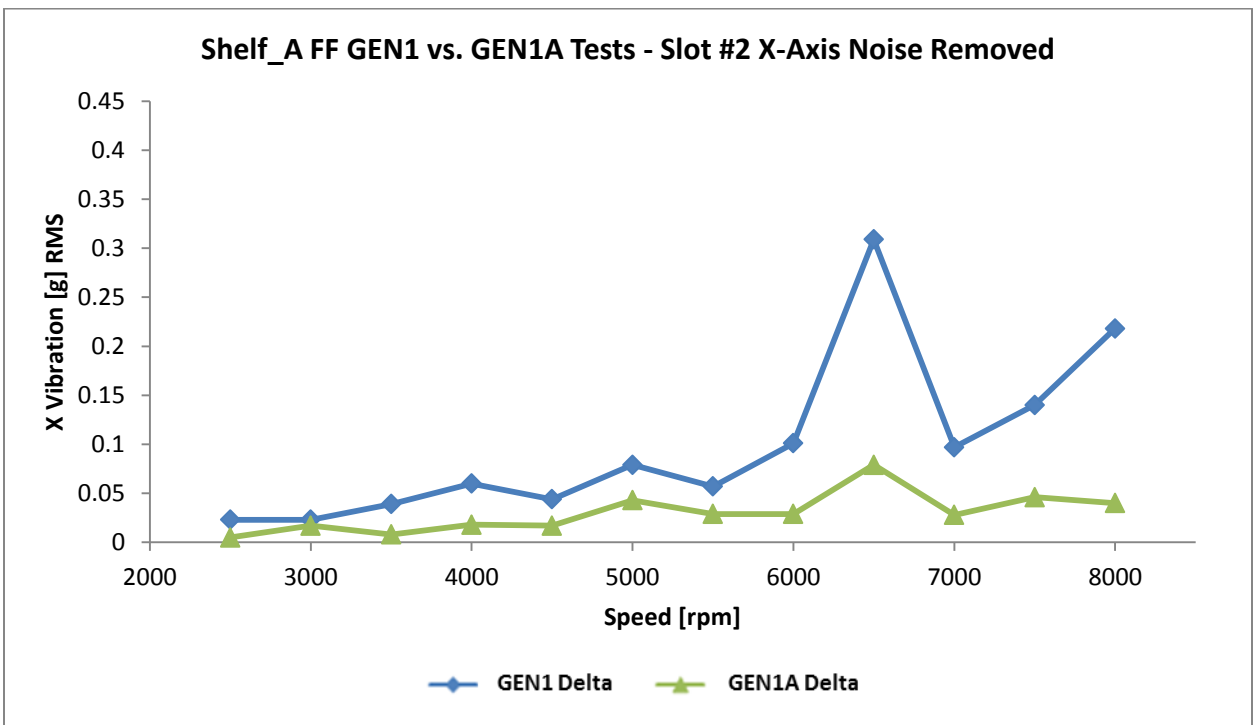


Figure 5.27: Shelf_A Slot #2 GEN1 vs. GEN1A Vibration Test X-Axis Noise Removed

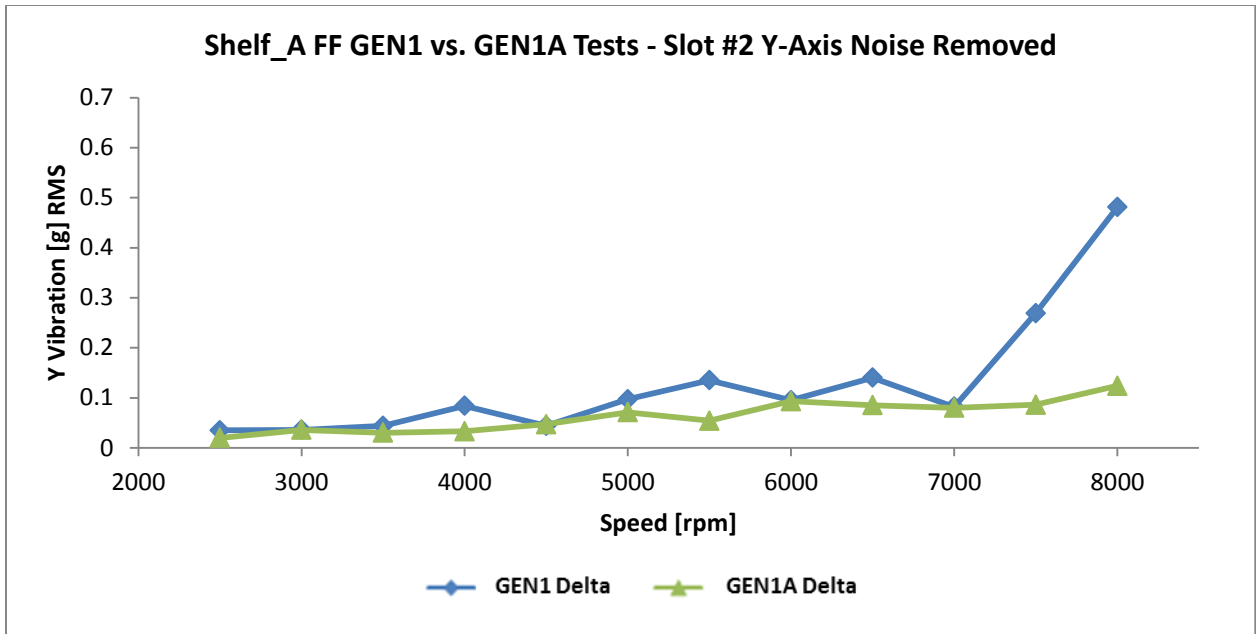


Figure 5.28: Shelf_A Slot #2 GEN1 vs. GEN1A Vibration Test Y-Axis Noise Removed

The above figures show a few trends that should be noted:

1. A resonance is clearly visible in the X-Axis around 6500 rpm. It is very pronounced in the GEN1, and its effect is almost completely mitigated in the GEN1A. This resonance seems to vary between 5700-6500 rpm depending on the test shelf used as well as the fan unit. The exact cause of this resonance is not of concern; it appears to be inherent to the system which cannot be changed. The goal is to mitigate its effect.
2. Shelf noise plots should be identical, but a slight variation is present. This variation is most pronounced at 8000 rpm in the X-Axis. This is likely due to test-to-test variation as a result of the vibration interaction of adjacent imbalanced fans, resulting in different characteristic beat frequencies, and resultant RMS values.
3. The GEN1 begins to show significantly higher vibration levels above 6000 rpm.
4. The GEN1A reduces the overall RMS vibration levels and produces a smoother, flatter curve in both axes.

Although the results demonstrate that the desired 0.1 g RMS maximum vibration level is exceeded, the reduction in vibration levels were sufficiently significant to warrant the immediate upgrade of the production design of the GEN1 to the GEN1A design in hopes of mitigating any new damages in the field with new shelf and fan unit deployments.

5.4 GEN1 Individual Fan Testing

During the course of testing, the focus was on reducing the RMS vibration levels by modifying components designed and manufactured by Ciena. It should be noted that the unworn fan unit from the alternate shelf product in section 3.2.3, uses a different fan manufacturer. The unworn fan unit used a fan with a cast zinc frame (CZF) manufactured by “Company_A” and the GEN1 used a fan with a plastic injection molded frame (PMF) manufactured by “Company_B”.

The difference in fan construction as well as potentially different manufacturing practices between fans from “Company_A” vs. “Company_B” might also have an impact on vibration levels.

To investigate this, the variables introduced by measuring vibration levels of fan units in shelves with varying geometries needed to be removed. A colleague mentor designed a benchtop vibration test fixture (Figure 4.4) to provide a platform to which any standard 92 mm or 120 mm fan could be mounted to test different fans as well as vibration isolation techniques. The test fixture had two different mounting tops, one with threaded mounting holes to test fans directly screwed to the fixture, the other with the same 1.5 mm mounting pins used in the GEN1A design.

The test jig was characterized by performing an impulse response test in all three axes. The test results are shown in Appendix B.

5.4.1 “Company_A” vs. “Company_B”

To compare the vibration levels of a fan from “Company_A” and “Company_B”, two fans of similar design were selected for analysis. The fans chosen were:

- “Company_A”: 92 mm, 8000 rpm fan with PMF (same fan as used in GEN1)
- “Company_B”: 92 mm, 6300 rpm fan with CZF (used in another one of Ciena’s products)

Four samples of each were serialized A1-A4 for “Company_A” and B1-B4 for “Company_B”. Each fan was screwed to the benchtop jig and run at 6300 rpm. Figure 5.29 shows the test set up and Figure 5.30 through Figure 5.32 shows the RMS results for each axis.



Figure 5.29: Individual Fan Test "Company_A" vs. "Company_B" Set Up Screwed Down Fan

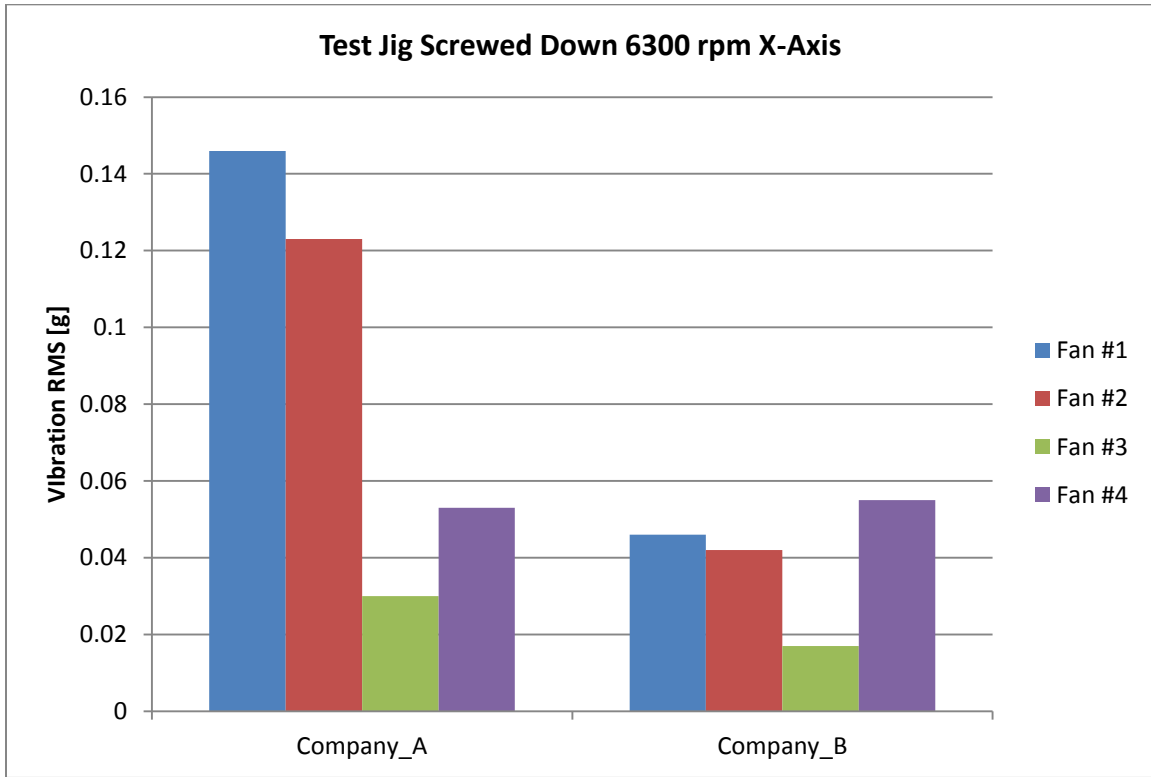


Figure 5.30: Individual Fan Test "Company_A" vs. "Company_B" Set Up Screwed Down Fan X-Axis

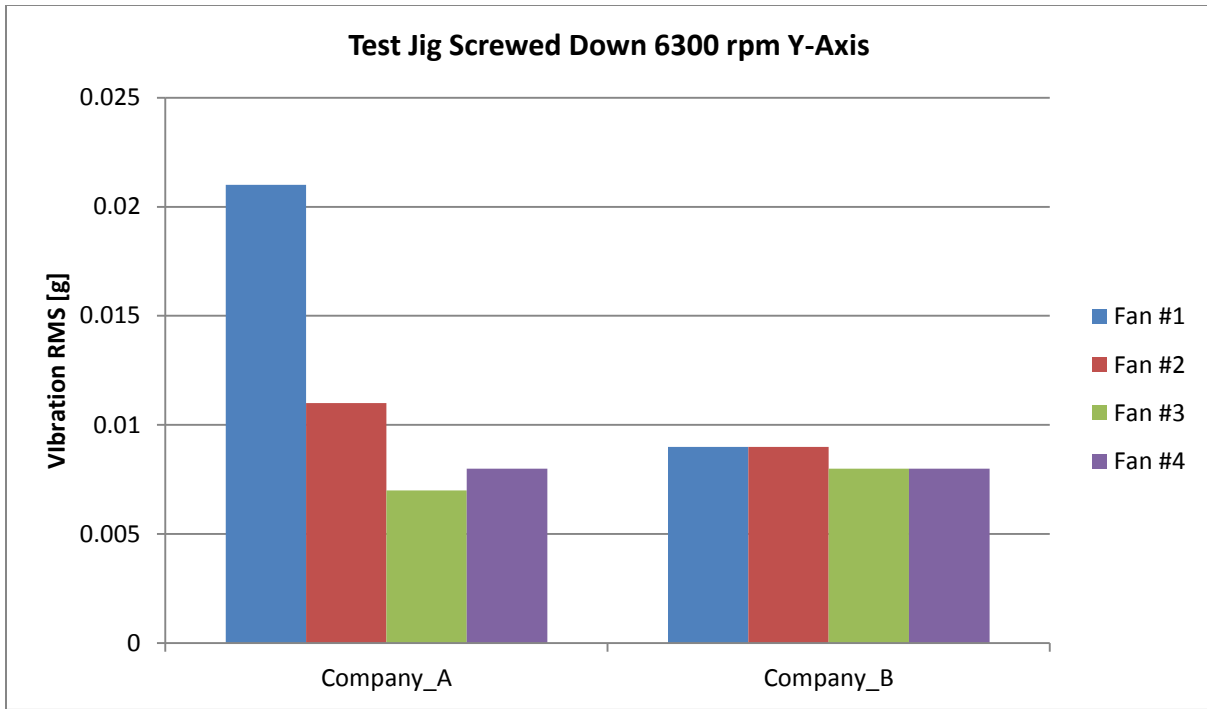


Figure 5.31: Individual Fan Test "Company_A" vs. "Company_B" Set Up Screwed Down Fan Y-Axis

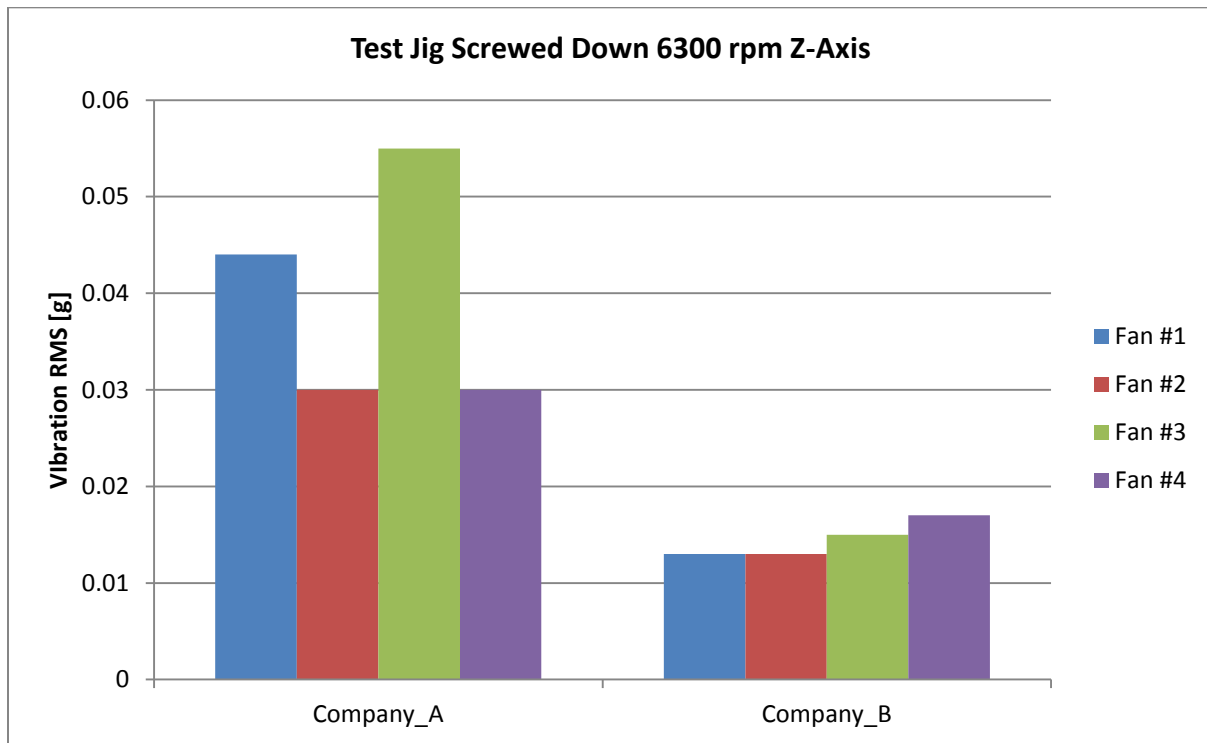


Figure 5.32: Individual Fan Test "Company_A" vs. "Company_B" Set Up Screwed Down Fan Z-Axis

The main conclusions that can be drawn from the above data are:

- A larger variation in vibration levels exists for fans made by “Company_A”
- The benchtop test jig is much more sensitive to vibration in the X-Axis. Theoretically, if the jig had a uniform design, the X-Axis and Y-Axis results would be very similar due to symmetrical construction of the fan. This is not an issue since the jig is to be used for 1:1 comparisons.
- RMS vibration levels for fans made by “Company_B” are lower and more consistent than those made by “Company_A”

The underlying reasons for why fans made by “Company_B” perform better are still not clear. It could be related to fan construction, motor design, PCB design, rotor balancing practices, etc.

Ciena thermal engineers began investigating “Company_B” fans that could be used for the GEN2 application. In the meantime, “Company_A” fans already in use or selected to be used will continue to be used in the near term. Once a “Company_B” fan is selected for the application, samples would be received and tested.

Chapter 6 Generation 2 Design Progression & Solution

6.1 GEN2 Individual Fan Testing

6.1.1 GEN2 Fan Characterization

The GEN2 requires a greater air flow, and thus a fan that operates at a faster speed. The initial fan selected by the thermal engineers for the GEN2 design was a 13000 rpm model made by “Company_A” with the same outer dimensions as the GEN1. The GEN2 was to become the main design focus at this stage since the GEN1 had an acceptable interim solution, and the GEN2 would allow systems to be upgraded to higher power line cards.

Fans tested were serialized as before, with GEN2 fans being denoted as AH1 (“Company_A” High-speed) with the number incrementing for each fan serialized. “Company_A” also improved their balancing procedures during the time that these tests were conducted. A sample was provided and tested; these fans are serialized as AHB1 (“Company_A” High-speed Balanced).

The initial tests conducted were performed on the benchtop jig with all fans screwed down, as in the LFU. Two methods of speed control were used for these tests:

1. **PWM Control:** fan speed is controlled using the fan’s internal controller which uses an input supplied by a square wave signal from a function generator. The PWM control allows for control between 20-80% duty cycle. As a result, the top of the fan speed range cannot be obtained using this method.
2. **Voltage Control:** fan speed is controlled by varying the input voltage. Nominal voltage for GEN1 fans is 12 V, GEN2 fans is 48 V. By varying the input above/below the nominal value, fan speed can be modified. The top of the speed range is obtainable with this method, but the bottom end of the speed range is not accessible.

Figure 6.1 shows a comparison between two different GEN1 fans A9, A10, a standard balanced GEN2 fan AH1, and a rebalanced GEN2 fan AHB1. Figure 6.2 shows the same plot but with greater detail at lower vibration levels. All figures show X-Axis only as this is of the most interest for current purposes.

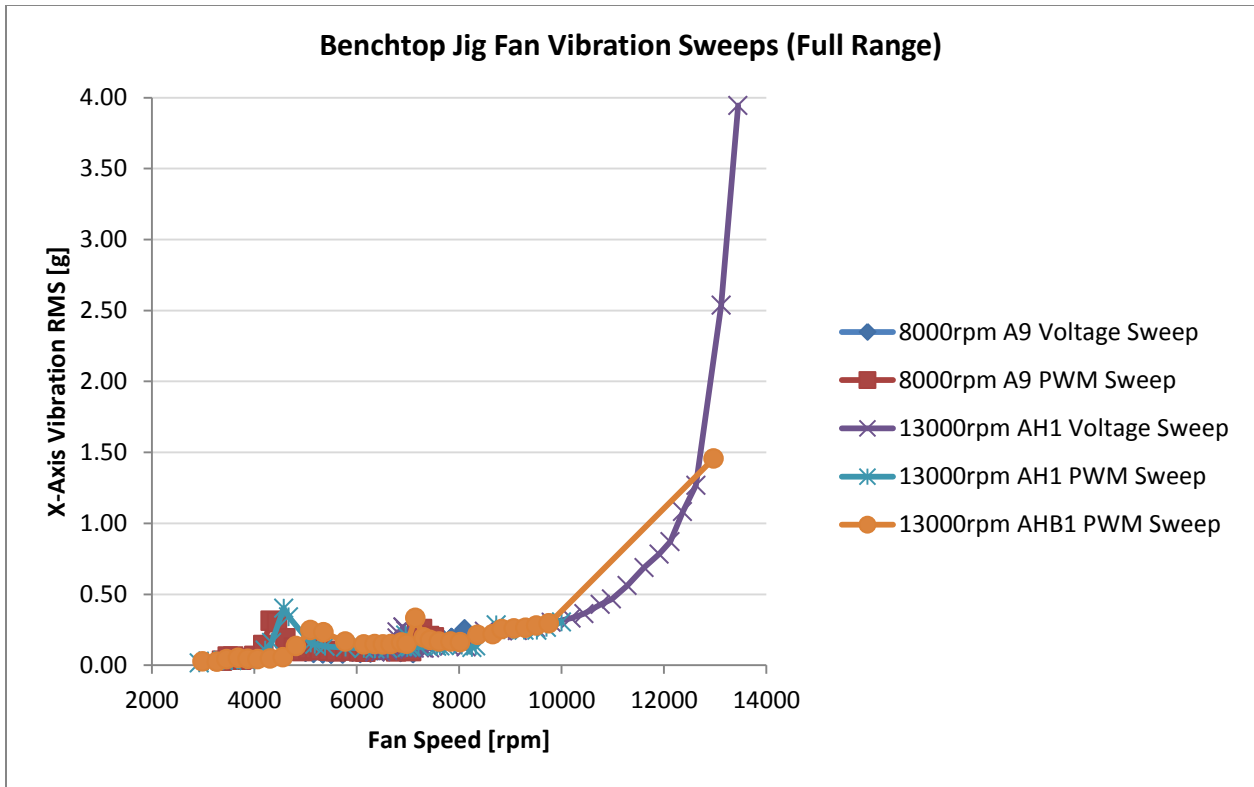


Figure 6.1: Benchtop Test Jig Fan Vibration Sweep GEN1 & GEN2 (Full Range)

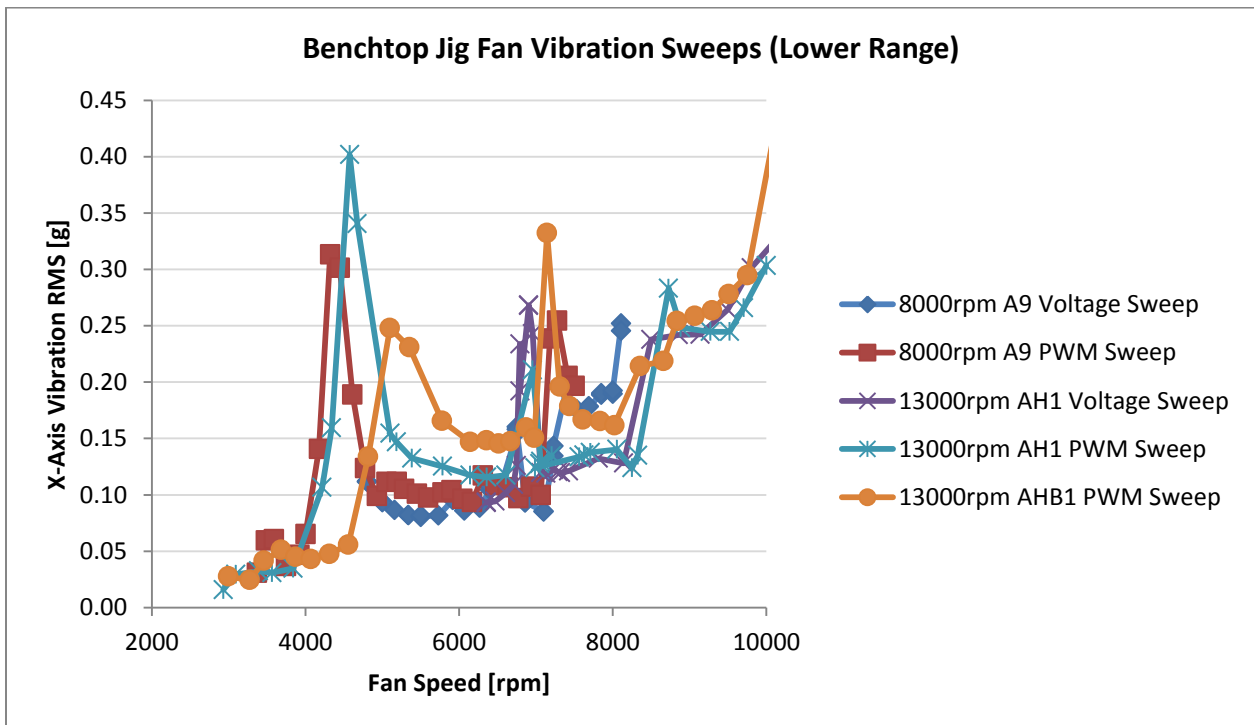


Figure 6.2: Benchtop Test Jig Fan Vibration Sweep GEN1 & GEN2 (Lower Range)

These above figures are not ideal for showing details of individual plots, but they do show the following overall trends:

1. A resonance is present around 4000 rpm. This appears in each data set and is not present in either the GEN1 or GEN1A. This may be ignored because it is a resonance inherent to the test jig and not relevant to the system being considered.
2. All fans show a resonance around 7000 rpm. This resonance appears to be related to fans manufactured by “Company_A”.
3. Both UFU fans show exponential vibration behaviour, with the transfer from the flat portion of the curve occurring at 10000 rpm. The overall amplitude at 13000 rpm was significantly greater for the standard AH fan. The balancing done on the AHB fan does have a significant impact on vibration levels. All UFU fans to be used in design will be AHB fans.

6.1.2 GEN2 Design with Retrofit Isolators Preliminary Testing

The GEN2 fan unit with retrofit isolators will be denoted as GEN2A. The same design as used on the GEN1A is planned to be tested on the GEN2A. The parts already exist in the supply chain and would be a simple solution to implement.

The GEN2 design itself is more complex than simply replacing the 8000 rpm fans with 13000 rpm fans; the internal PCBs need to be redeveloped and all other aspects of the internal design are also open for change. Implementing the same vibration isolation parts as the GEN1A will allow for design and development of the other fan unit components to move forward while a more comprehensive vibration isolation solution is devised.

For the GEN2A design, various materials were tested for the cylindrical isolator. *PORON 4701-30-15 (extra soft)*, *PORON 4701-60-15 (extra firm)*, and *Bisco HT-6360 (stiffest)* were used. The materials selected are urethane foam materials which come in sheets and can be easily water jet cut into a cylindrical shape which is ideal for the retrofit isolator design. Urethane foams are designed for use in vibration reduction applications, and by selecting and testing a wide range of stiffnesses, the optimal material can be determined. Figure 6.3 shows an OM top view of a *PORON 4701-30-15* isolator as used for testing.

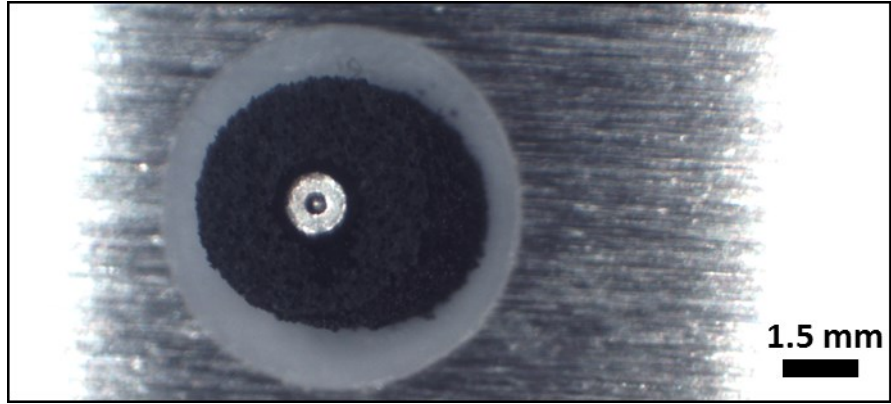


Figure 6.3: OM top view of GEN1A/GEN2A Isolator

The X-Axis results of the material variation tests as done on the benchtop test jig are shown in Figure 6.4 as compared to the same AHB1 fan screwed to the test jig.

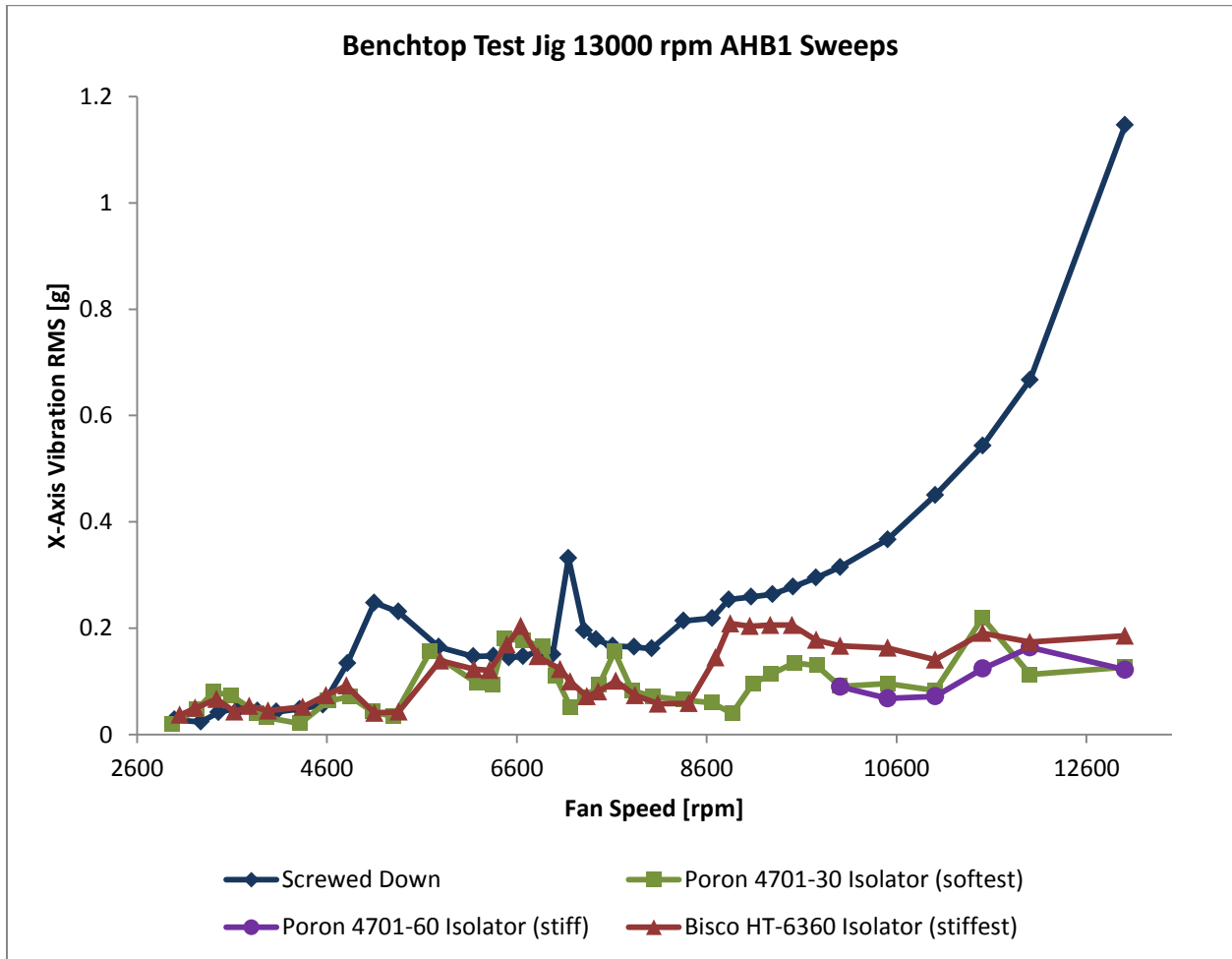


Figure 6.4: Benchtop Test Jig Fan Vibration Sweep GEN2A Materials Variation

As shown above, the isolator material that performs the best appears to be the *PORON 4701-30-15*. However, the difference with stiffer materials is not significant and can be attributed to imperfections and errors in the testing. The stiffer *PORON 4701-60-15* had similar vibration damping characteristics at higher fan speeds (10000 – 13000 rpm).

This stiffer *PORON 4701-60-15* material was preferred as longer functional life would be expected in comparison to the softer material. Going forward, it is to be used on the GEN1A and GEN2A to improve yields due to install-ability damage as well as long term life. Install-ability damage could be caused by the edge of the fan mounting hole contacting the isolator and ripping the isolator material.

6.2 GEN2 Solution Using Retrofit Isolators (GEN2A)

As a result of the *PORON 4701-60-15* material selection in the previous section for GEN1A and GEN2A designs, this solution needed to be tested in a fan unit in a shelf.

The GEN2A design uses the same design changes and form factor as the GEN1A (section 5.3). Critical dimensions of the GEN2A Alpha prototype are shown in Figure 6.5.

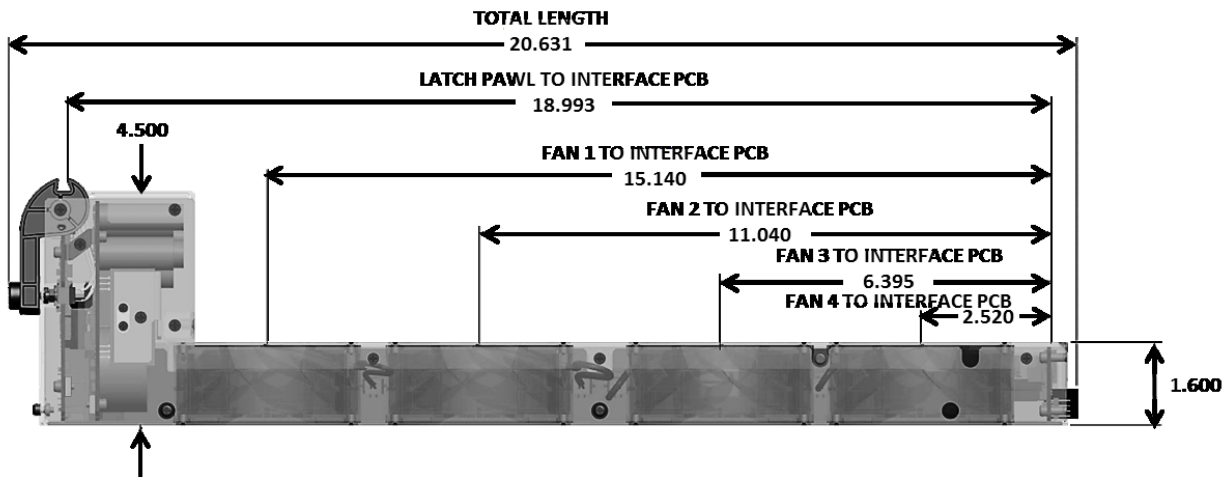


Figure 6.5: GEN2A Critical Dimensions (side) [inches]

Five initial Alpha prototype units were received with AHB fans and *PORON 4701-60-15* isolators. Feedback from the CM revealed that the assembly process with this isolator design was difficult, especially dealing with the small parts and keeping the adhesive contained only to the pin area.

An alternate solution was devised to replace the isolator, PTFE washer, and adhesive used in the GEN1A and GEN2A design with a single injection molded part to make the assembly process easier and hopefully improve vibration performance. With the input of an external company, an isolator geometry was designed that would incorporate the cylindrical isolator and washer into one part. The geometry chosen would negate the need to use adhesive. Figure 6.6 shows the part geometry.

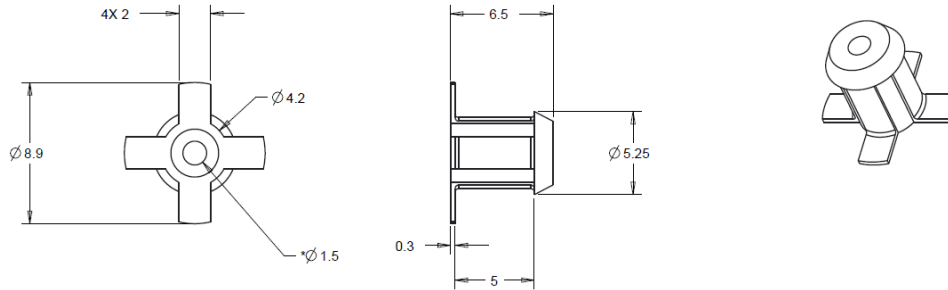


Figure 6.6: GEN1A/GEN2A Integrated Isolator Design [mm]

The part was molded using *EAR 3M Isoloss SL-20300*, the mechanical properties of which are shown in Table 6.1. [54]

Table 6.1: EAR Isoloss SL-20300 Physical Properties

Durometer (Shore “A”)	Maximum Temp. Intermittent (°C)	Max. Continuous Temp. (°C)
20	100	90

The five initial prototypes were tested in Shelf_A in the top row. The shelf software was not yet updated to allow the software to control GEN2As with their updated circuit design and fan speeds. As a result, the power engineers wired leads from the GEN2As that connected directly to the PWM control built into each individual AHB fan. This allowed a function generator to control fan speed, and with the PWM control removed, the fans would default to their maximum speed, 13000 rpm. The bottom row of fans were GEN1s and installed but not powered.

Two different prototypes of five GEN2As were tested (Figure 6.7 through Figure 6.9):

1. As received GEN2A with *PORON 4701-60-15* isolators
2. Modified GEN2A with *Isoloss SL-20300* integrated isolators

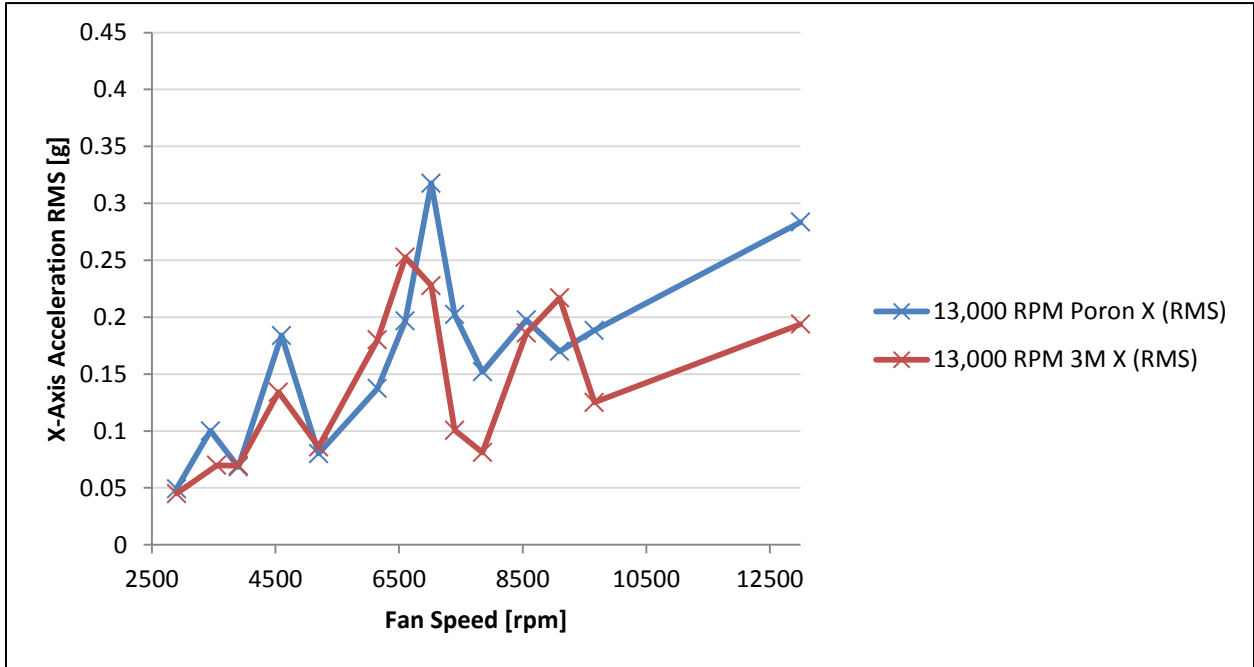


Figure 6.7: Shelf_A Slot #2 GEN2A Sweep *Poron* vs. *Isoloss* X-Axis

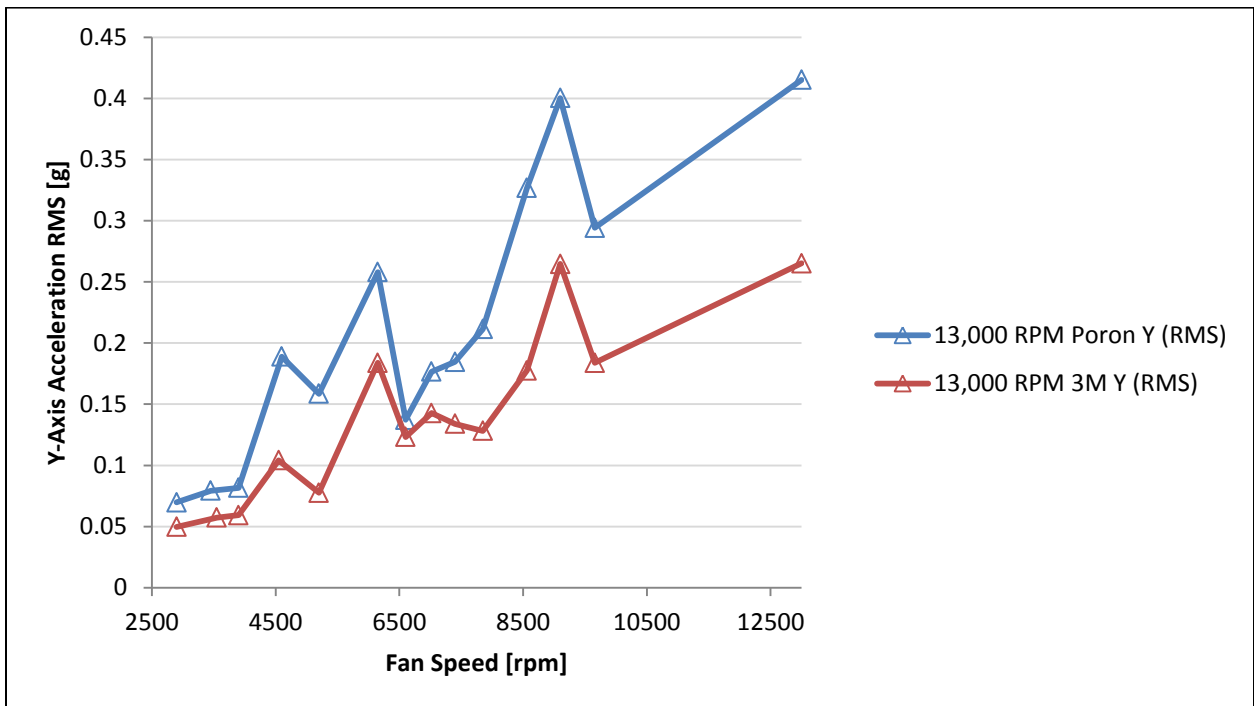


Figure 6.8: Shelf_A Slot #2 GEN2A Sweep *Poron* vs. *Isoloss* Y-Axis

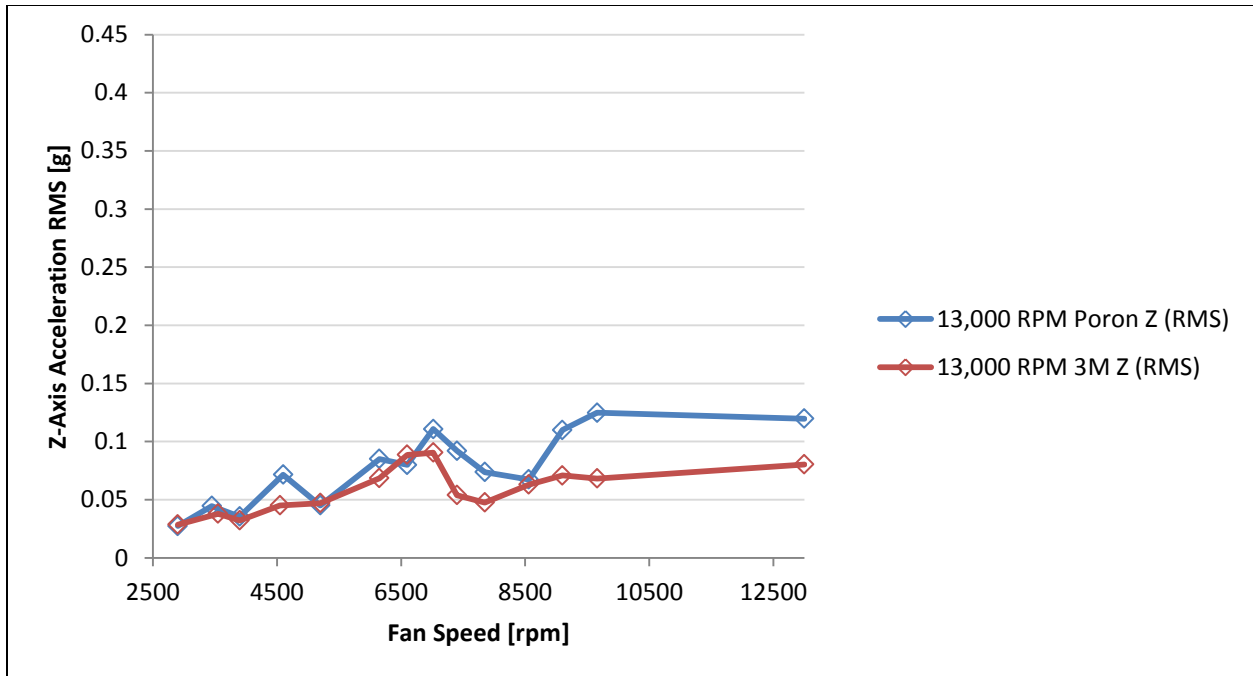


Figure 6.9: Shelf_A Slot #2 GEN2A Sweep *Poron* vs. *Isoloss* Z-Axis

These results show a significant vibration reduction when compared to AHB1 screwed to the benchtop test jig. These plots also show that the vibration curve is noisy and unpredictable, with the fan resonance around 5700-7000 rpm still present. This had been damped out in the past, but with the introduction of five GEN2As installed as they would be at a customer site, this vibration resonance has returned. The resonance may have returned as a result of changing to a new 13000 rpm fan with different motor dynamics since it is designed to operate at nearly twice the speed as the original fan; or the mounting hole tolerance on the 13000 rpm fans was tighter than that of the original 8000 rpm fan since the injection molding tool for the new fan had just started production and the 8000 rpm fan had been produced for a longer period of time. Nonetheless, the *Isoloss* prototype showed an improvement over the *Poron* solution, but not significant enough to justify the cost of buying production tooling to implement the change.

Maximum RMS vibration levels are still on the order of 0.3 to 0.4 g RMS. Ultimately, it has been shown that a better solution is likely needed in order to reduce the vibration to acceptable levels.

6.3 Development and Testing to Find Ultimate GEN2 Solution

By this stage of the development process, the thermal engineers had been in contact with “Company_B” about a fan of equivalent performance to that of the 13000 rpm fan manufactured by “Company_A”. “Company_B” specially developed a fan that has the same airflow performance and dimensions that operated at a maximum speed of 12000rpm; these fans will be referred to as BH fans. Four samples were delivered to Ciena in Ottawa for further testing and qualification. Figure 6.10 shows a BH fan, note the cast zinc frame construction.

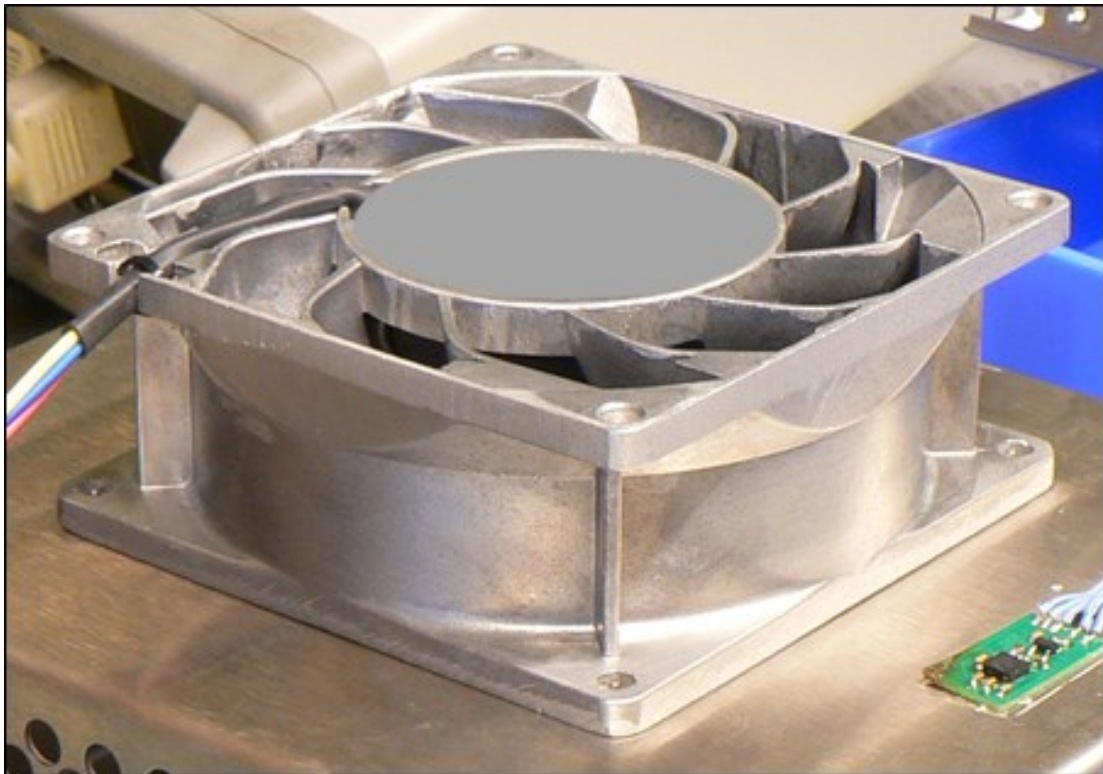


Figure 6.10: "Company_B" BH 12000rpm fan

All fans tested up until this point were of standard construction with four corner mounting flanges per face. The next step will be to consider alternatives and to determine the maximum amount of vibration reduction achievable if the standard fan envelope were to be modified.

Modification of the fan construction itself was an option that was only considered as a last resort.

The reasons that modifying the fan housing was not desirable were:

1. **Tooling cost:** the tooling for casting the frames would have to be purchased by Ciena. This is a large upfront cost and is non-recoverable in terms of company profit. The benefit of owning the tool is that Ciena is the only company that can make use of it.
2. **Non-standard geometry:** the fans created would be of non-standard geometry and likely unique to specific applications. This would likely result in a higher cost per fan since the production volumes would be lower.
3. **No second source:** the custom fan would only be available from one manufacturer where the tooling was purchased. If an issue were to develop with the fan, sourcing an alternate fan from another manufacturer would not be possible unless a second similar tooling set were purchased separately from that company.
4. **One chance:** the tooling of new fan geometry would need to be as close to the final design as possible. Modifications to the tooling would be possible once it had been created but changes are limited depending upon the construction of the tool; they can also be very costly.

However, if returns in the form of greatly reduced vibration levels could be proven if the fan geometry were modified, taking the above risks would be justified.

This stage of the design aims to reduce the vibration level by any method necessary, within reason, including modifying the fans themselves.

6.3.1 Single Unit in Shelf Results: GEN1 & GEN2

Large quantities of vibration data for various fans were accumulated. This data consist of individual fan units of each type assembled to Slot #2 of Shelf_A and operated at various speeds to obtain RMS vibration data.

The above mentioned BH fans were also tested in the same manner by being inserted in a prototype GEN2A in place of the AHB fans provided by the CM.

The results obtained are shown in Figure 6.11. Only the instrumented fan is powered in these plots: the obtained values cannot be directly compared with other vibration plots obtained under different test conditions. Initial un-isolated GEN2 data is not provided as it is inappropriate for comparison due to overly excessive vibration levels.

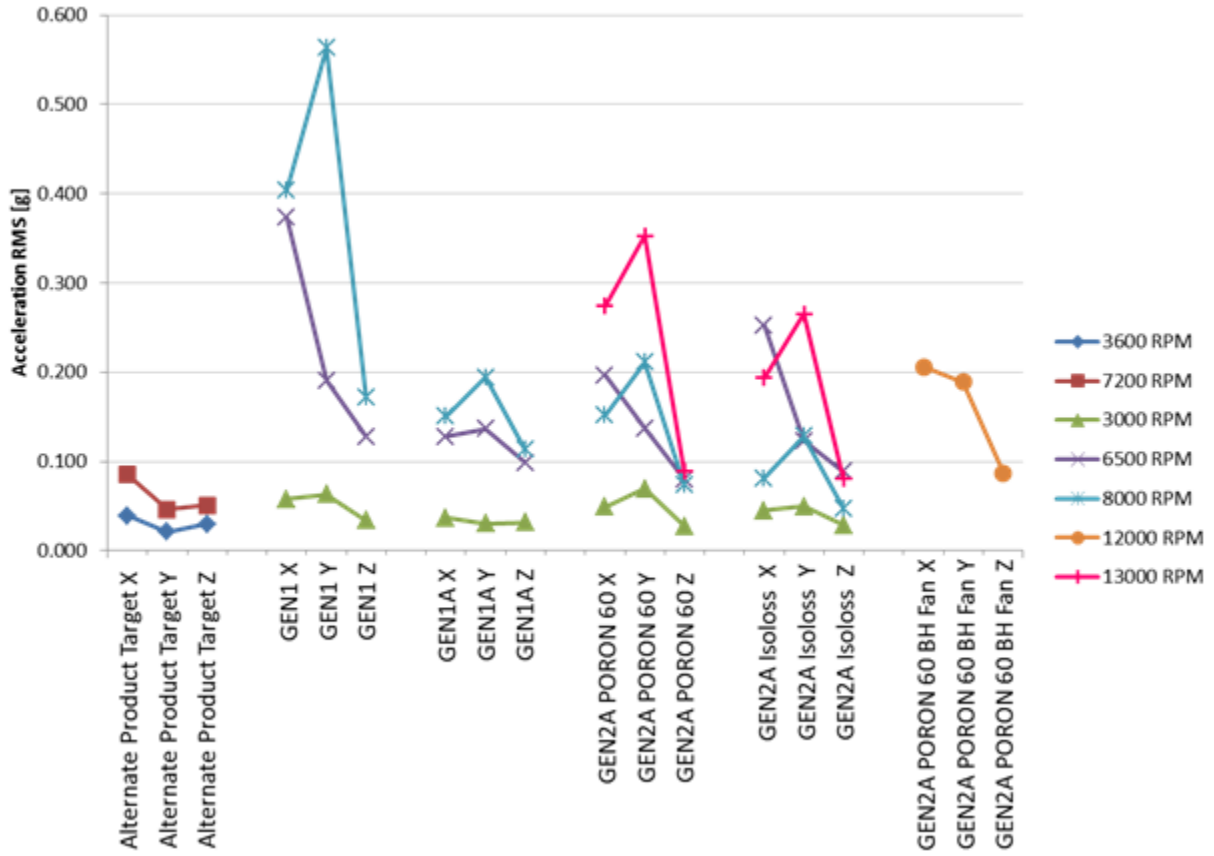


Figure 6.11: Shelf_A Slot #2 Single Fan Unit Only – Alternate Product Target Provided as Reference Only

The comparison in Figure 6.11 illustrates that although vibration reductions are achieved and vibration levels, especially at high frequencies, are reduced, vibration levels are still above the target value. These vibration levels will only increase under FF conditions. It is thus clear that modifications to the standard fan itself are required. This ultimate GEN2 fan unit will involve modifying the fan housing itself, this fan unit will be denoted GEN2B.

6.3.2 GEN2B Individual Fan Testing

In order to quickly test various vibration isolation methods, testing was returned to the benchtop test jig so that only one fan needed to be modified per test. Different isolator variables would be tested on both the AHB and BH fans and compared to the vibration levels obtained from one of the fans from the alternate product attached to the test jig.

The variables considered in this testing were:

1. Height of isolator (Z-dimension)
2. Size of isolator (X-, Y-dimension)
3. Material

To simplify testing, it was assumed that no external constraints on the system were considered (fan and shelf geometry). As a result, fan flanges were not modified in order to test thicker isolators; the fans themselves were mounted directly on top of the isolators. The main goal was to examine the possibilities in vibration isolation for the fans being considered. Once achievable vibration levels are known, then a solution that fits into the existing fan and shelf structure can be considered.

AHB fans were used only for this test to minimize variables. It has already been shown that BH fans outperform AHB fans, so any vibration reduction seen on AHB fans should at a minimum also be observed on the BH fans.

Isolator Materials AHB Fan

The UFUI solution was tested in Shelf_A in order to compare the cylindrical *PORON 60* isolators for the *Isoloss SL20300* isolators. Two harder durometers of *Isoloss* material were also provided from the manufacturer but not yet tested: *Isoloss SL35300* and *Isoloss SL50300*.

In an effort to determine the optimal durometer for the isolator materials to be tested, an AHB fan was mounted on the test jig using the interim vibration isolation solution incorporating materials with various durometers.

Table 6.2 shows the durometers of each material tested.

Table 6.2: Isolator Material Properties (Durometer)

Manufacturer	Material	Material Construction	Durometer (Shore A)
3M EAR	SL50300	synthetic rubber	47
3M EAR	SL35300	synthetic rubber	32
Rogers	PORON 60	urethane foam	30
3M EAR	SL20300	synthetic rubber	20
Rogers	Bisco BF-2000	urethane foam	1

The durometer of the material tested was the most critical parameter tested. All other characteristics such as the long term life of the material as well as manufacturing methods associated with fabricating an isolator for each material type was a secondary consideration.

A sweep was conducted using PWM control for most points, and voltage control for the 13000 rpm data point. Figure 6.12 shows the results of the test with the target vibration value also indicated.

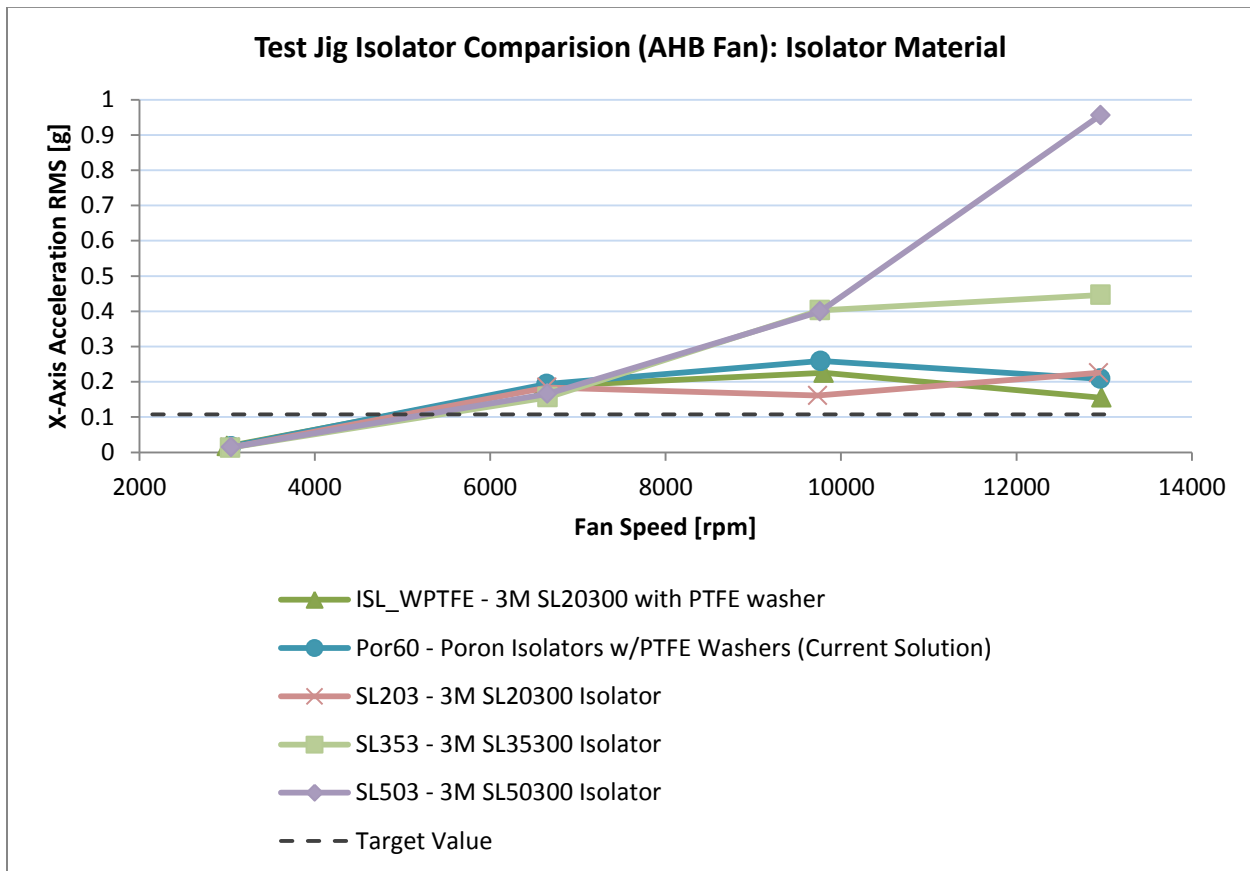


Figure 6.12: Isolator Test Jig Material Durometer Comparison

It can be shown from the above data that the softer materials perform better, but diminishing returns become apparent below approximately Shore A 30, which is currently used in the GEN1A and GEN2A designs.

Isolator Height & Size AHB Fan

The next goal was to determine the effect of larger isolators on fan performance. *BF-2000* foam was used to create isolator pads of various sizes and shapes to place under all four corner flanges of the fan. The configurations tested were:

1. Isolator height:
 - a. 0.125 in thick foam triangle with *PORON 60* isolators
 - b. 0.250 in thick foam triangle with *PORON 60* isolators
2. Isolator size:
 - a. 0.3 in diameter 0.250 in thick with *SL20300* isolators
 - b. 0.6 in diameter 0.250 in thick with *SL20300* isolators

Figure 6.13 shows the test set up for the “0.3 in diameter 0.250 in thick with *SL20300* isolators” configuration for reference.

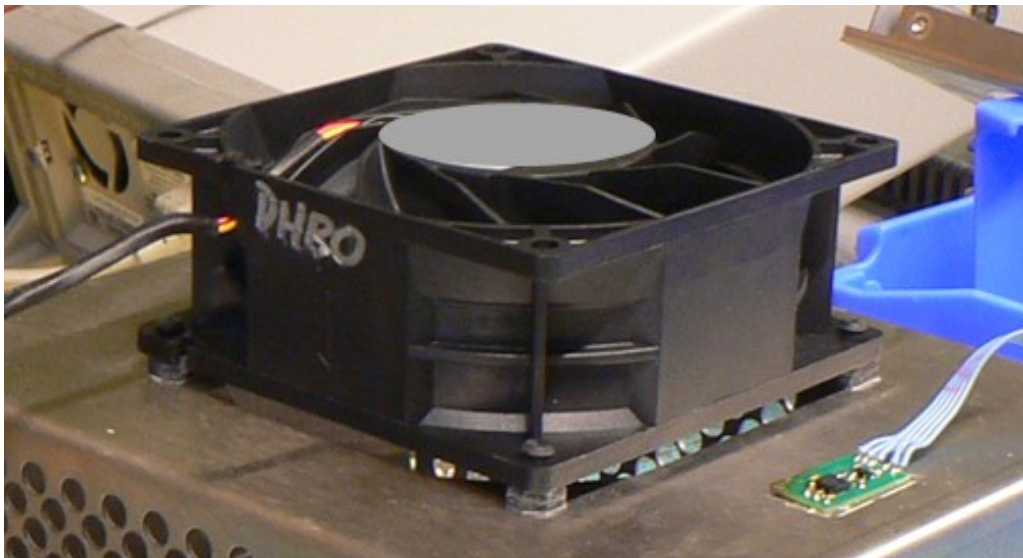


Figure 6.13: AHB Fan Test Jig “0.3 in diameter 0.250 in thick with *SL20300* isolators”

Figure 6.14 shows the results of the testing.

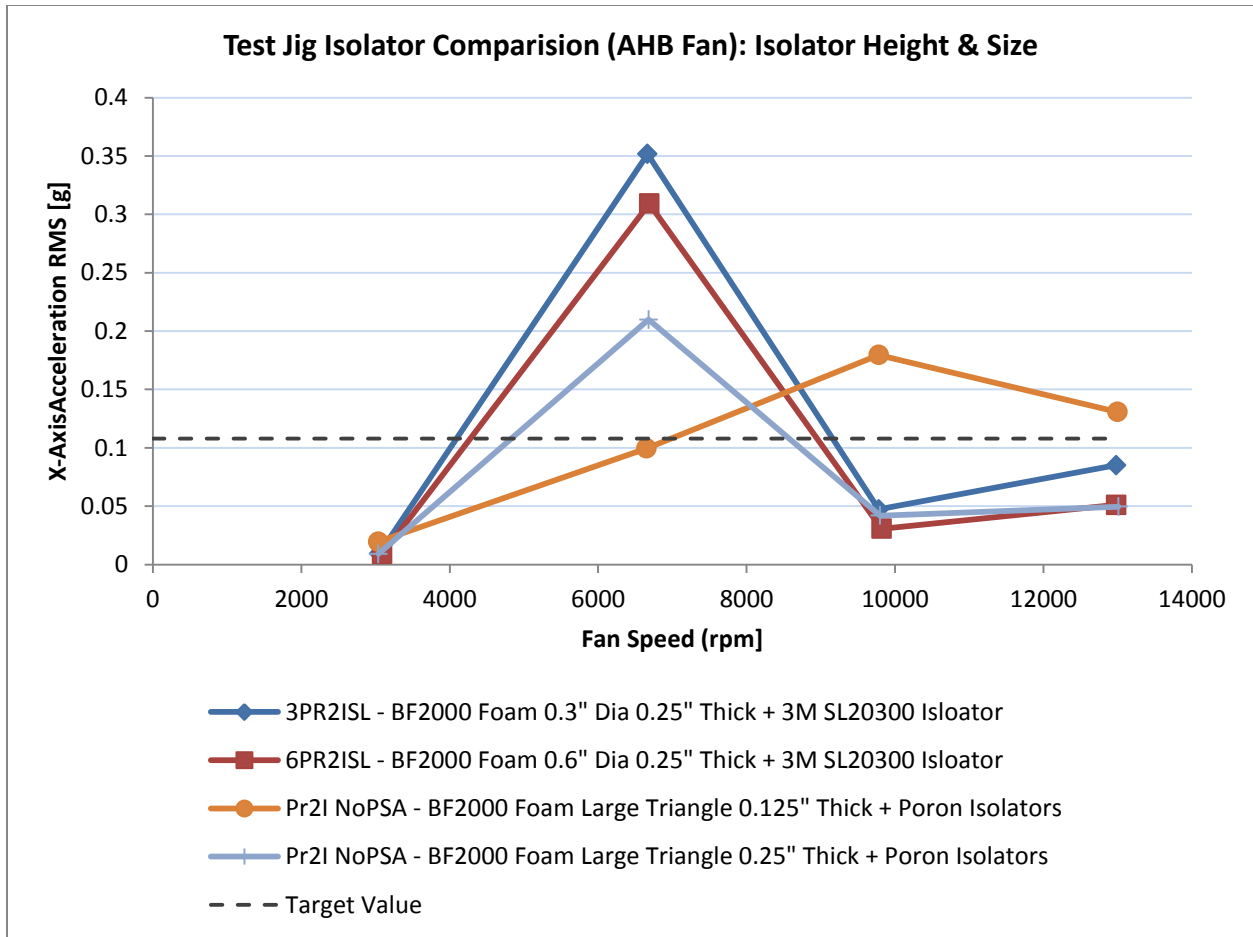


Figure 6.14: Isolator Test Jig Height & Size Comparison

Two conclusions can be drawn from these results:

1. **Height:** Greater isolator height provides greater vibration reduction
2. **Size:** Greater isolator size provides greater vibration reduction

Intuitively, this is as expected, but it confirms that greater reductions in vibration can be achieved if the fans are modified to accommodate larger isolators. A block diagram proposing an initial concept of what this design would look like is shown in Figure 6.15.

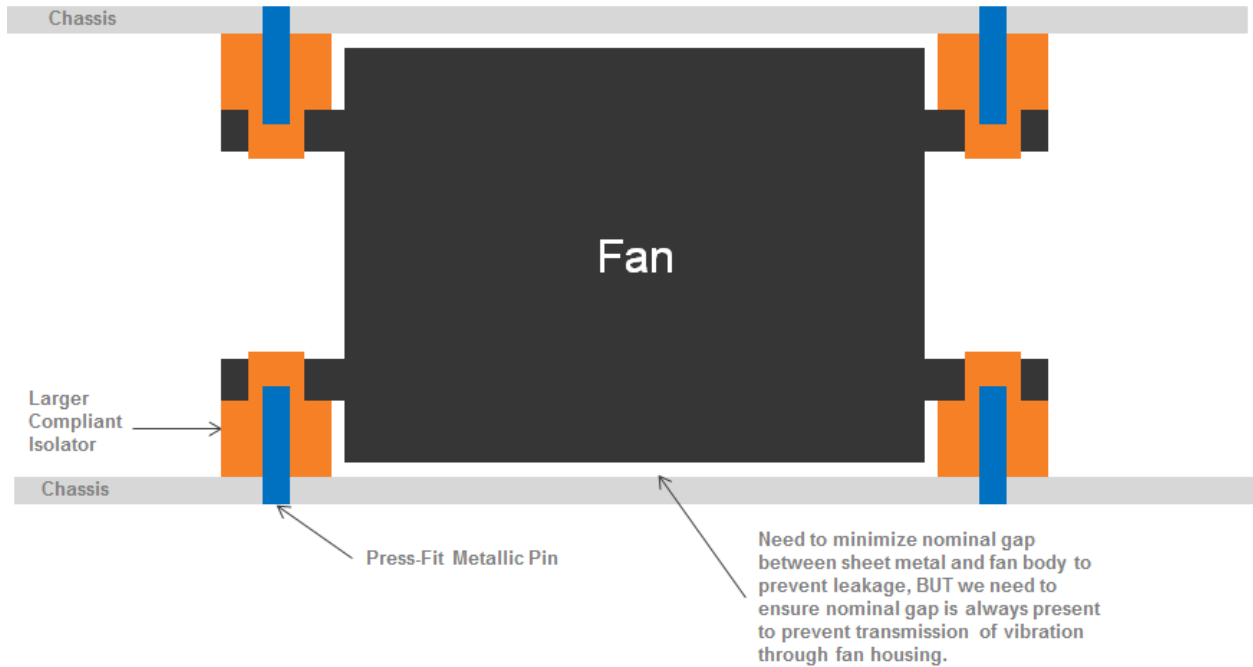


Figure 6.15: GEN2B Flange Isolator with Modified Fan Flanges Block Diagram Concept

6.3.3 Modified Alpha Prototype GEN2 Isolator Designs & Results

The Alpha GEN2A prototypes were modified to test the new vibration isolator concepts. These vibration isolators were designed and injection molded by *EAR 3M* out of *Isoloss SL20300* material. Two types of vibration isolators were proposed for this round of testing (these isolators are Patent Pending):

1. **Fan flange isolators:** as described in the previous section. Figure 6.16 shows the proposed isolator design. In order to install these isolators on fans and test them in a GEN2, the flanges of 5 sets of standard AHB fans were removed by an external CM. Custom flanges were designed, 3D printed and glued to the modified fans using *Loctite 4205*. The final modified AHB prototype (AHBM) is shown in Figure 6.17. AHB fans were used since only four prototypes of BH fans existed and were too valuable to modify. If this design is implemented, it would use modified BH fans (BHM).

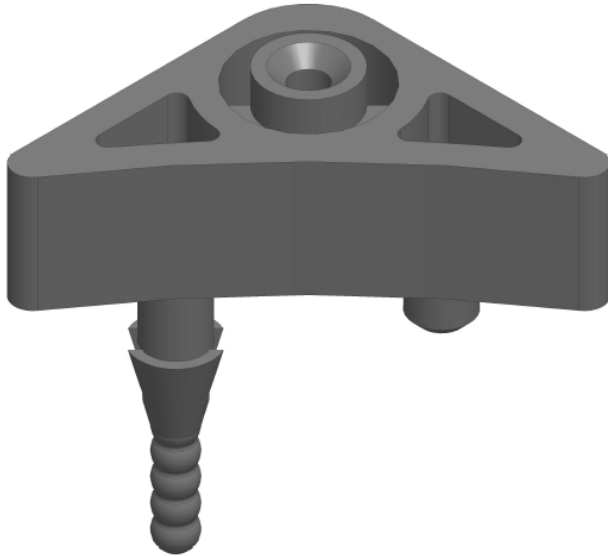


Figure 6.16: Flange Isolator Design (CAD)

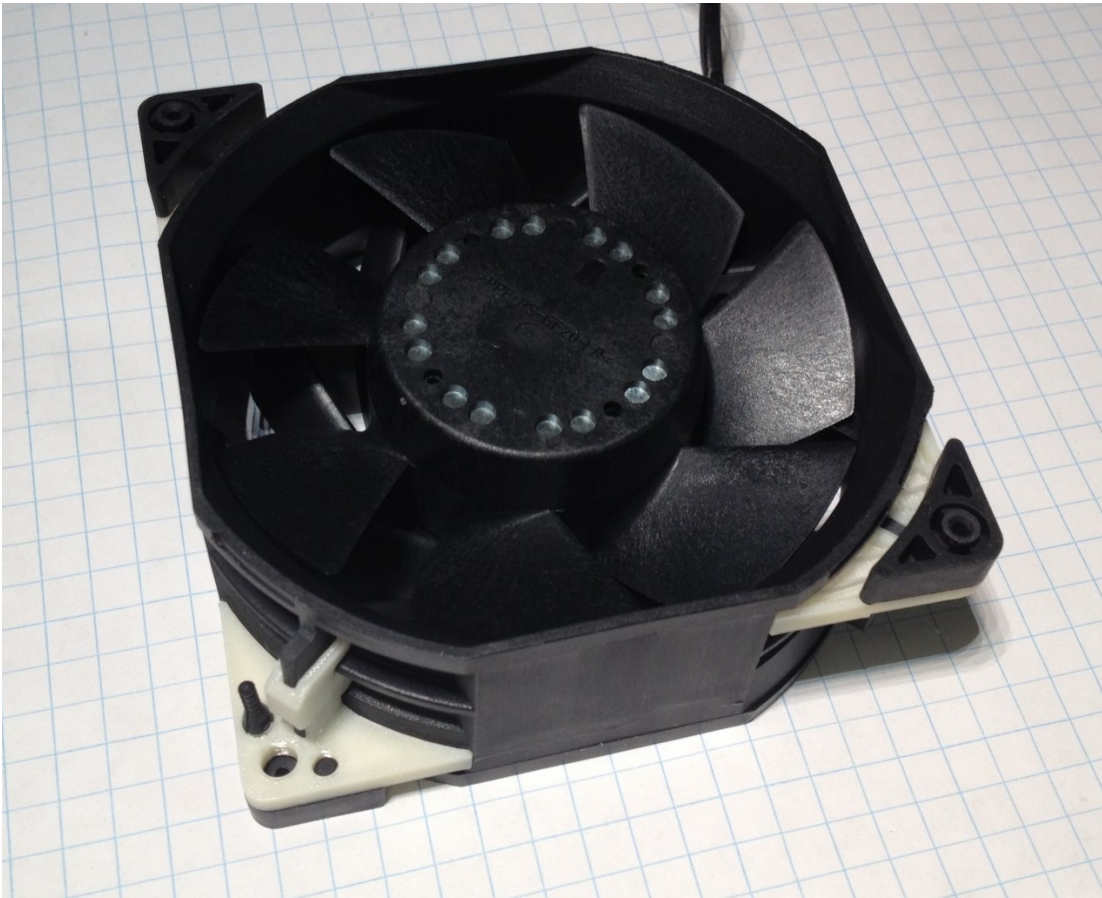


Figure 6.17: AHBM Modified Flange AHB Fan with Flange Isolators

2. **PCB isolators:** currently the PCB that contains the backplane connector is rigidly connected to the fan sheet metal using screws. Proposed isolators replace the rigid connection with an isolated joint as shown in Figure 6.18, effectively floating the backplane connector PCB. This design requires a larger PCB hole, and therefore a PCB redesign if the modified prototype shows a marked reduction in vibration. For testing purposes, larger holes were drilled in the existing PCB and the fan units were modified to operate from an external power supply.

It is also important to note that the GEN2 design incorporates an interconnect PCB that connects the rear PCB to the front two PCB that control the fan and filter the incoming power. In the Alpha GEN2A design, a connector rigidly connects the backplane connector PCB to the interconnect PCB and the top and bottom fan flanges of the nearest fan nest above and below this connector. In order to clear this connector with the AHBM, one of the flanges needed to be removed on this corner; for symmetry, half of the total flanges were removed.

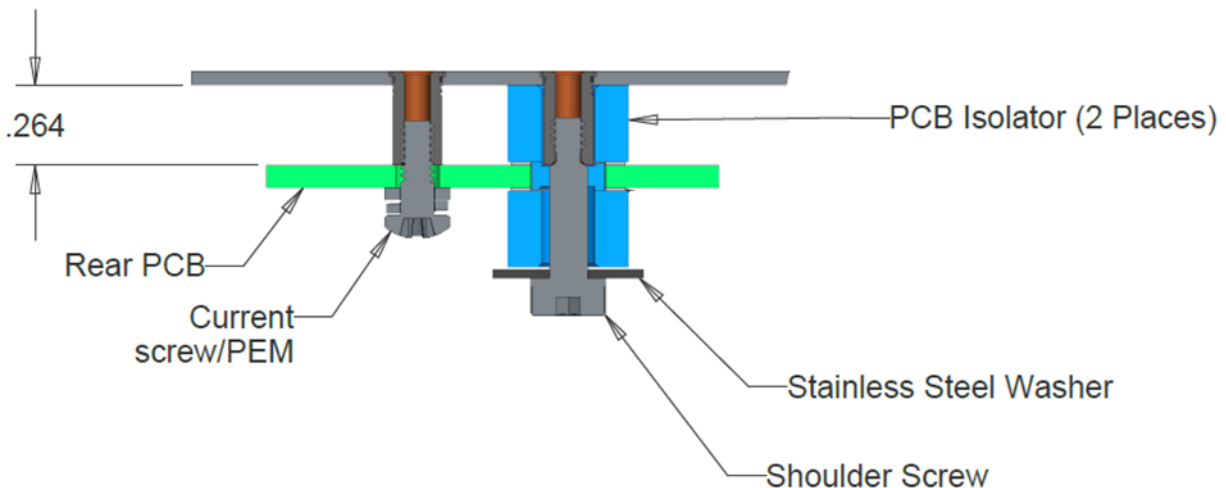


Figure 6.18: PCB Isolator Design vs. Rigid Connection

Five sets of Alpha GEN2As with AHBM fans were constructed with help from the power team in order to power them externally from the shelf.

Four test cases were chosen, each with different modifications performed to the modified fan units, as summarized in Table 6.3. Figure 6.19 through Figure 6.22 show CAD images (some parts hidden) of each test case.

The results of these test cases were compared to a set of five GEN2A fans with *PORON 60* isolators. All tests were performed in Shelf_A in the top and bottom five fan slots. The instrumented fan was located in Slot #2 and Slot #7 respectively.

Table 6.3: Modified Alpha GEN2A with AHBM Fans Test Cases

Test Case	Test Case Name	Flange Isolators	PCB Isolators	Rigid PCB	Float PCB
1	Flange Isolators (Rigid PCB)	X		X	
2	Flange & PCB Isolators (Rigid PCB)	X	X	X	
3	Flange & PCB Isolators (Float PCB)	X	X		X
4	Flange Isolators (Float PCB)	X			X

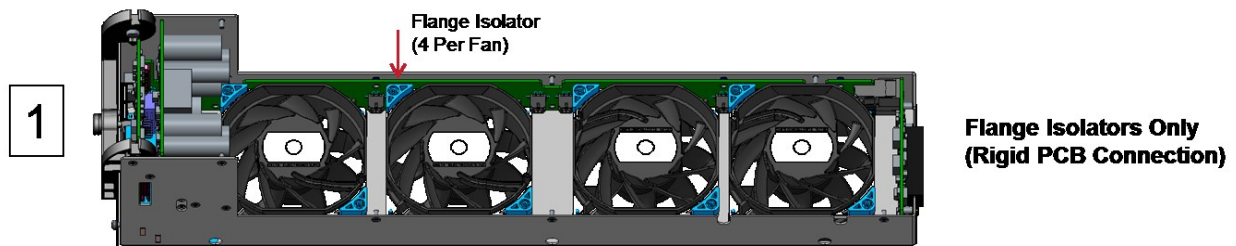


Figure 6.19: GEN2A with AHBM Test Case #1: Flange Isolators (Rigid PCB)

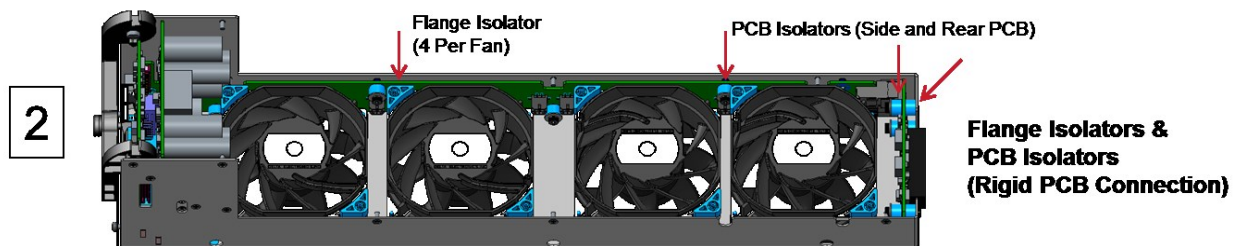


Figure 6.20: GEN2A with AHBM Test Case #2: Flange & PCB Isolators (Rigid PCB)

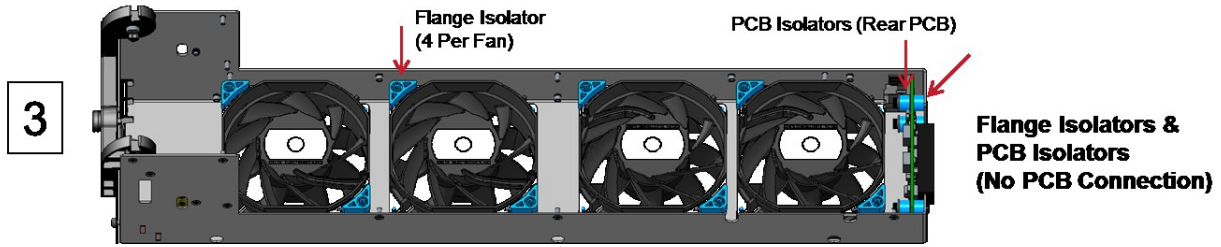


Figure 6.21: GEN2A with AHBM Test Case #3: Flange & PCB Isolators (Float PCB)

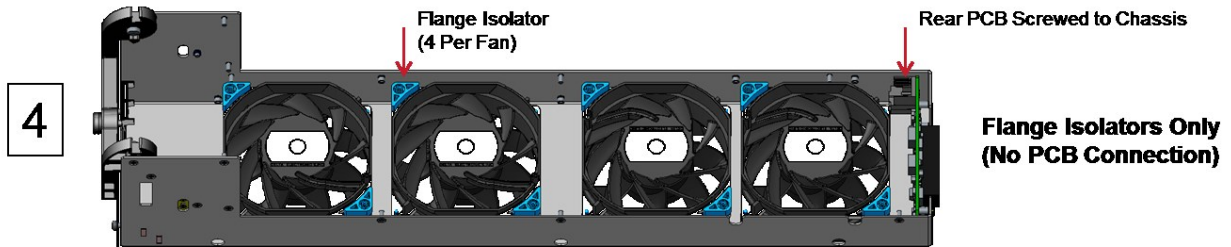


Figure 6.22: GEN2A with AHBM Test Case #4: Flange Isolators (Float PCB)

Both the X-Axis and Y-Axis data for the top and bottom slots was plotted and are shown in Figure 6.23 through Figure 6.26.

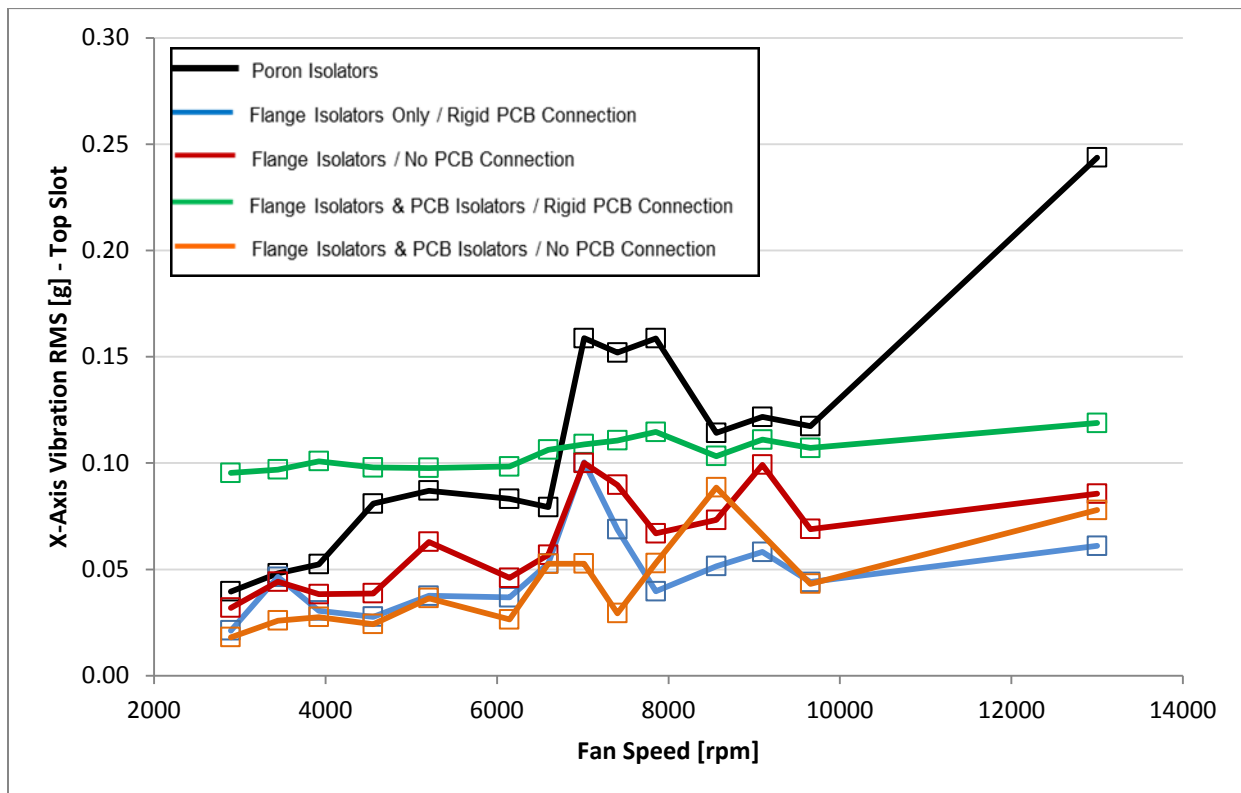


Figure 6.23: GEN2A with AFBM Test Cases Top Slot X-Axis

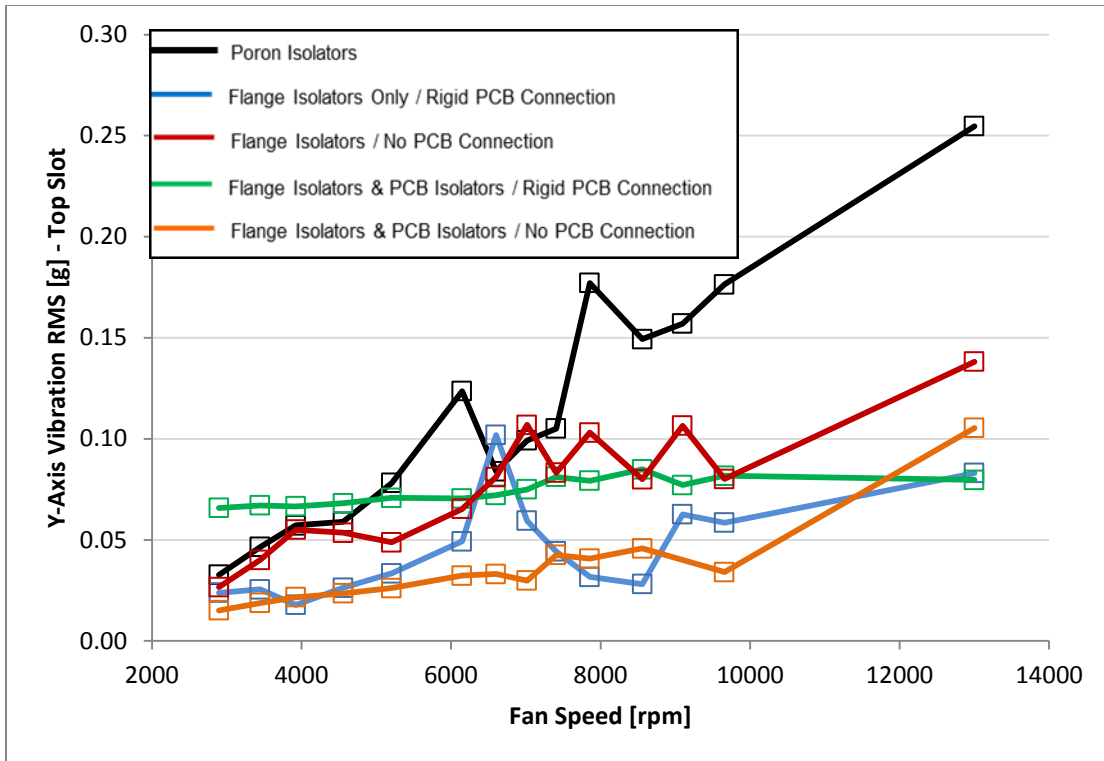


Figure 6.24: GEN2A with AFBM Test Cases Top Slot Y-Axis

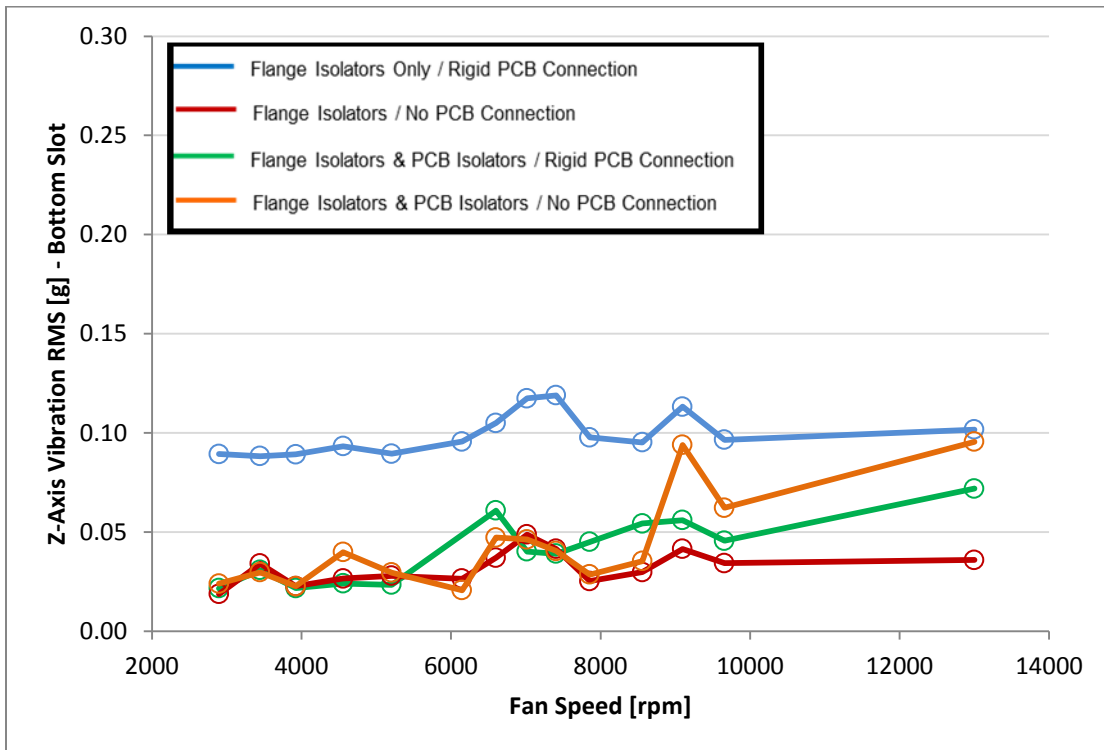


Figure 6.25: GEN2A with AFBM Test Cases Bottom Slot X-Axis

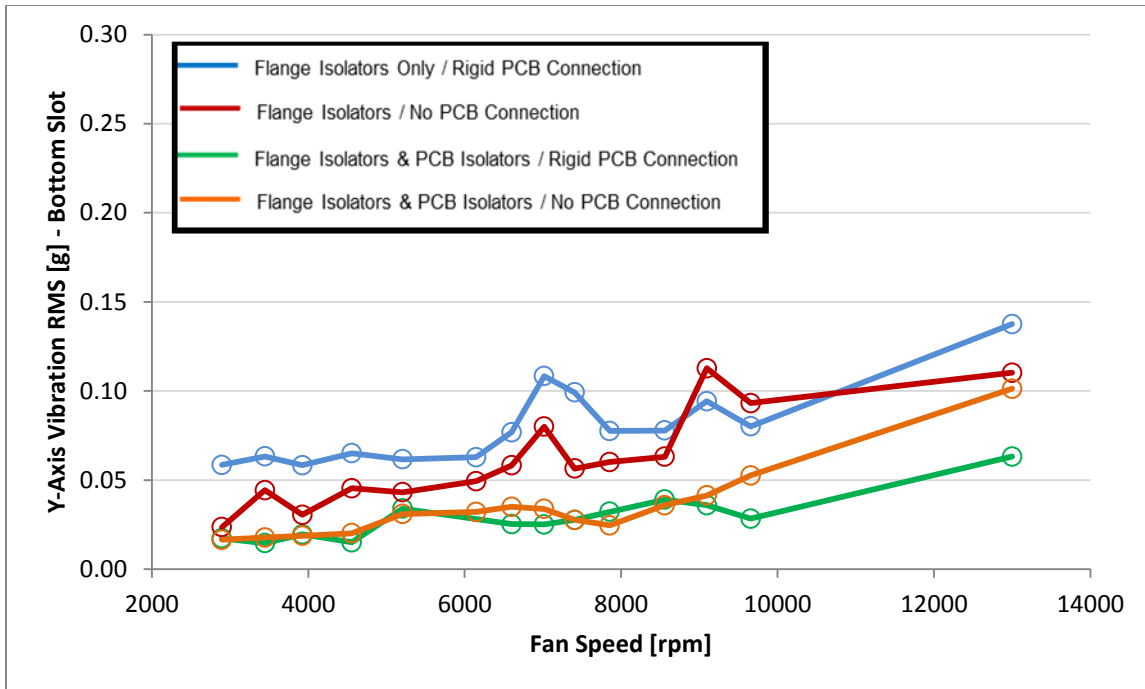


Figure 6.26: GEN2A with AFBM Test Cases Bottom Slot Y-Axis

All test cases provide a marked reduction in vibration to the current GEN2A with *PORON 60* isolators. When all of the above plots are compared, it can be seen that Test Case #3 “Flange & PCB Isolators (Float PCB)” gives the best vibration reduction in all instances and achieves the target vibration value.

The GEN2B design going forward will make use of the following design elements:

1. Flange isolators
2. BHM fans (tooling to be purchased from “Company_B”)
3. PCB Isolators on rear backplane connector PCB only
4. Floating connection between rear backplane connector PCB and interconnect PCB

It should be noted that this test was conducted with carefully, handmade, highly modified fans with only half of the shelf’s fans being powered. The purpose of this test was to determine the design to use moving forward. The actual vibration levels obtained with HBM fans and production GEN2B will likely be on the order of the values obtained here, but cannot be guaranteed to be as shown above.

Chapter 7 – Ultimate Flange Isolator Design & Results

The flange isolator design was also incorporated into the GEN1 fan unit as the GEN1B. Both the GEN1B and GEN2B designs will both make use of the same flange isolator design in order to maximize the vibration reduction.

The overall concept of the flange isolator design is shown in Figure 7.1 (Patent Pending). For the final design, it was necessary to reduce the gap between the bottom of the fan and the chassis in order to reduce the air gap at the fan inlet. This would prevent recirculation, which would in turn degrade thermal performance.

A benefit of this design is the offset flanges which allow for larger isolators, but also retain a flange on the fan housing for mounting the fan directly to a fan unit chassis in other applications. Other applications might include future fan units in alternate products that are designed to accommodate larger and improved vibration isolation solutions. Thus, the same fan can be used in a wider range of applications beyond retrofit scenarios.

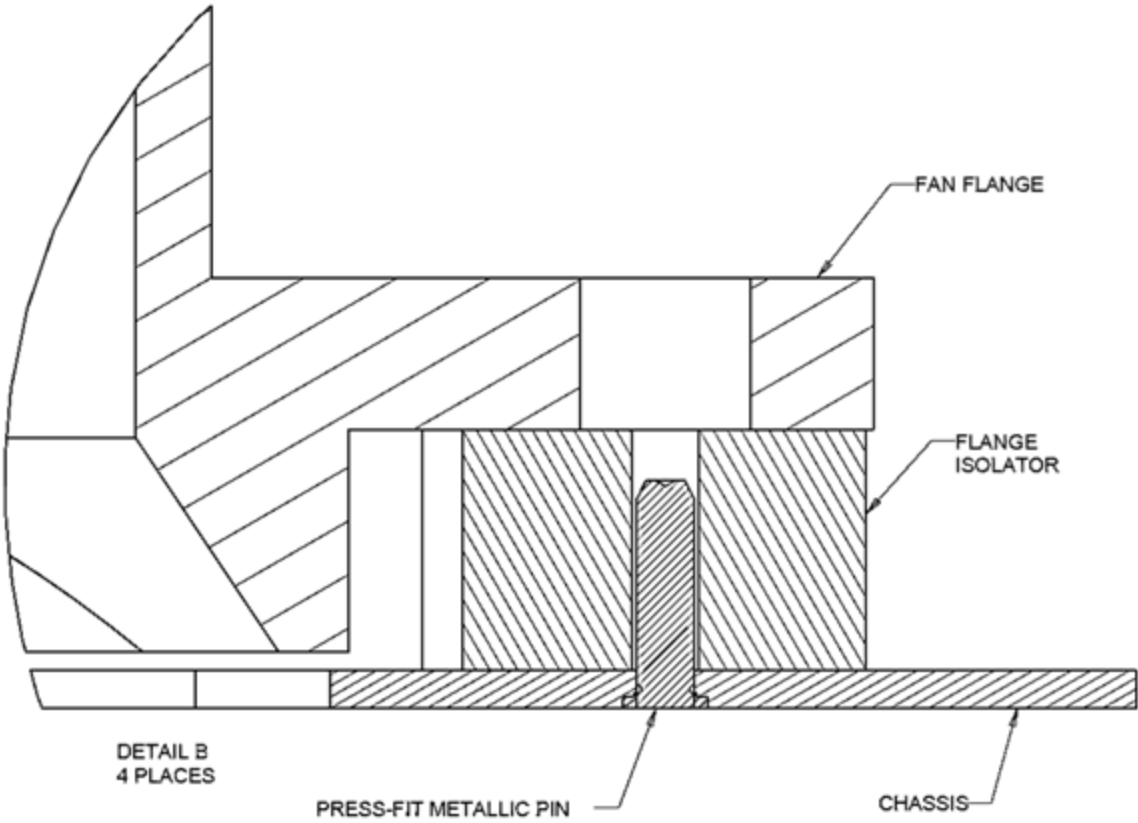


Figure 7.1: GEN1B and GEN2B Flange Isolator Cross-Section

7.1 GEN2B Design

The final design of the BHM fan itself is shown as a CAD model in Figure 7.2.

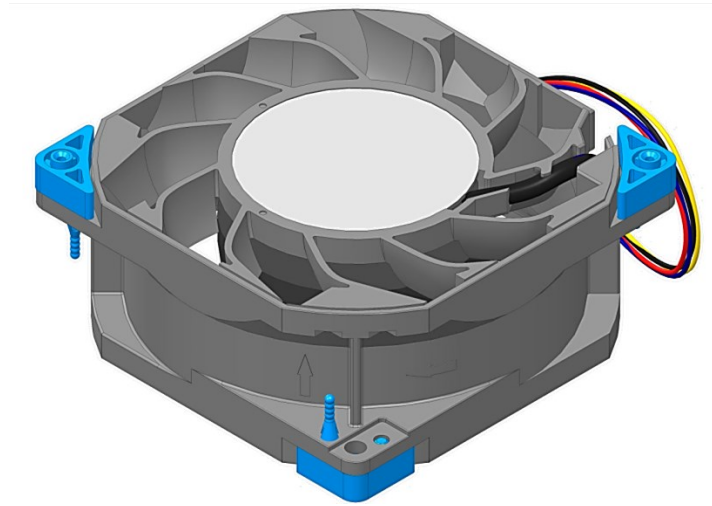


Figure 7.2: BHM 12000rpm Fan CAD Model Final

The final internal geometry of the GEN2B showing the PCB and flange isolators are shown in Figure 7.3.

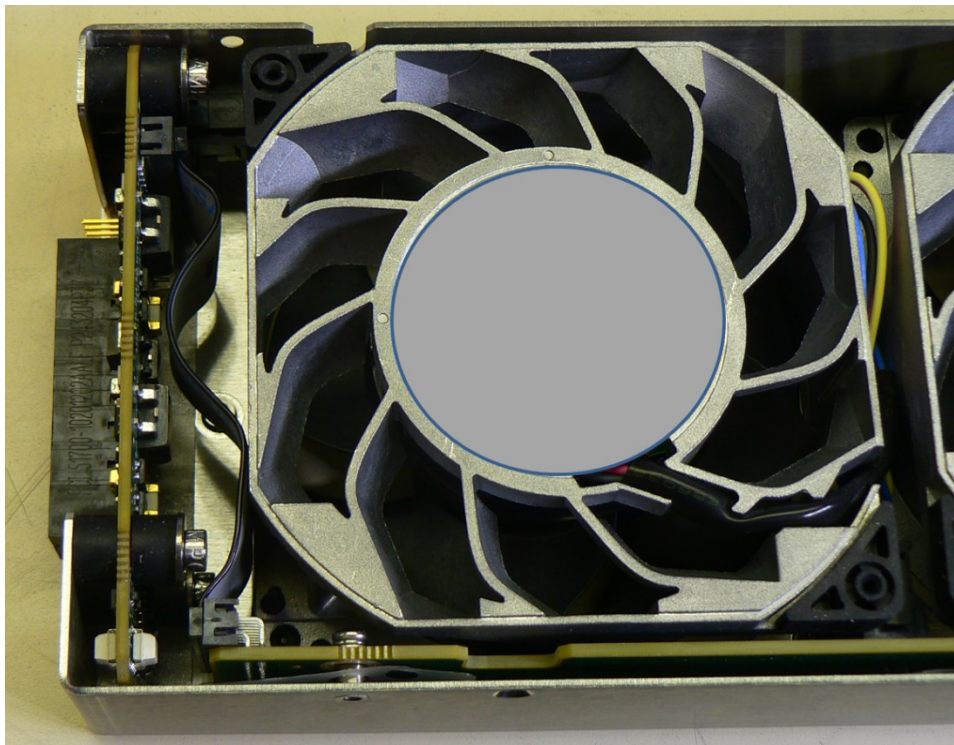


Figure 7.3: GEN2B Internal Detail Rear Fan

A vibration test was devised to test the final GEN2B fan design. This was the first time a vibration test was conducted in the shelf with a FF of GEN2 fans. This test was a sweep of an instrumented GEN2B fan in each slot of Shelf_A between 8000 and 12000 rpm.

The results of this test are displayed in the 3D plots in Figure 7.4 through Figure 7.6.

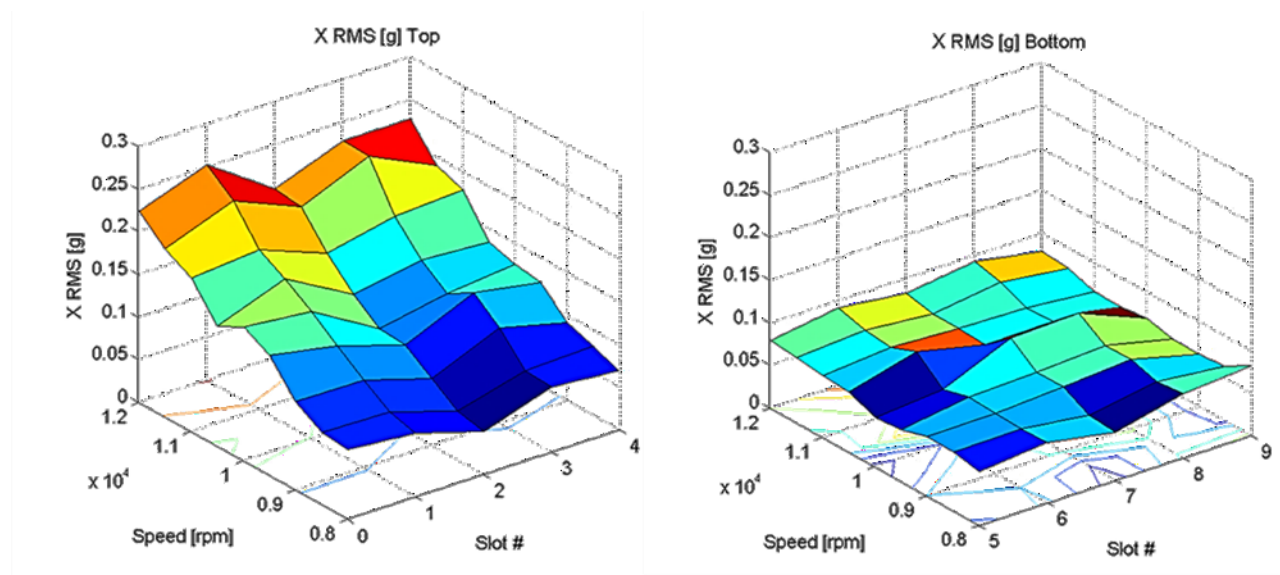


Figure 7.4: GEN2B 3D Slot Plot Shelf_A X-Axis

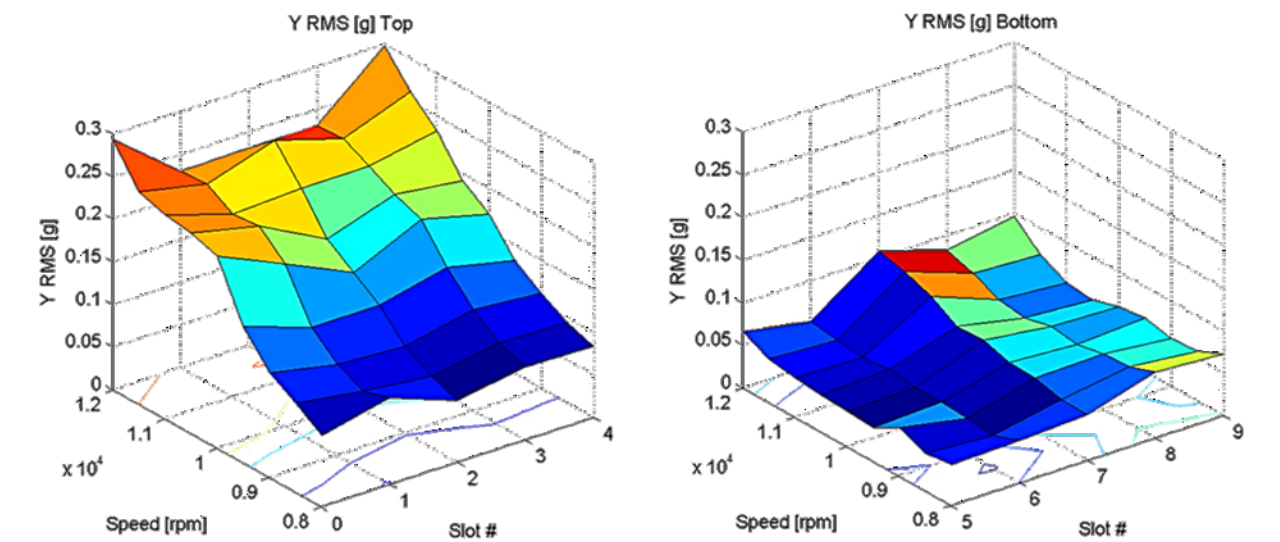


Figure 7.5: GEN2B 3D Slot Plot Shelf_A Y-Axis

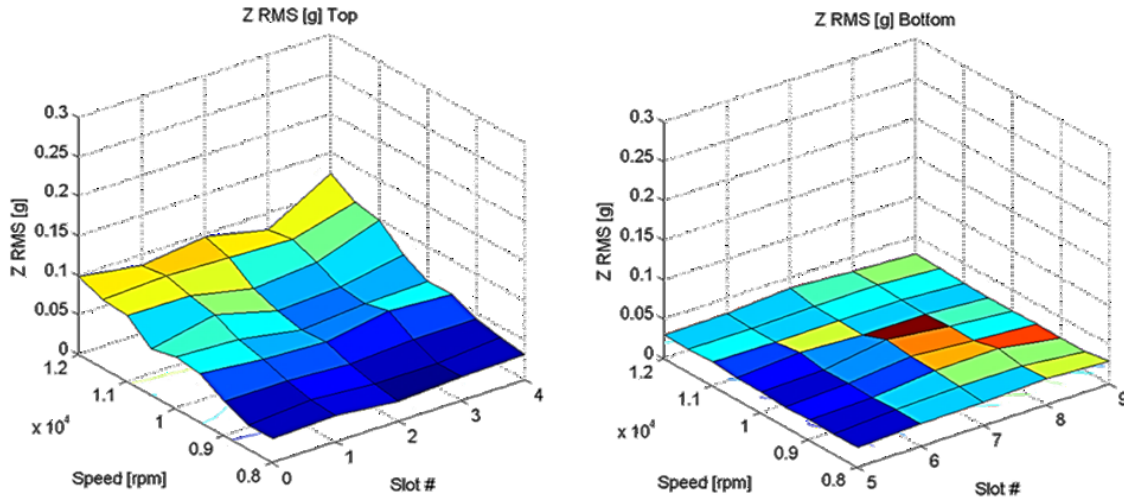


Figure 7.6: GEN2B 3D Slot Plot Shelf_A Z-Axis

These plots show some points worth noting:

1. The results obtained with the GEN2B fans show higher levels of vibration in the top of the shelf compared to the Test Case #3 modified Alpha prototype GEN2A fans. This change is somewhat expected since this is the first FF case tested.
2. Vibration levels for all speeds in the bottom slots are below the target value threshold of 0.1 g RMS
3. Vibration levels in the top shelf slots are higher in the end slots than in the middle slots.

The end vibration results obtained for the GEN2B are a significant vibration reduction compared to all other fan units tested. The target value was not reached in the top slots, but the level of vibrations that causes damage is not known. Damage-inducing vibrations can only be determined through a lengthy test where a shelf would be fitted with GEN2B fans and run undisturbed for the life of the product, or until wear is observed. Such a test is difficult to conduct and impractical.

For practical purposes, the vibration reduction achieved is significant, especially since the fans will never operate for an extended length of time at their maximum speed. Most of the fans will experience lower speeds for much of their service life. Below 8500 rpm, the GEN2B fans all experience vibration levels below the target of 0.1g RMS in all slots and orientations.

Ultimately, the GEN2B is a successful design and is currently being shipped to customer sites in new shelves.

7.2 GEN1B Design

The design of the GEN1B with the flange isolators was given to another designer once the GEN2B was completed. The “Company_A” 8000 rpm fans were modified (AM) to accommodate the flange isolators. No PCB isolators were used since that would require the rear backplane connector PCB to be redesigned, which would be difficult and costly.

Another designer tested the GEN1B in a FF of the shelf with a full speed sweep. Figure 7.7 through Figure 7.9 below show the results of these tests as compared to the data already acquired for the GEN1, and GEN1A.

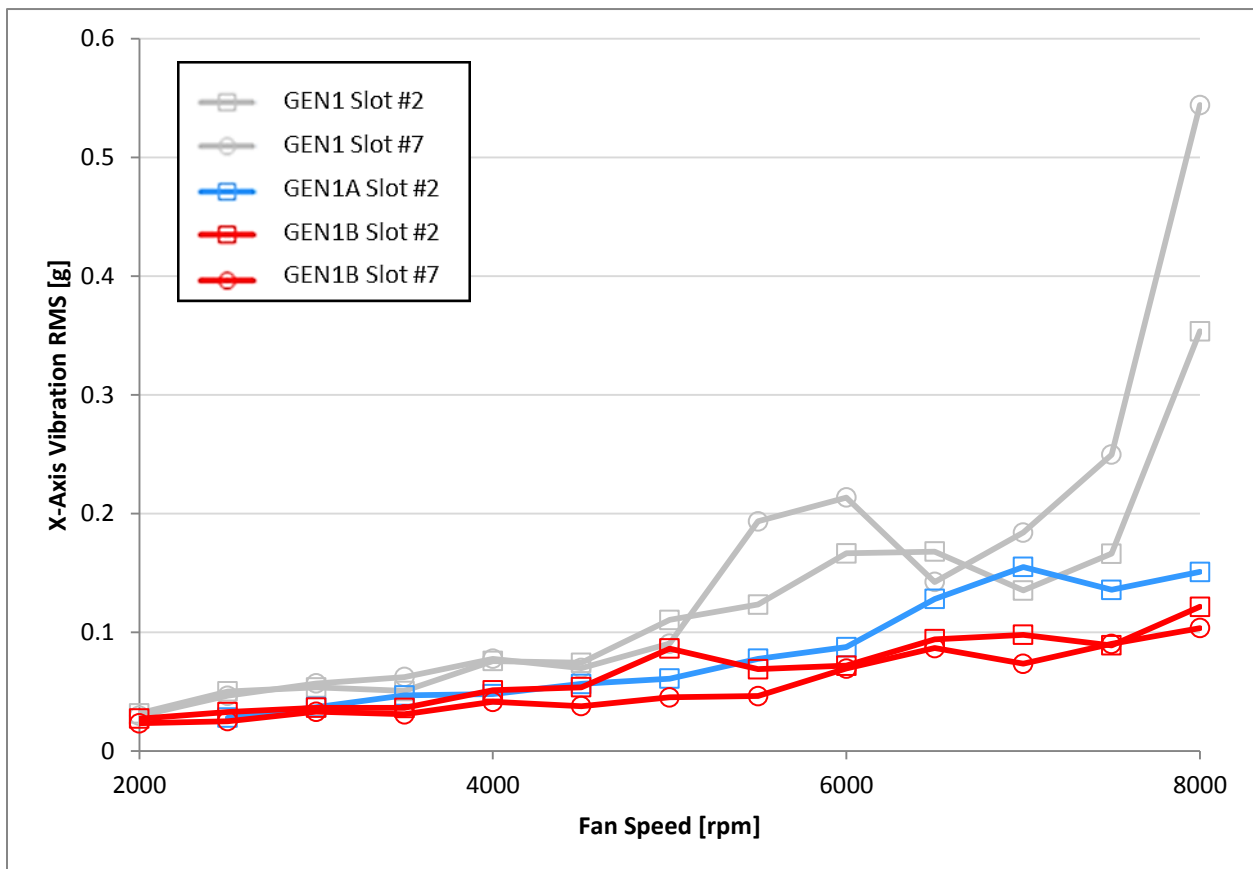


Figure 7.7: GEN1B FF Shelf_A Sweep Comparison X-Axis

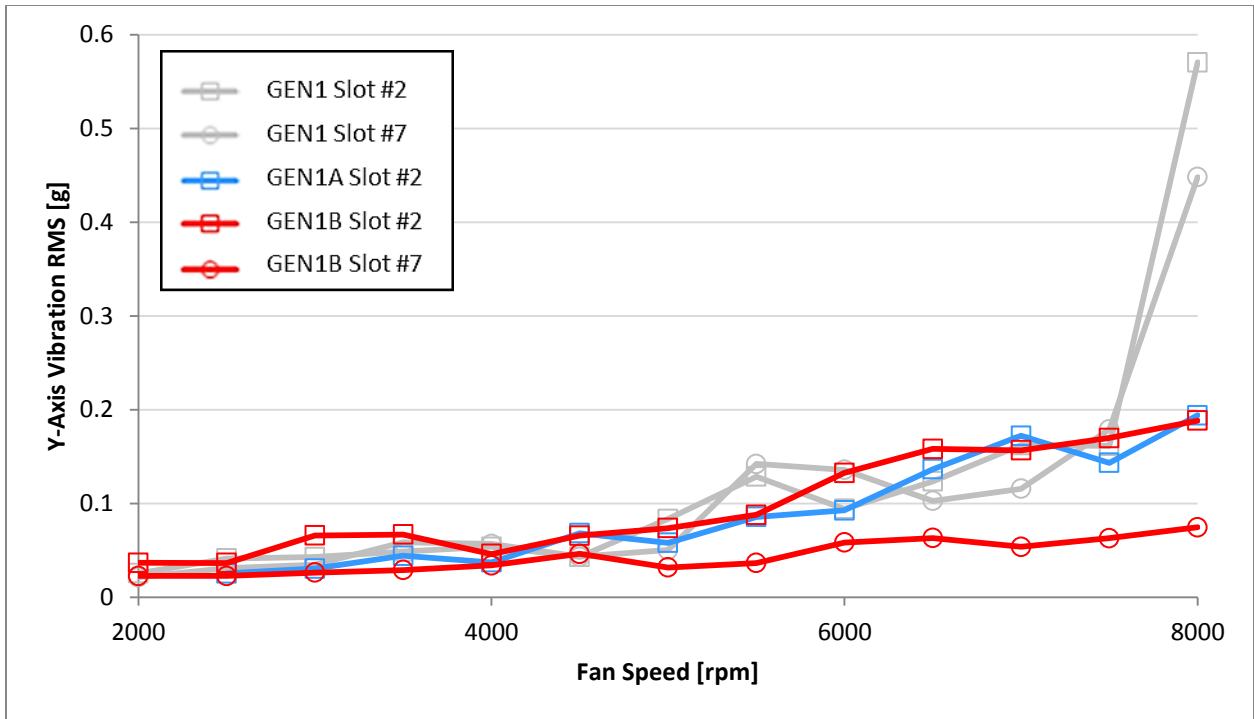


Figure 7.8: GEN1B FF Shelf_A Sweep Comparison Y-Axis

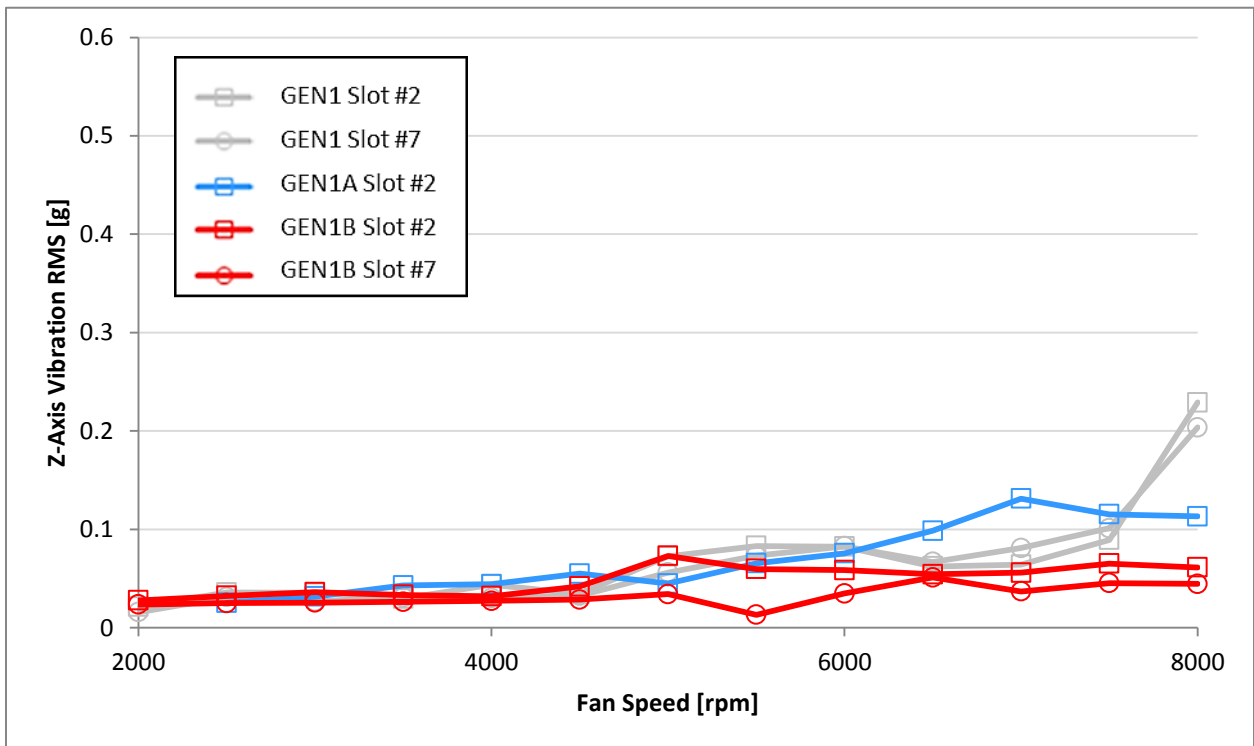


Figure 7.9: GEN1B FF Shelf_A Sweep Comparison Z-Axis

The GEN1B shows a reduction in vibration levels in the X- and Z-Axis when compared to the GEN1A. No change is observed in the Y-Axis in the top slot, but the bottom slot shows similar vibration levels to that of the GEN2B.

With the exception of the top of the shelf in the Y-Axis, the GEN1B shows vibration levels below that of the target of 0.1 g RMS. The vibration reduction is significant enough compared to the GEN1 and the target value to also declare the GEN1B a successful design.

As with the GEN2B, a long term vibration test to confirm the vibration performance and absence of fretting corrosion is difficult to conduct and impractical.

Chapter 8 Discussion and Conclusions

8.1 Discussion

8.1.1 Vibration Reduction

Most vibration levels for the GEN1B 8000 rpm fan units and the GEN2B 12000 rpm fan units were reduced to the target value of 0.1g RMS as found in an alternate shelf product that had shown no fretting corrosion on the fan backplane connector after eight years of continual service. In particular, the top slots of the shelf in the Y-Axis do not meet the target value above 8500 rpm for the GEN2B and above 5500 rpm for the GEN1B. However, the vibration level for fretting corrosion of the backplane connector to be inhibited is not known.

It should also be noted that fan-to-fan variation, and thus fan unit-to-fan unit variations also have an effect on the vibration levels. Some will perform better than the values measured and some will perform worse. It is expected that these trends follow that of a normal distribution.

The question of whether or not the final vibration levels achieved are low enough to prevent fretting corrosion of the backplane connectors cannot easily be answered. The test required to do so would require two shelf units dedicated to running the GEN1B and GEN2B constantly for years. This would tie up a large amount of company resources and is impractical for addressing such an issue.

Under normal operating conditions, most fan units will hardly ever enter the higher speed ranges of the fans since these are reserved for more critical situations such as a fan unit failure. If one of the shelf's fan units were to fail, all other fan units would speed up to maximum rpm. When this happens, a system alarm is raised and personnel are required to replace the malfunctioning fan unit as soon as possible. Therefore, most fan units will not be subject to these high speeds for any significant length of time.

8.1.2 Other Design Considerations

The main focus of this thesis was on the vibration reduction and isolator design itself. There were many other considerations to be made and detailed design that were not covered in the body of this thesis. Multiple tolerances analyses were conducted and minor dimensional changes made in order to accommodate for the isolator designs herein. Though these fine details appear minor,

they allowed each design to be successful. These details were not included in the main body so as to not detract from the main points being made.

Another consequence of greater airflow requirements is taking into consideration the safety of the operator. The GEN1 had safety grilles on the bottom chassis and top cover which protected the operator from the spinning blades when removing the fan unit from the shelf. To gain every percentage of increased airflow possible, these grilles were removed for all GEN2 designs. With increased fan speeds of 12000 rpm and 13000 rpm, the operator is a greater risk of injury. As a result, an electrical fan brake was added to the fan design by the fan manufacturer, “Company_B”. While helping to reduce fan speed, this still did not reduce the fan speed to a safe level when being removed from the shelf.

To fully ensure that the fan would not be spinning when removed from the shelf, a latch switch mechanism was designed to turn off the fan power prior to removal from the shelf. A lever mechanism was designed and installed inside the fan unit behind the front sheet metal face near the latch. By closing the latch and screwing in the thumb screw, this lever mechanism would be actuated and press on two redundant surface mount switches on the PCB inside the fan unit. When depressed, these switches would then power up the fan unit. When removing from the shelf, the thumb screw is unscrewed, and during this process, the mechanism would lose contact with the switches, and the fan unit would power down. When the fan unit is fully unscrewed and removed from the shelf, the fans have stopped spinning. This design is also Patent Pending.

Another such detail was of the fan unit assembly itself. The flange isolator used in the GEN2B and GEN1B design is very compliant, and as a result, aligning the pins in the top cover to the holes in the isolators during final assembly proved very difficult for the CM. Assembly jigs were developed (by the author for the GEN2B, and by a colleague for the GEN1B) that sit on the top surface of the fan unit prior to top cover installation. As the top cover is assembled, features of the top cover align with features on the assembly jig, ultimately aligning the pins in the top cover to the holes in the isolators.

8.1.3 Simulations, Analytical Models, & Statistics

Simulations and analytical models were not considered for use in this thesis due to the complexity of the systems involved as well as the complexity of the vibration modes and friction

models involved. In order to somewhat accurately create a representative model of the system, it would be a very large, complex model and as a result would likely not generate results that would translate as expected to the actual physical design. Even modelling of the fan unit and shelf mating connectors would present a challenge to model accurately. As a result, all of the experiments conducted in this thesis were physical experiments in the lab with real equipment.

Another item of note regarding the physical experiments is that in most instances only a single data point was obtained for a given fan configuration and fan speed for each chart produced. The reason for this is that each data point takes a significant amount of set up time and data acquisition time to collect. When it was determined that anomalous results were obtained during the testing process, certain data points were re-tested for accuracy. This means that statistical models are not obtainable from the data sets presented in this thesis. However, a statistical analysis is not required for the purposes of this thesis as the majority of the results obtained were for direct comparison within the specific figure or test circumstance.

8.2 Conclusions

In conclusion, both the final designs of the GEN1B and GEN2B were successful. Both of the designs have been produced by an external contract manufacturer and are intended to be sold and used at customer sites worldwide. Currently, the GEN2B is already deployed.

Both of the isolator designs developed in this thesis are also usable in any other fan unit design going forward or in other retrofit applications where vibration isolation is required in a constrained space.

8.3 Thesis Contributions

The main contributions of this thesis are as follows:

1. Acceptable vibration level threshold was determined to be 0.1g RMS by evaluation of vibration levels of an alternate existing product with no known wear issues.
2. A retrofit vibration isolation solution to greatly reduce the vibration levels of the GEN1 as well as the GEN2 was designed and implemented. This design (GEN1A, GEN2A) requires minimal changes to the existing legacy design and requires no fan modifications. This design is currently Patent Pending.

3. An ultimate flange vibration isolation solution was developed to significantly reduce the vibration levels of both fan units (GEN1B, GEN2B) to below the threshold value in most operating scenarios was designed and implemented. This design requires extensive changes to the legacy design as well as custom fans and flange isolators. This design is also Patent Pending.

4. The research conducted developed two designs that can be used specifically in smaller cooling systems such as those used in telecommunications equipment to reduce excessive vibrations as a result of fan imbalance.

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Chapter 9 Appendix A: Reference Information

Detailed Test Procedure for Acquiring Raw Vibration Data

The following test procedure was developed by myself with the help of a colleague mentor to specifically address the problem as defined in this thesis.

Initial Calibration & DAQ Setup

1. Plug DAQ into laptop and open *InstaCal*
2. Calibrate the DAQ
3. Under the “Calibrate” menu set the inputs to “single ended”
4. Close *InstaCal*

Accelerometer Installation

1. Cut a square of adhesive transfer tape roughly the same footprint as the accelerometer PCBA
2. Attach the accelerometer to the equipment to be tested:
 - a. Fan Unit:

Attach accelerometer to top of backplane connector shroud as indicated in Figure 4.3. Route the ribbon cable through the inside of the fan unit and out the front faceplate (Figure 9.1). Figure 4.3 also shows how the fan axes are always configured for such a test. From here on, each of the axes will be denoted as follows: X-axis, Y-axis, and Z-axis. Both the X-axis and Y-axis correspond to in-plane vibration, and the Z-axis corresponds to the axial vibration.

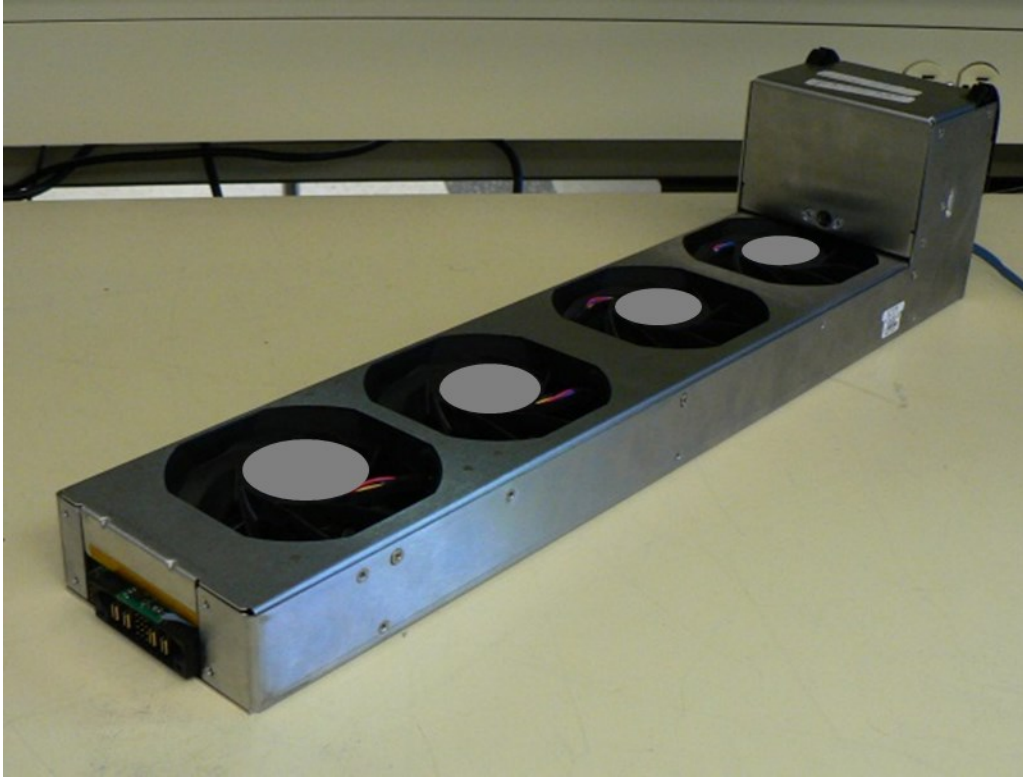


Figure 9.1: Fan unit showing Accelerometer Cable Exit

b. Test Fixture:

Attach accelerometer to top of base within the indicated score marks (Figure 4.4).

3. Using Figure 4.1 as a reference, attach the ground lead to any of the “AGND” analog ground points indicated on the DAQ (Figure 9.2). Attach:
 - a. Voltage-in lead to the “+5V” port (Port #42)
 - b. X Axis-out lead to the “CH0” port (Port #1)
 - c. Y Axis-out lead to the “CH1” port (Port #4)
 - d. Z Axis-out lead to the “CH2” port (Port #7)

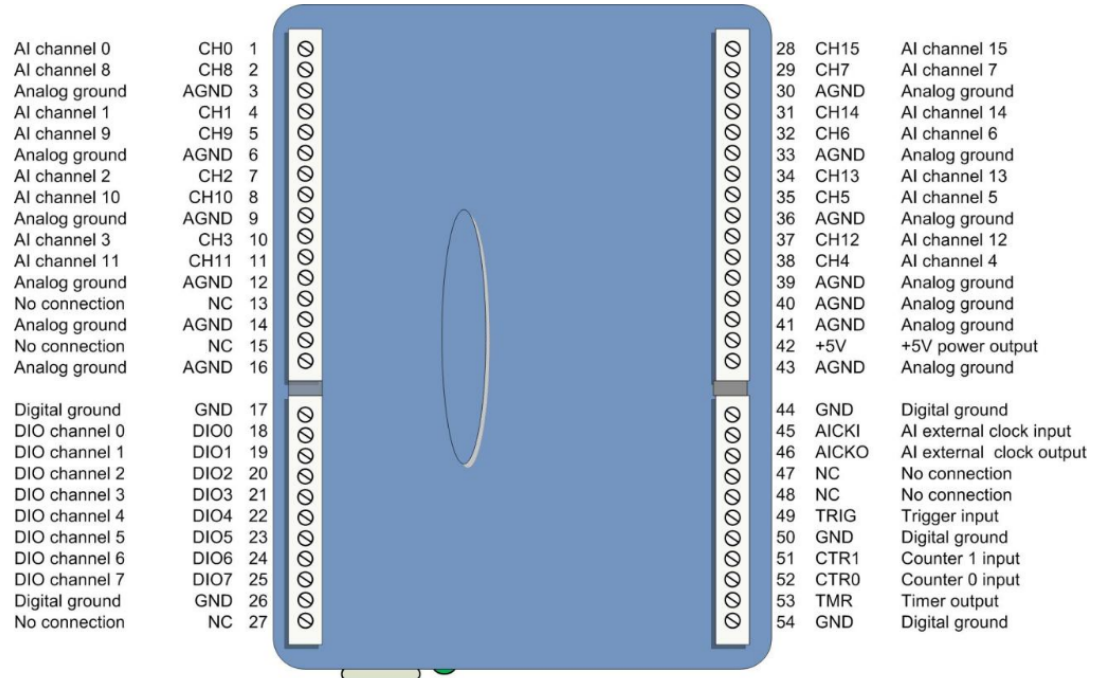


Figure 9.2: DAQ Ports (Single Ended Mode)

4. Repeat steps 1-3 for any additional accelerometers. For step 3, continue the pattern of attaching the X, Y, and Z-axis leads sequentially to “CH3”, “CH4”, etc.

Note: Attaching more than two accelerometers simultaneously is not recommended since interference becomes apparent in the data sets when any leads are attached to “CH8” or higher.

Data Acquisition:

Fan Unit Testing (in shelf):

1. Install the fan unit into the slot to be tested on the shelf and securely latch it to the shelf using a screwdriver.
2. Controlling the fan speed can be done one of two ways:
 - a. Connect a function generator to the pulse width modulation (PWM) wire of each fan and input a square wave signal (based on the fan's datasheet). Adjust the duty cycle of the function generator between 20-80% to adjust the fan speed.

Note: the fan speeds must be validated by first bench testing a single fan and marking one of the blades with a contrasting colour. By adjusting the function generator to each desired speed, the RPM can be determined by using a stroboscope. This can then be used to create a look-up table of fan speeds (see Table 11)

- b. Log into the shelf's (proprietary) software and control the fan speed directly through the fan unit's control loop.
3. Set fan speed to RPM to be tested at and allow the speed to reach steady state.
Note: Some wander of ± 100 RPM may be present due to internal fan control loops or control loops in the shelf software.
4. Run the applicable *Matlab* script "MCC_DAQ_USB_1608GX_XXXX_YYYY_3CH_REV_A.m" and follow the prompts (see Appendix A). Default capture rate for data is 8333 Hz for a duration of 20 s. This allows for any beat frequencies to make themselves present.
5. The script will output a spreadsheet with the raw data of the accelerometer output in volts to the working directory.
Note: Nominal sensitivity is 0.170 V/g as per the ADXL 325 datasheet. Testing conducted by flipping the accelerometer along each axis verified this performance, knowing that a flip corresponds to a response of 2g. See Table 9.2 of Appendix A.
6. Repeat for each RPM data point required.

Results:

1. Copy all raw data files into a single working folder including the *Matlab* script “Accelerometer_Analysis_v04.m” (see Appendix A).
2. Run the script. It will analyze the data and output data plot summaries of the vibration levels on the X, Y, and Z axes, including the RMS values. Output will be saved as PDF and JPEG.

Note: Options exist to also output FFT plots of each axis for further analysis.

Table 9.1: PWM Look-up Table 12,000 rpm GEN2 Fan (measured by stroboscope)

Duty Cycle [%]	Min RPM	Max RPM	Average RPM	Sample Std. Dev.
20	2844	2946	2895	51
21	3005	3090	3047.5	42.5
22	3110	3110	3110	0
23	3210	3309	3259.5	49.5
24	3308	3370	3339	31
25	3410	3481	3445.5	35.5
26	3537	3575	3556	19
27	3596	3705	3650.5	54.5
28	3718	3778	3748	30
29	3815	3830	3822.5	7.5
30	3885	3963	3924	39
31	3978	4089	4033.5	55.5
32	4161	4191	4176	15
33	4296	4331	4313.5	17.5
34	4417	4443	4430	13
35	4542	4569	4555.5	13.5
36	4680	4680	4680	0
37	4789	4854	4821.5	32.5
38	4958	4973	4965.5	7.5
39	5049	5116	5082.5	33.5
40	5184	5228	5206	22
41	5340	5358	5349	9
42	5549	5596	5572.5	23.5
43	5701	5730	5715.5	14.5
44	5926	6013	5969.5	43.5
45	6100	6192	6146	46
46	6204	6229	6216.5	12.5
47	6298	6331	6314.5	16.5
48	6367	6415	6391	24
49	6454	6508	6481	27
50	6582	6619	6600.5	18.5
51	6618	6684	6651	33
52	6749	6814	6781.5	32.5
53	6814	6853	6833.5	19.5
54	6922	6955	6938.5	16.5
55	6984	7048	7016	32
56	7093	7112	7102.5	9.5
57	7138	7213	7175.5	37.5

58	7249	7263	7256	7
59	7276	7300	7288	12
60	7390	7421	7405.5	15.5
61	7429	7495	7462	33
62	7506	7600	7553	47
63	7629	7655	7642	13
64	7768	7798	7783	15
65	7853	7855	7854	1
66	7967	7974	7970.5	3.5
67	8088	8133	8110.5	22.5
68	8271	8278	8274.5	3.5
69	8410	8432	8421	11
70	8559	8559	8559	0
71	8690	8694	8692	2
72	8769	8815	8792	23
73	8895	8914	8904.5	9.5
74	8955	8990	8972.5	17.5
75	9080	9111	9095.5	15.5
76	9178	9205	9191.5	13.5
77	9324	9354	9339	15
78	9391	9426	9408.5	17.5
79	9556	9576	9566	10
80	9655	9660	9657.5	2.5

Table 9.2: Accelerometer Calibration Data - Validating No Calibration Needed

Test	Unit	Axis	Direction	Mean Value (V)	Sensitivity (V/g)
Accelerometer_...-xCAL-1_20131114_082828.xlsx	acc6	X	up	1.658	
Accelerometer_...-xCAL-2_20131114_082923.xlsx	acc6	X	down	1.321	0.169
Accelerometer_...-yCAL-1_20131114_083218.xlsx	acc6	Y	up	1.676	
Accelerometer_...-yCAL-2_20131114_083314.xlsx	acc6	Y	down	1.337	0.170
Accelerometer_...-zCAL-1_20131114_082531.xlsx	acc6	Z	up	1.678	
Accelerometer_...-zCAL-2_20131114_082639.xlsx	acc6	Z	down	1.342	0.168

Table 9.3: GEN1 and GEN2 Fan Speed Software Look-Up Table

	GEN1		GEN2 Legacy Mode		GEN2	
Ambient Temp. (°C)	Standard RPM	RPM with Hotter LM	Standard RPM	RPM with Slow Response LM	Standard RPM	RPM with Slow Response LM
<10	1700	4000	1700	4000	3400	6000
11-15	2000	5000	2000	5000	4000	7200
16-20	2500	6000	2500	6000	5000	8300
21-25	2700	6500	2700	6500	5400	9500
26-30	3500	7000	3500	7000	7000	10500
31-35	4300	7500	4300	7500	8600	11700
36-40	5000	8000	5000	8000	10000	13000
41-45	5700	8000	5700	8500	11400	13000
>46	6500	8000	6500	9000	13000	13000

Data Acquisition Matlab Script

```
%=====
%Accelerometer data acquisition using Measurement Computing USB-1608GX

%NOTE: Matlab 32 bit, R2012a or higher must be used
%NOTE 2: User must have Admin account on laptop or else analoginput
%         command fails without explanation

%Author: Trevor Meunier
%Date: July 23, 2013
%Revision: A
%=====

AI = analoginput('mcc'); %Add analog input from Measurement Computing USB-
1608GX
%Add channels for each accelerometer on fan and shelf
set(AI, 'InputType', 'SingleEnded')
Channels = [{'acc8_x'}, {'acc8_y'}, {'acc8_z'}];
addchannel(AI, 0:2, Channels);

%Check Analog Input Voltage Ranges

out = daqhwinfo(AI);
out.InputRanges;

%Set all channel voltage input ranges

AI.Channel.InputRange = [-5 5];

%Set Data Logging Mode

set(AI, 'LogFileName', 'Accelerometer_Data_5400_fan.txt');
set(AI, 'LoggingMode', 'disk&memory');

%Test duration Inputs

duration = 20 %specify acquisition duration

%Check Valid Sampling Rates

ValidRates = propinfo(AI, 'SampleRate');
ValidRates.ConstraintValue

set(AI, 'SampleRate', 8333) %[Hz]
ActualRate = get(AI, 'SampleRate');
set(AI, 'SamplesPerTrigger', duration*ActualRate)
set(AI, 'TriggerType', 'Manual')
blocksize = get(AI, 'SamplesPerTrigger');
Fs = ActualRate;

%Model Series
series = questdlg('Shelf Series Used:', ...
    'Selection', ...
```

```

    'XXXX', 'YYYY', 'None', 'None');
switch series
case '5400'
    series_type = 'XXXX';
case '6500'
    series_type = 'YYYY';
case 'None'
    series_type = 'Free';
end

%Unit Used
unit = questdlg('Fan Unit Used:', ...
    'Selection', ...
    'XXXX', 'None', 'YYYY', 'YYYY');
switch unit
case '5400'
    unit_type = 'XXXX';
case 'None'
    unit_type = 'None';
case '6500'
    unit_type = 'YYYY';
end

%Test type input
data = questdlg('Type of Test:', ...
    'Selection', ...
    'Baseline', 'Data_Set', 'Data_Set');
switch data
case 'Baseline'
    data_type = 'Baseline';
case 'Data_Set'
    data_type = 'Data_Set';
end

i = 0;
while i < 1
    prompt = 'Input Data Description (20 Characters):\n';
    str = input(prompt, 's')
    if length(str)~= 20
        continue
    else
        i = 1;
    end
end

%Set trigger & collect data
info = 'Starting DAQ'
start(AI)
trigger(AI)
wait(AI, duration + 1)
[data, time, abstime, events] = getdata(AI);
info = 'Stopping DAQ'

figure

plot(time, data)

```

```

grid on
ylabel('Volts (V)')
xlabel('Time (s)')
title('Voltage vs. Time Output')
leg1 = legend(Channels);
set(leg1, 'Location', 'EastOutside')
hold all
t={'Time (s)'};

XLSout =
sprintf('Accelerometer_%s_3CH_%s_%s_%s_%s.xlsx',series_type,unit_type,data_ty
pe,str,datestr(now,'yyymmdd_HHMMSS'));
xlswrite(XLSout,Channels,'Sheet1','A1');
xlswrite(XLSout,t,'Sheet1','M1');
xlswrite(XLSout,data,'Sheet1','A2');
xlswrite(XLSout,time,'Sheet1','M2');

delete(AI)
clear AI

```

Data Processing *Matlab* Script (colleague's code)

```
% Accelerometer Analysis v04
%
% Walks through a directory of xlsx files containing accelerometer data
% and performs an analysis
%
% Assumes each file has the following internal format:
% Column A-C: Fan1 X-Z, Column D-F Fan 2 X-Z, etc., Column M: Time (s)
%
% Revision History:
%
% v01 series - alpha testing version using ADXL326 ( $\pm 16G$ ), non-PCB mounted.
% v02 series - beta testing version using ADXL325 ( $\pm 5g$ ), pcb mounted.
%               accelelration now stored internally in g not m/s/s
% v03 series - filtering window added to determine amplitude at various
%               frequencies.
% v04 series - all filtering code removed. Calibration data set to nominal
%               by default. Axes allowed to autoscale.

close all;
clear all;
clc;

CHANNELS = 3;
UNITS = CHANNELS/3;
%UNIT_NAMES = {'Fan Slot 0' 'Fan Slot 2'};
%UNIT_NAMES = {'Fan Slot 7 (Bottom)'};
UNIT_NAMES = {'Fan Slot 2 (Top)'};

% Calibration data (V/g), must be matched to file structure
% Note that ADXL325 Accelerometers have a nominal sensitivity
% of 0.174 V/g
cal = [0.174 0.174 0.174];

axis_names = ['X' 'Y' 'Z'];
unit_colors = [[100/255 149/255 237/255]; [205/255 92/255 92/255]];
fname_list = dir('A*.xlsx');
output_fileid = fopen('Results_Summary.txt','w');
fprintf(output_fileid, 'Test\tX0 (RMS)\tY0 (RMS)\tZ0 (RMS)\tX2 (RMS)\tY2
(RMS)\tZ2 (RMS)\n');

for file_number = 1:length(fname_list)
    % Open file and read data
    fname = fname_list(file_number).name;
    fprintf('Processing File: %s\n', fname)
    [num,txt,raw] = xlsread(fname, 'Sheet1');
    t = num(:,13);
    n_samples = length(t);
    sample_freq = 1/(t(2)-t(1));
    fname = strrep(fname, '_', ' ');
    fname_split = 'Set';
    fname_split_pos = strfind(fname, fname_split) + length(fname_split) - 1;
    plot_fname_1 = fname(1:fname_split_pos);
    plot_fname_2 = fname(fname_split_pos+1:length(fname));
end
```

```

% Apply calibrations and calculate acceleration
fprintf('\n\tApplying calibrations: Channel ')
acl = zeros(length(num),CHANNELS);
for i = 1:CHANNELS
    fprintf('%d ',i)
    % calibration data is in V/g
    % convert fnum (V/g) into g's then m/s/s
    acl(:,i) = (num(:,i)-mean(num(:,i)))/cal(i);
end

% Additional calculators
acl_rms = rms(acl,1);

% Calculate Fourier transforms
fprintf('\n\tCalculating Fourier Transforms: Channel ');
F_spacing = sample_freq/n_samples;
fft_plot_freq = 0:F_spacing:sample_freq/2;
fft_acl = zeros(length(fft_plot_freq),CHANNELS);
for i=1:(CHANNELS)
    fprintf('%d ',i)
    F_in = fft(acl(:,i));
    fft_acl(:,i) = 2*abs(F_in(1:floor(n_samples/2)+1)/n_samples);
end

% Plot Unfiltered Results
fprintf('\n\tPlotting results.\n')

for unit = 1:UNITS
    unit_name = UNIT_NAMES{unit};
    figure('PaperOrientation','Portrait','PaperPosition',[0.0 0.0 8.5
11]);
    subplot(4,2,1, 'Visible', 'Off')
        text(0,0.8, sprintf(...
            'Filename: %s\n          %s\n\nUnit: %s\nSample Frequency:
%0.0f Hz\n\nX Acceleration: %0.6f g RMS\nY Acceleration: %0.6f g RMS\nZ
Acceleration: %0.6f g RMS',...
            plot_fname_1, plot_fname_2, unit_name, sample_freq,
acl_rms(1,1), acl_rms(1,2), acl_rms(1,3)), 'FontSize', 8);
    subplot(4,2,2)
        image(imread('Fan_Axes-134-0306-800.png'));
        axis image
        axis off

    for i=1:(CHANNELS/UNITS)
        subplot(4,2,i*2+1)
            plot(t,acl(:,i), 'Color', unit_colors(unit,:));
            axis([0 max(t) -1 1])
            xlabel('Time (s)')
            ylabel(sprintf('%s Acceleration (g)',axis_names(i)));
            grid on
        subplot(4,2,i*2+2)
            plot(fft_plot_freq, fft_acl(:,i), 'Color', unit_colors(unit,:))
            % axis scaling - comment out next line for autoscaling
            axis([0 sample_freq/2 0 .05])
            xlabel('Frequency')

```

```

        ylabel('|A|')
    end

    % Save Plot to PDF
    output_fname = sprintf('%s-unit-%d.pdf', fname(1,1:(length(fname)-5)),
unit);
    print('-dpdf', output_fname)
    %output_fname = sprintf('%s-unit-%d.png', fname(1,1:(length(fname)-
5)), unit);
    %print('-dpng', '-r600', output_fname)

    end
    fprintf(output_fileid, '%s', fname);
    for i=1:length(acl_rms)
        fprintf(output_fileid, '\t%f', acl_rms(1,i));
    end
    fprintf(output_fileid, '\n');
end

fclose(output_fileid);

```

Final Data Plotting Matlab Script

```
clear
%Excel Filename of Processed RMS Vibration Values
filename = '5430_full_fill_summary';

%Create vector of 8000-12000 rpm fan speeds
speed = xlsread(filename,2, 'D3:D11');

%Create matrix of fan speeds (useful for plotting without formatting each
%data series
speedM =
transpose([transpose(speed);transpose(speed);transpose(speed);transpose(speed)
);transpose(speed);transpose(speed);transpose(speed);transpose(speed);transpo
se(speed);transpose(speed)]);

%Create vector of 5430 slot #s
slot = [0 1 2 3 4 5 6 7 8 9];

%Create matrix of 5430 slot #s (useful for plotting without formatting each
%data series
slotM = [slot;slot;slot;slot;slot;slot;slot;slot;slot];

%Split data series into top/bottom
slot_top = slotM(:,1:5);
slot_bot = slotM(:,6:10);

%Split speed matrix in half
speed_half = speedM(:,1:5);

%Reads vibration levels of each of the 5430 slots and saves them to arrays
S0 = xlsread(filename,2, 'E3:G11');
S1 = xlsread(filename,2, 'E12:G20');
S2 = xlsread(filename,2, 'E21:G29');
S3 = xlsread(filename,2, 'E30:G38');
S4 = xlsread(filename,2, 'E39:G47');
S5 = xlsread(filename,2, 'E48:G56');
S6 = xlsread(filename,2, 'E57:G65');
S7 = xlsread(filename,2, 'E66:G74');
S8 = xlsread(filename,2, 'E75:G83');
S9 = xlsread(filename,2, 'E84:G92');

%Additional 5430 Vibration Data (full fill)
S2_831 = xlsread(filename,1, 'D40:F48');
S7_831 = xlsread(filename,1, 'D53:F61');
S2_840 = xlsread(filename,1, 'D79:F87');

speed2 = transpose(xlsread(filename,1, 'C40:C48'));

%Read per slot vibration data into matrices
X =
transpose([transpose(S0(:,1));transpose(S1(:,1));transpose(S2(:,1));transpose
(S3(:,1));transpose(S4(:,1));transpose(S5(:,1));transpose(S6(:,1));transpose(
S7(:,1));transpose(S8(:,1));transpose(S9(:,1))]);
```

```

Y =
transpose([transpose(S0(:,2));transpose(S1(:,2));transpose(S2(:,2));transpose
(S3(:,2));transpose(S4(:,2));transpose(S5(:,2));transpose(S6(:,2));transpose(
S7(:,2));transpose(S8(:,2));transpose(S9(:,2))]);
Z =
transpose([transpose(S0(:,3));transpose(S1(:,3));transpose(S2(:,3));transpose
(S3(:,3));transpose(S4(:,3));transpose(S5(:,3));transpose(S6(:,3));transpose(
S7(:,3));transpose(S8(:,3));transpose(S9(:,3))]);

%Split X, Y, Z matrices into top/bottom components
Xtop = X(:,1:5);
Xbot = X(:,6:10);
Ytop = Y(:,1:5);
Ybot = Y(:,6:10);
Ztop = Z(:,1:5);
Zbot = Z(:,6:10);

%Axis limits for plots
limits2D = [0 14000 0 0.6]
limits3Dtop = [0 4 8000 12000 0 0.3]
limits3Dbot = [5 9 8000 12000 0 0.3]

%Plot 3D series of slot to slot variation for X, Y, Z; top and bottom
figure
subplot(2,3,1)
Xtop_plot = surf(slot_top,speed_half,Xtop)
axis(limits3Dtop)
title('X RMS [g] Top')
xlabel('Slot #')
ylabel('Speed [rpm]')
zlabel('X RMS [g]')

subplot(2,3,2)
Ytop_plot = surf(slot_top,speed_half,Ytop)
axis(limits3Dtop)
title('Y RMS [g] Top')
xlabel('Slot #')
ylabel('Speed [rpm]')
zlabel('Y RMS [g]')

subplot(2,3,3)
Ztop_plot = surf(slot_top,speed_half,Ztop)
axis(limits3Dtop)
title('Z RMS [g] Top')
xlabel('Slot #')
ylabel('Speed [rpm]')
zlabel('Z RMS [g]')

subplot(2,3,4)
Xbot_plot = surf(slot_bot,speed_half,Xbot)
axis(limits3Dbot)
title('X RMS [g] Bottom')
xlabel('Slot #')
ylabel('Speed [rpm]')
zlabel('X RMS [g]')

```

```

subplot(2,3,5)
Ybot_plot = surf(slot_bot,speed_half,Ybot)
axis(limits3Dbot)
title('Y RMS [g] Bottom')
xlabel('Slot #')
ylabel('Speed [rpm]')
zlabel('Y RMS [g]')

subplot(2,3,6)
Zbot_plot = surf(slot_bot,speed_half,Zbot)
axis(limits3Dbot)
title('Z RMS [g] Bottom')
xlabel('Slot #')
ylabel('Speed [rpm]')
zlabel('Z RMS [g]')

%Resize and save figure as PDF, PNG
set(gcf, 'Position', get(0,'Screensize'))
set(gcf, 'Units', 'inches');
screenposition = get(gcf, 'Position');
set(gcf, ...
    'PaperPosition', [0 0 screenposition(3:4)], ...
    'PaperSize', [screenposition(3:4)]);
print -dpdf -painters 5430_Fan_Vibration_Slot_Plots
print -dpng -painters 5430_Fan_Vibration_Slot_Plots

%Plot X Vibration data for 5430 full fill scenarios
figure
Xplot = plot(speedM(:,1:1),X(:,1:1), '-d', speedM(:,2:2),X(:,2:2), '-o',
speedM(:,3:3),X(:,3:3), '-^', speedM(:,4:4),X(:,4:4), '-* ',
speedM(:,5:5),X(:,5:5), '-s', speedM(:,6:6),X(:,6:6), '--d',
speedM(:,7:7),X(:,7:7), '--o', speedM(:,8:8),X(:,8:8), '--^',
speedM(:,9:9),X(:,9:9), '--*', speedM(:,10:10),X(:,10:10), '--s',
speed2,S2_831(:,1:1), '-.d', speed2,S7_831(:,1:1), '-.o',
speed2,S2_840(:,1:1), '-.^', 'LineWidth',2, 'MarkerSize',10)
legend('Slot 0', 'Slot 1', 'Slot 2', 'Slot 3', 'Slot 4', 'Slot 5', 'Slot 6', 'Slot 7',
'Slot 8', 'Slot 9', 'Slot 2 831', 'Slot 7 831', 'Slot 2 840', 'Location', 'eastoutside')
axis(limits2D)
xlabel('Speed [rpm]')
ylabel('X RMS [g]')
title('X RMS [g] 5430 Shelf Full Fill')
%grid on

%Resize and save figure as PDF, PNG
set(gcf, 'Position', get(0,'Screensize'))
set(gcf, 'Units', 'inches');
screenposition = get(gcf, 'Position');
set(gcf, ...
    'PaperPosition', [0 0 screenposition(3:4)], ...
    'PaperSize', [screenposition(3:4)]);
print -dpdf -painters 5430_Fan_Vibration_2D_X_Slot_Plot
print -dpng -painters 5430_Fan_Vibration_2D_X_Slot_Plot

%Plot Y Vibration data for 5430 full fill scenarios

```

```

figure
Yplot = plot(speedM(:,1:1),Y(:,1:1),'-d',speedM(:,2:2),Y(:,2:2),'-
o',speedM(:,3:3),Y(:,3:3),'-^',speedM(:,4:4),Y(:,4:4),'-
*',speedM(:,5:5),Y(:,5:5),'-s',speedM(:,6:6),Y(:,6:6),'--
d',speedM(:,7:7),Y(:,7:7),'--o',speedM(:,8:8),Y(:,8:8),'--
^',speedM(:,9:9),Y(:,9:9),'--*',speedM(:,10:10),Y(:,10:10),'--
s',speed2,S2_831(:,2:2),'-.d',speed2,S7_831(:,2:2),'-
.o',speed2,S2_840(:,2:2),'-.^','LineWidth',2,'MarkerSize',10)
legend('Slot 0','Slot 1','Slot 2','Slot 3','Slot 4','Slot 5','Slot 6','Slot
7','Slot 8','Slot 9','Slot 2 831','Slot 7 831','Slot 2
840','Location','eastoutside')
axis(limits2D)
xlabel('Speed [rpm]')
ylabel('Y RMS [g]')
title('Y RMS [g] 5430 Shelf Full Fill')
%grid on

%Resize and save figure as PDF, PNG
set(gcf, 'Position', get(0,'Screensize'))
set(gcf,'Units','inches');
screenposition = get(gcf,'Position');
set(gcf,...
    'PaperPosition',[0 0 screenposition(3:4)],...
    'PaperSize',[screenposition(3:4)]);
print -dpdf -painters 5430_Fan_Vibration_2D_Y_Slot_Plot
print -dpng -painters 5430_Fan_Vibration_2D_Y_Slot_Plot

%Plot Z Vibration data for 5430 full fill scenarios
figure
Zplot = plot(speedM(:,1:1),Z(:,1:1),'-d',speedM(:,2:2),Z(:,2:2),'-
o',speedM(:,3:3),Z(:,3:3),'-^',speedM(:,4:4),Z(:,4:4),'-
*',speedM(:,5:5),Z(:,5:5),'-s',speedM(:,6:6),Z(:,6:6),'--
d',speedM(:,7:7),Z(:,7:7),'--o',speedM(:,8:8),Z(:,8:8),'--
^',speedM(:,9:9),Z(:,9:9),'--*',speedM(:,10:10),Z(:,10:10),'--
s',speed2,S2_831(:,3:3),'-.d',speed2,S7_831(:,3:3),'-
.o',speed2,S2_840(:,3:3),'-.^','LineWidth',2,'MarkerSize',10)
legend('Slot 0','Slot 1','Slot 2','Slot 3','Slot 4','Slot 5','Slot 6','Slot
7','Slot 8','Slot 9','Slot 2 831','Slot 7 831','Slot 2
840','Location','eastoutside')
axis(limits2D)
xlabel('Speed [rpm]')
ylabel('Z RMS [g]')
title('Z RMS [g] 5430 Shelf Full Fill')
%grid on

%Resize and save figure as PDF, PNG
set(gcf, 'Position', get(0,'Screensize'))
set(gcf,'Units','inches');
screenposition = get(gcf,'Position');
set(gcf,...
    'PaperPosition',[0 0 screenposition(3:4)],...
    'PaperSize',[screenposition(3:4)]);
print -dpdf -painters 5430_Fan_Vibration_2D_Z_Slot_Plot
print -dpng -painters 5430_Fan_Vibration_2D_Z_Slot_Plot

% %Single Fan Plots, Slot 2, 7 Comparison

```

```

% S2_1 = xlsread(filename,3,'D10:F18');
% S7_1 = xlsread(filename,3,'D27:F35');
% S2U_1 = xlsread(filename,3,'D119:F127');
%
% figure
% X_S2_plot = plot(speedM(:,1:1),S2_1(:,1:1),'-
d',speedM(:,1:1),S7_1(:,1:1),'-o',speedM(:,1:1),S2U_1(:,1:1),'-
^','LineWidth',2,'MarkerSize',10)
% legend('Slot 2','Slot 7','Slot 2 Flipped Fans','Location','eastoutside')
% axis(limits2D)
% xlabel('Speed [rpm]')
% ylabel('X RMS [g]')
% title('X RMS [g] 5430 Shelf Single Fan')
% grid on
%
% set(gcf, 'Position', get(0,'Screensize'))
% set(gcf,'Units','inches');
% screenposition = get(gcf,'Position');
% set(gcf,...
%     'PaperPosition',[0 0 screenposition(3:4)],...
%     'PaperSize',[screenposition(3:4)]);
% print -dpdf -painters 5430_Fan_Vibration_2D_X_Single_Fan_Plot
% print -dpng -painters 5430_Fan_Vibration_2D_X_Single_Fan_Plot
%
% figure
% Y_S2_plot = plot(speedM(:,2:2),S2_1(:,2:2),'-
d',speedM(:,2:2),S7_1(:,2:2),'-o',speedM(:,2:2),S2U_1(:,2:2),'-
^','LineWidth',2,'MarkerSize',10)
% legend('Slot 2','Slot 7','Slot 2 Flipped Fans','Location','eastoutside')
% axis(limits2D)
% xlabel('Speed [rpm]')
% ylabel('Y RMS [g]')
% title('Y RMS [g] 5430 Shelf Single Fan')
% grid on
%
% set(gcf, 'Position', get(0,'Screensize'))
% set(gcf,'Units','inches');
% screenposition = get(gcf,'Position');
% set(gcf,...
%     'PaperPosition',[0 0 screenposition(3:4)],...
%     'PaperSize',[screenposition(3:4)]);
% print -dpdf -painters 5430_Fan_Vibration_2D_Y_Single_Fan_Plot
% print -dpng -painters 5430_Fan_Vibration_2D_Y_Single_Fan_Plot
%
% figure
% Z_S2_plot = plot(speedM(:,3:3),S2_1(:,3:3),'-
d',speedM(:,3:3),S7_1(:,3:3),'-o',speedM(:,3:3),S2U_1(:,3:3),'-
^','LineWidth',2,'MarkerSize',10)
% legend('Slot 2','Slot 7','Slot 2 Flipped Fans','Location','eastoutside')
% axis(limits2D)
% xlabel('Speed [rpm]')
% ylabel('Z RMS [g]')
% title('Z RMS [g] 5430 Shelf Single Fan')
% grid on
%
% set(gcf, 'Position', get(0,'Screensize'))
% set(gcf,'Units','inches');

```

```

% screenposition = get(gcf,'Position');
% set(gcf,...
%     'PaperPosition',[0 0 screenposition(3:4)],...
%     'PaperSize',[screenposition(3:4)]);
% print -dpdf -painters 5430_Fan_Vibration_2D_Z_Single_Fan_Plot
% print -dpng -painters 5430_Fan_Vibration_2D_Z_Single_Fan_Plot

%Plot X Vibration data for 5430 full fill scenarios
figure
Xplot2 = plot(speedM(:,5:5),X(:,5:5),'-s',speedM(:,8:8),X(:,8:8),'--
^',speed2,S2_831(:,1:1),'-.d',speed2,S2_840(:,1:1),'-
.^','LineWidth',2,'MarkerSize',10)
% legend('Gen 2 Slot 4','Gen 2 Slot 7','Legacy Slot 2','Legacy Vib. Sol. #1
Slot 2','Location','eastoutside')
axis(limits2D)
xlabel('Speed [rpm]')
ylabel('X RMS [g]')
title('X RMS [g] 5430 Shelf Full Fill')
%grid on

%Resize and save figure as PDF, PNG
% set(gcf, 'Position', get(0,'Screensize'))
% set(gcf,'Units','inches');
% screenposition = get(gcf,'Position');
% set(gcf,...
%     'PaperPosition',[0 0 screenposition(3:4)],...
%     'PaperSize',[screenposition(3:4)]);
print -dpdf -painters 5430_Fan_Vibration_2D_X_Slot_Plot2
print -dpng -painters 5430_Fan_Vibration_2D_X_Slot_Plot2

%Plot Y Vibration data for 5430 full fill scenarios
figure
Yplot2 = plot(speedM(:,5:5),Y(:,5:5),'-s',speedM(:,8:8),Y(:,8:8),'--
^',speed2,S2_831(:,2:2),'-.d',speed2,S2_840(:,2:2),'-
.^','LineWidth',2,'MarkerSize',10)
% legend('Gen 2 Slot 4','Gen 2 Slot 7','Legacy Slot 2','Legacy Vib. Sol. #1
Slot 2','Location','eastoutside')
axis(limits2D)
xlabel('Speed [rpm]')
ylabel('Y RMS [g]')
title('Y RMS [g] 5430 Shelf Full Fill')
%grid on

%Resize and save figure as PDF, PNG
% set(gcf, 'Position', get(0,'Screensize'))
% set(gcf,'Units','inches');
% screenposition = get(gcf,'Position');
% set(gcf,...
%     'PaperPosition',[0 0 screenposition(3:4)],...
%     'PaperSize',[screenposition(3:4)]);
print -dpdf -painters 5430_Fan_Vibration_2D_Y_Slot_Plot2
print -dpng -painters 5430_Fan_Vibration_2D_Y_Slot_Plot2

%Plot Z Vibration data for 5430 full fill scenarios
figure

```

```

Zplot2 = plot(speedM(:,5:5),Z(:,5:5),'-s',speedM(:,8:8),Z(:,8:8),'--
^',speed2,S2_831(:,3:3),'-.d',speed2,S2_840(:,3:3),'-
.^','LineWidth',2,'MarkerSize',10)
% legend('Gen 2 Slot 4','Gen 2 Slot 7','Legacy Slot 2','Legacy Vib. Sol. #1
Slot 2','Location','eastoutside')
axis(limits2D)
xlabel('Speed [rpm]')
ylabel('Z RMS [g]')
title('Z RMS [g] 5430 Shelf Full Fill')
%grid on

%Resize and save figure as PDF, PNG
% set(gcf, 'Position', get(0,'Screensize'))
% set(gcf,'Units','inches');
% screenposition = get(gcf,'Position');
% set(gcf,...
%     'PaperPosition',[0 0 screenposition(3:4)],...
%     'PaperSize',[screenposition(3:4)]);
print -dpdf -painters 5430_Fan_Vibration_2D_Z_Slot_Plot2
print -dpng -painters 5430_Fan_Vibration_2D_Z_Slot_Plot2

```

Chapter 10 Appendix B: Results Output

Benchtop Test Jig Impulse Frequency Characterization

The test jig was characterized to determine its natural frequencies so that they are known when comparing vibration data between fans. The test jig was lightly hit with a hammer in all three axes and its vibration response recorded and analyzed by a fast Fourier transform (FFT).

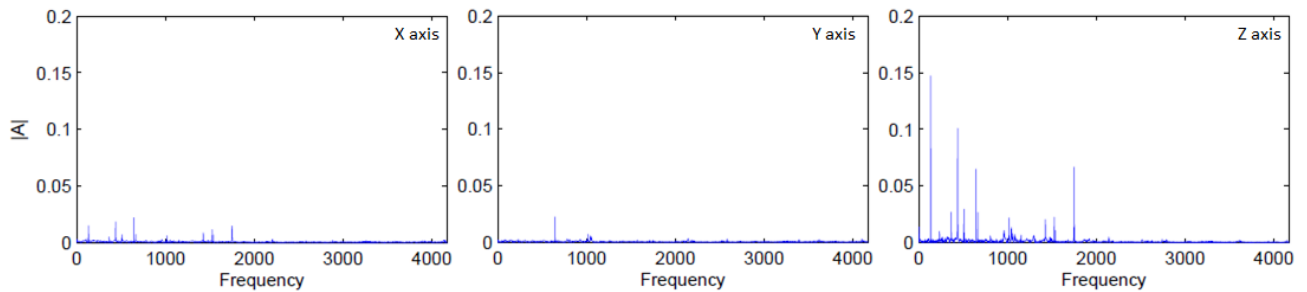


Figure 10.1: Benchtop Test Jig X-Axis Impulse FFT [Hz]

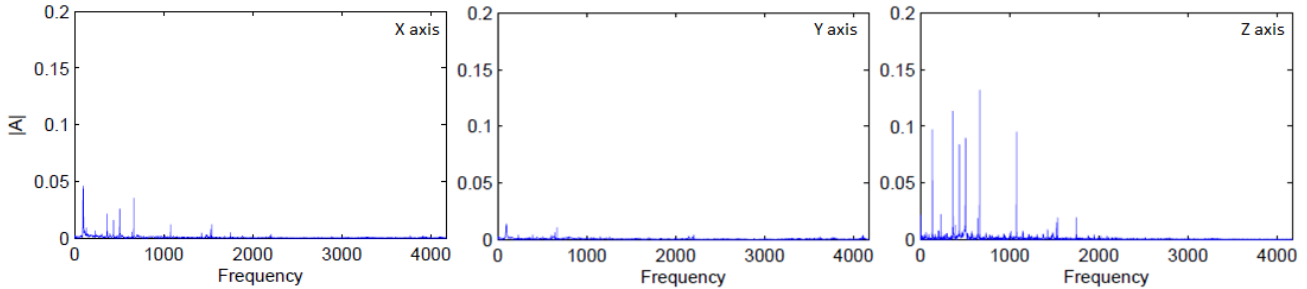


Figure 10.2: Benchtop Test Jig Y-Axis Impulse FFT [Hz]

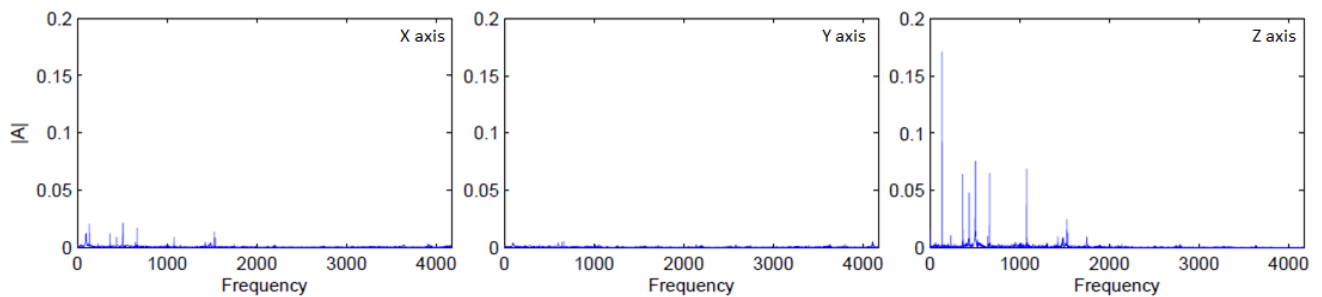


Figure 10.3: Benchtop Test Jig Z-Axis Impulse FFT [Hz]

Chapter 11 Appendix C: Additional Microscopy/Spectroscopy Results

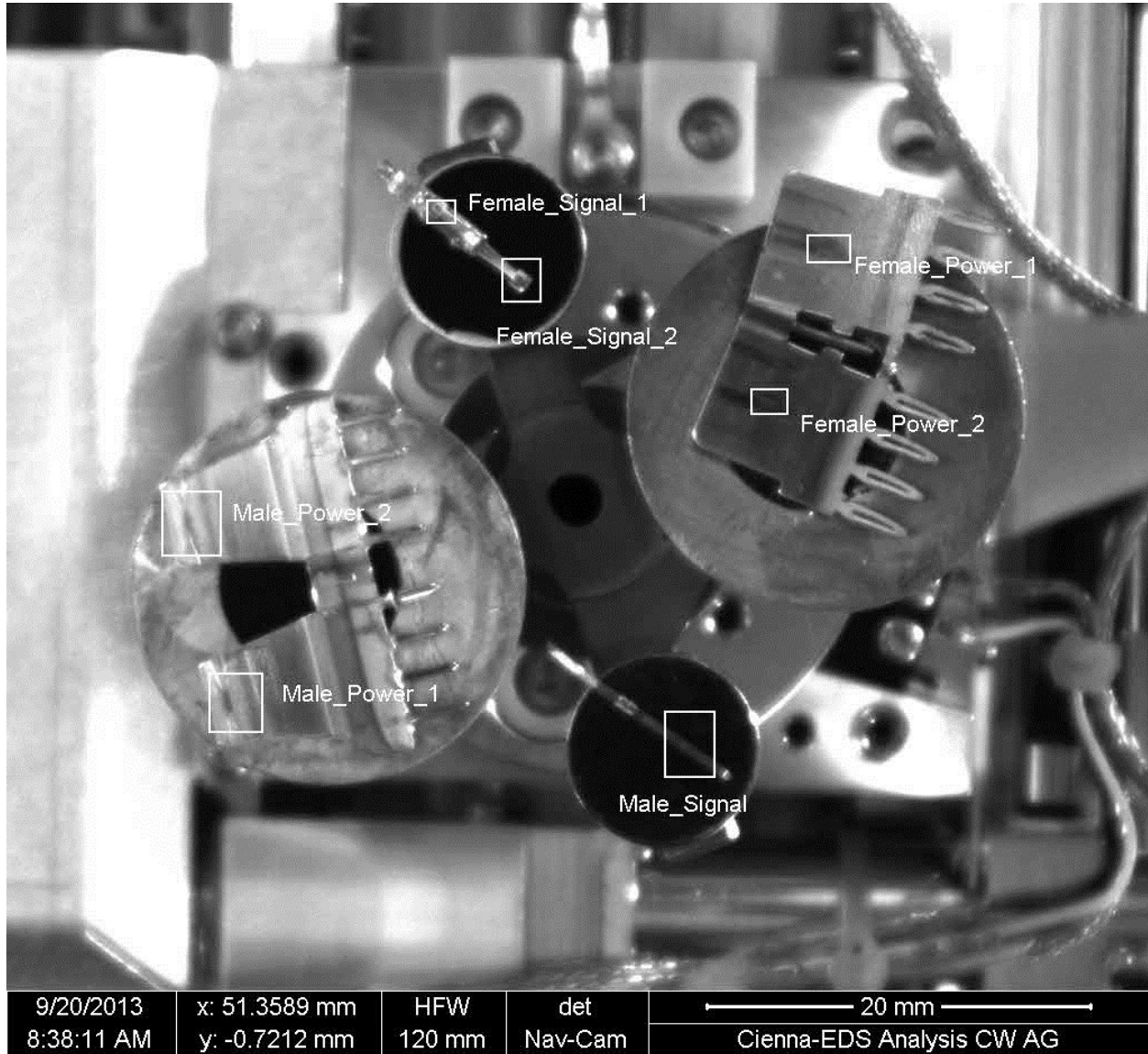


Figure 11.1: Connector contacts tested during EDX

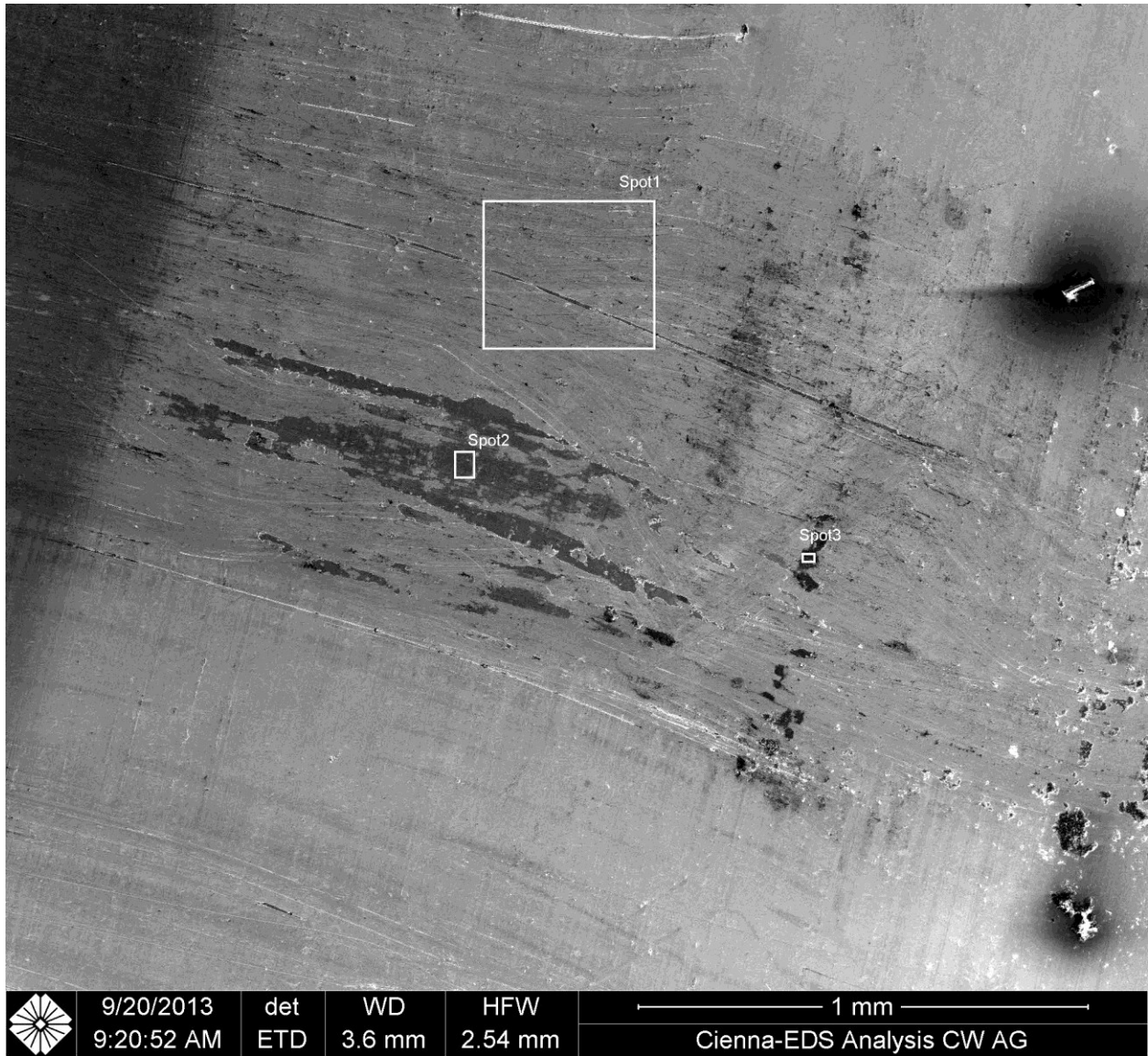


Figure 11.2: Female Power Blade #1 Regions Tested for EDX

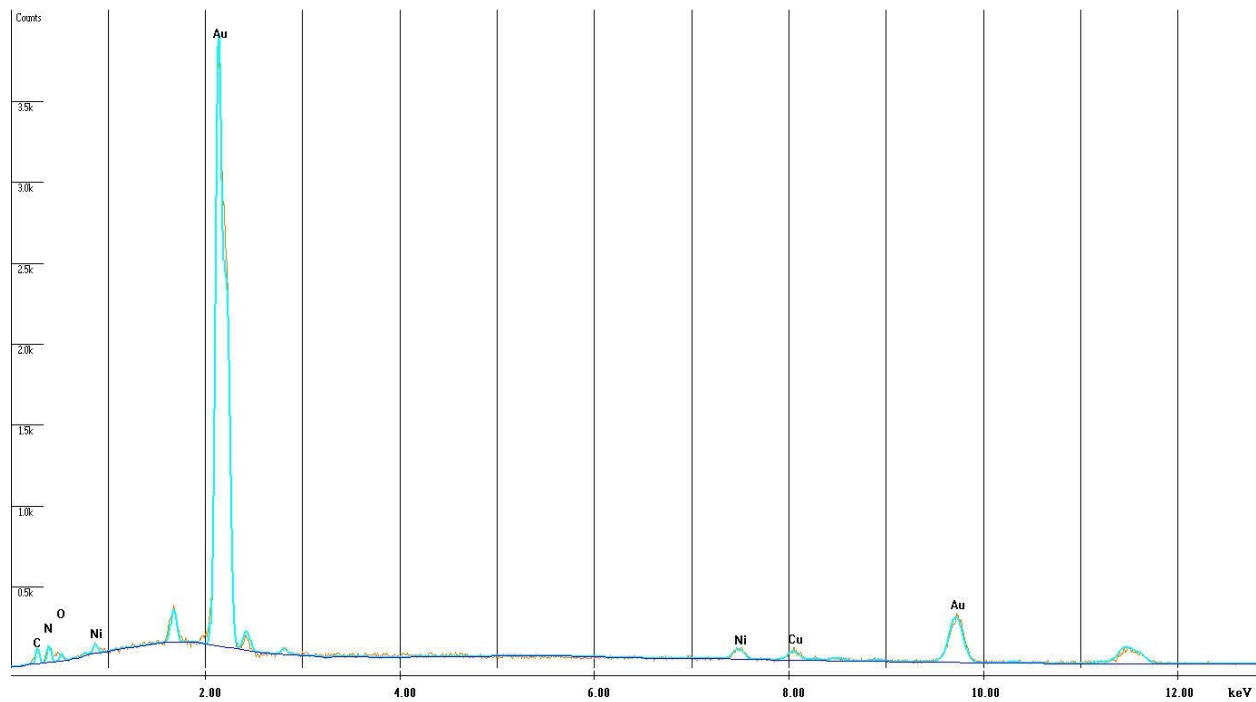


Figure 11.3: Female Power Blade #1 EDX Analysis Unworn Region Spot #1

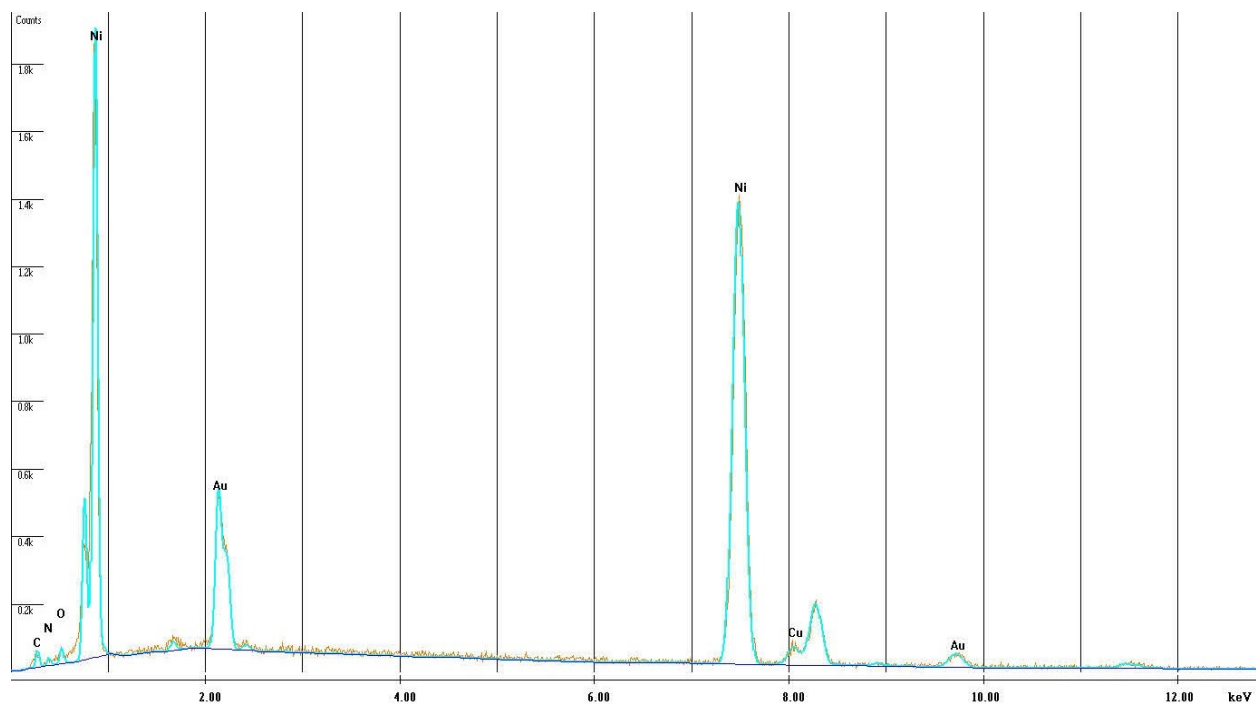


Figure 11.4: Female Power Blade #1 EDX Analysis Worn Region Spot #2

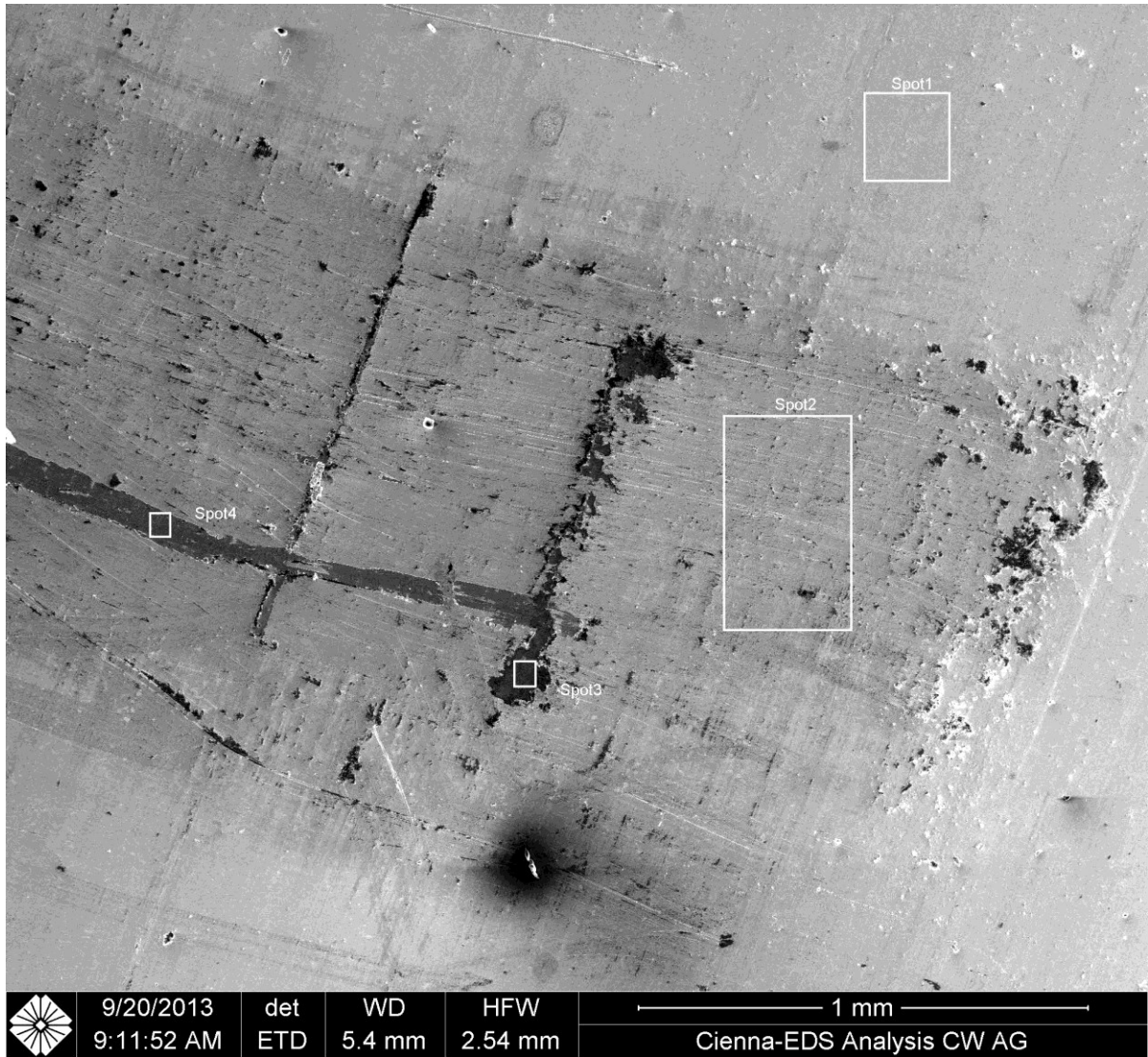


Figure 11.5: Female Power Blade #2 Regions Tested for EDX

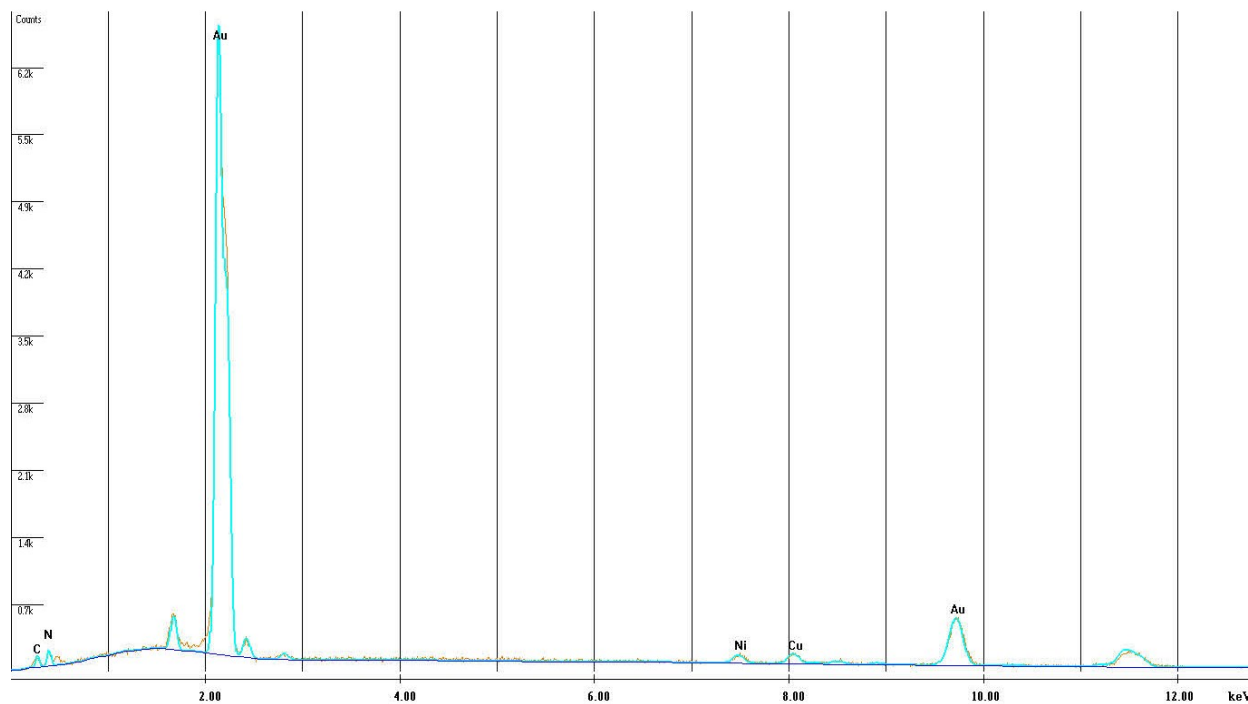


Figure 11.6: Female Power Blade #2 EDX Analysis Unworn Region Spot #1

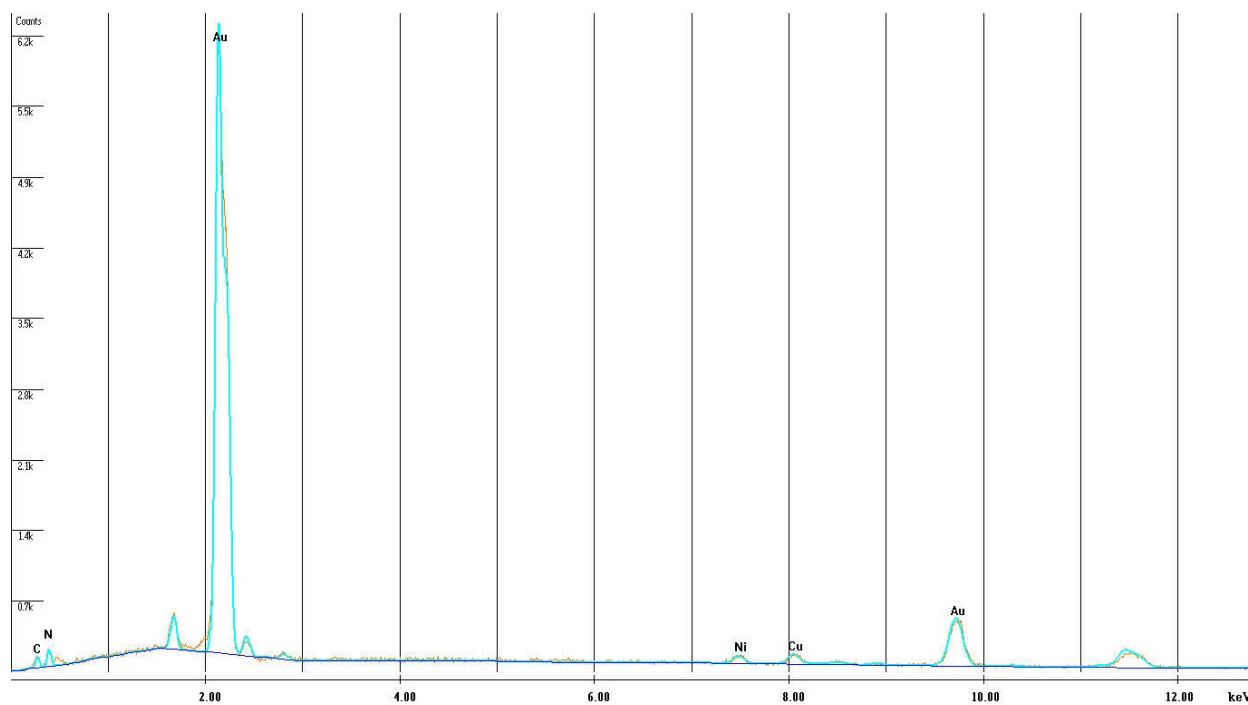


Figure 11.7: Female Power Blade #2 EDX Analysis Worn Region (Wear Track) Spot #2

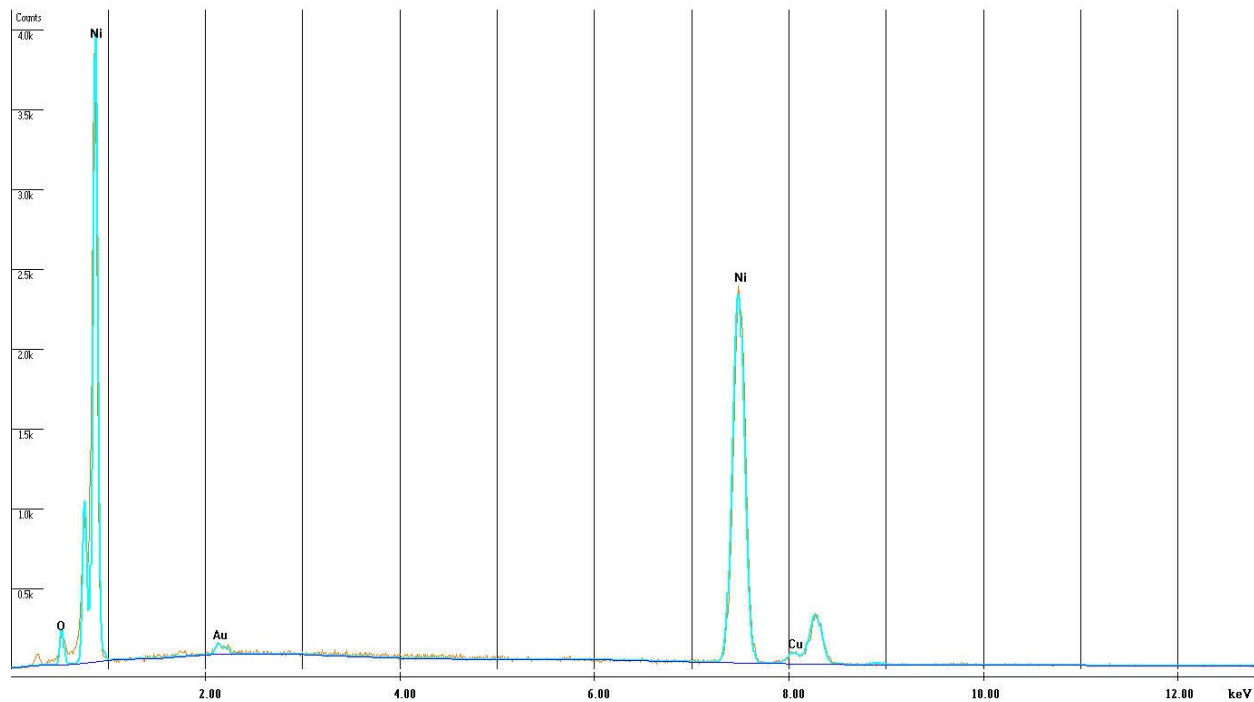


Figure 11.8: Female Power Blade #2 EDX Analysis Worn Region (Vertical) Spot #3

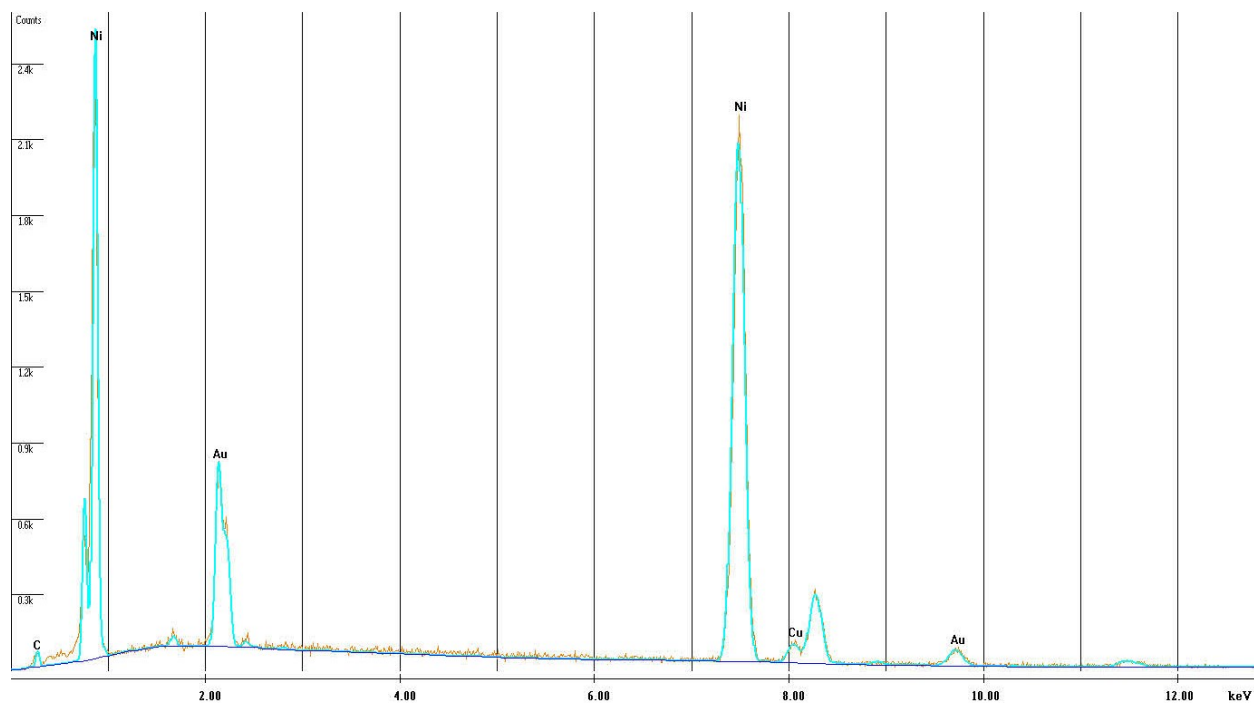


Figure 11.9: Female Power Blade #2 EDX Analysis Worn Region (Horizontal) Spot #4

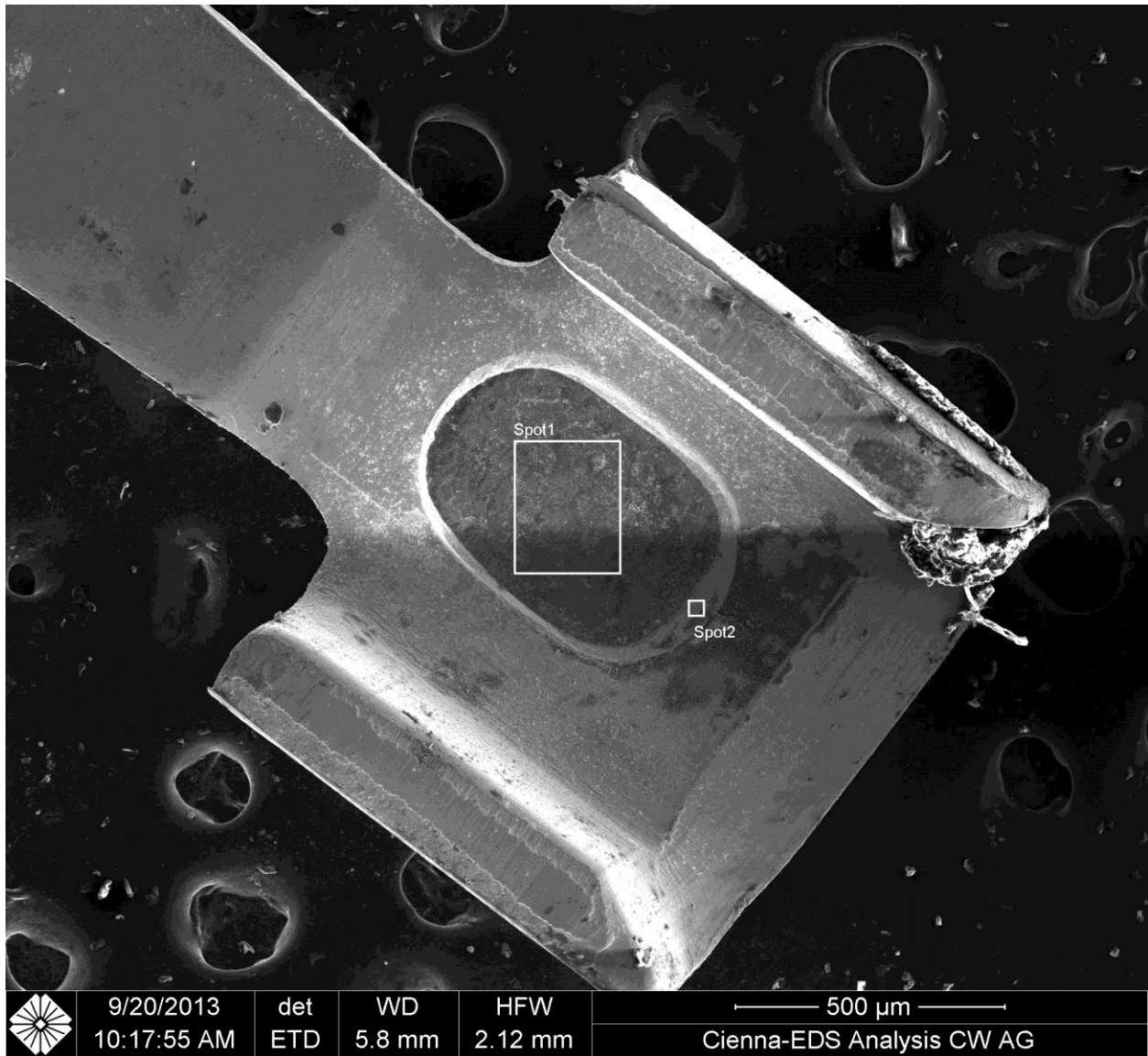


Figure 11.10: Backplane Female Signal Pin Contact #2 Regions Tested for EDX

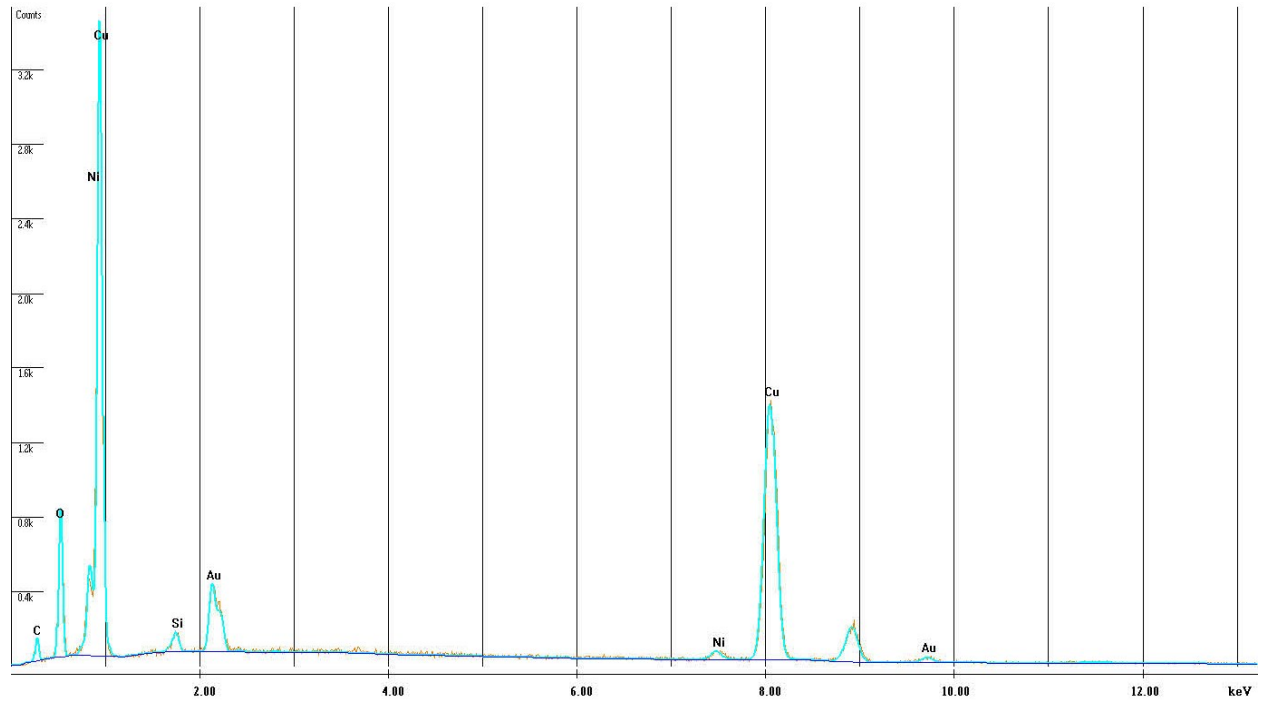


Figure 11.11: Backplane Female Signal Pin Contact #2 Worn Region Spot #1

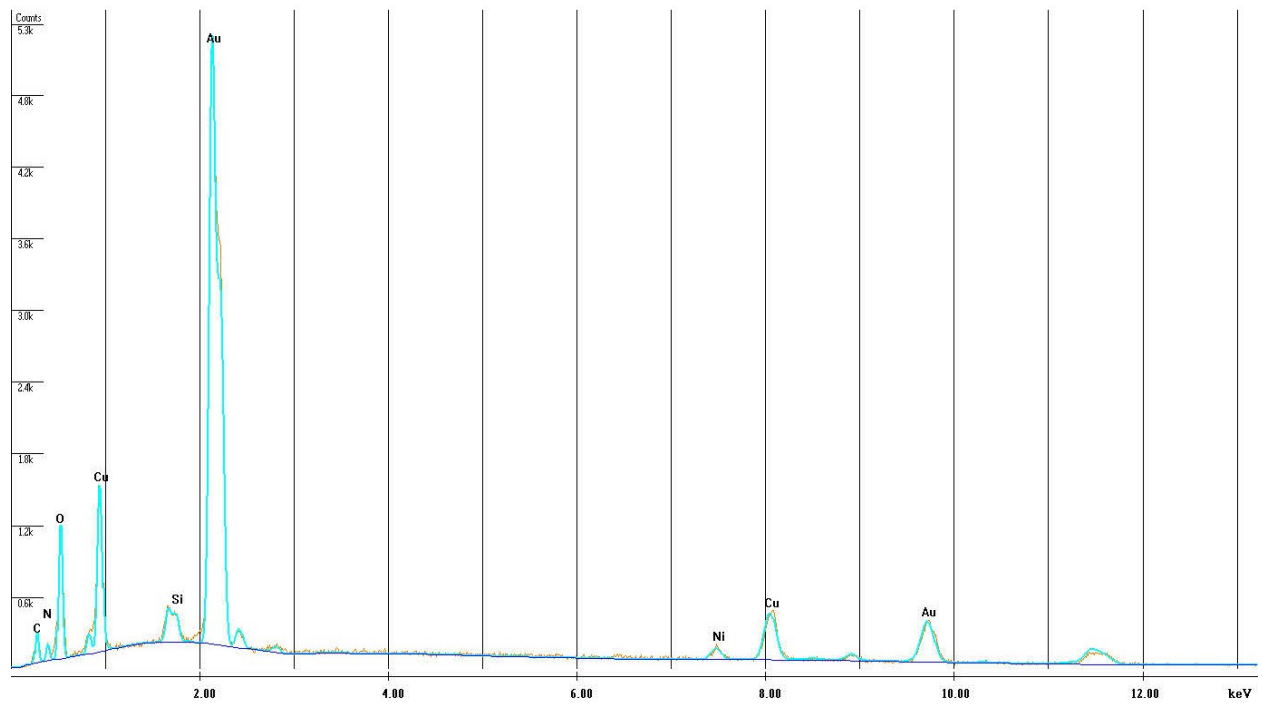


Figure 11.12: Backplane Female Signal Pin Contact #2 Unworn Region Spot #2



Figure 11.13: Male Power Blade #1 Regions Tested for EDX

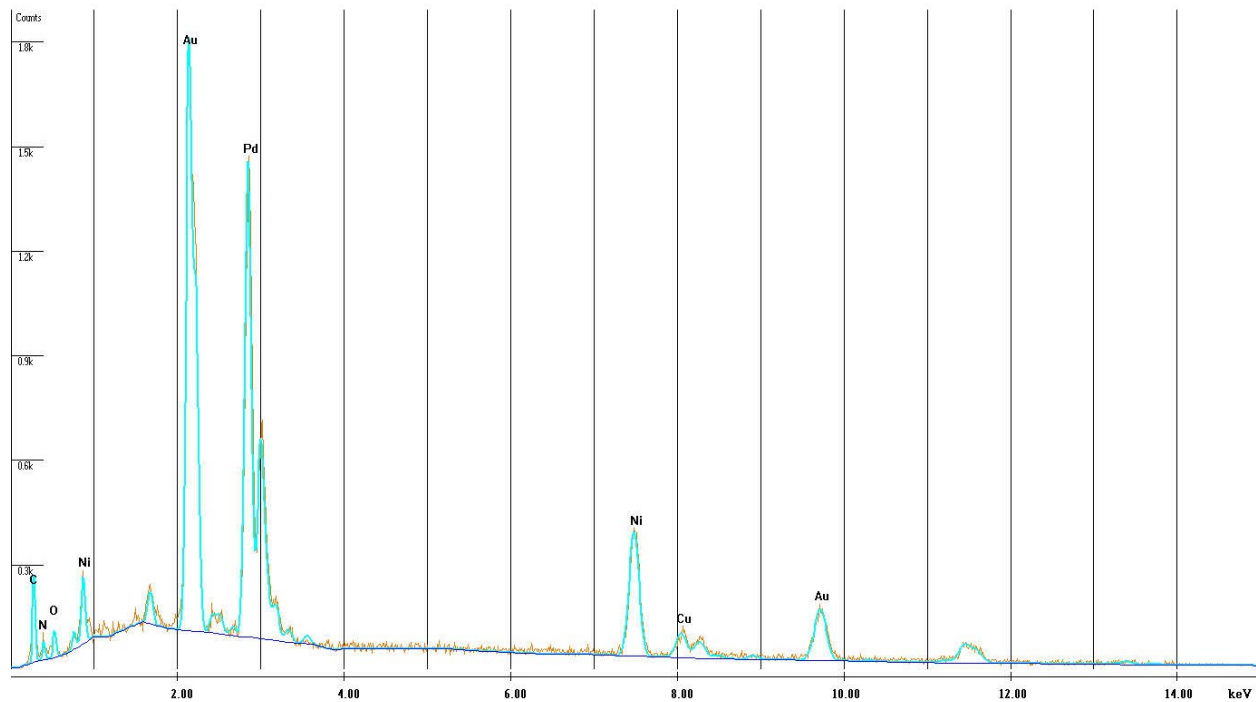


Figure 11.14: Male Power Blade #1 EDX Analysis Worn Region Spot #1

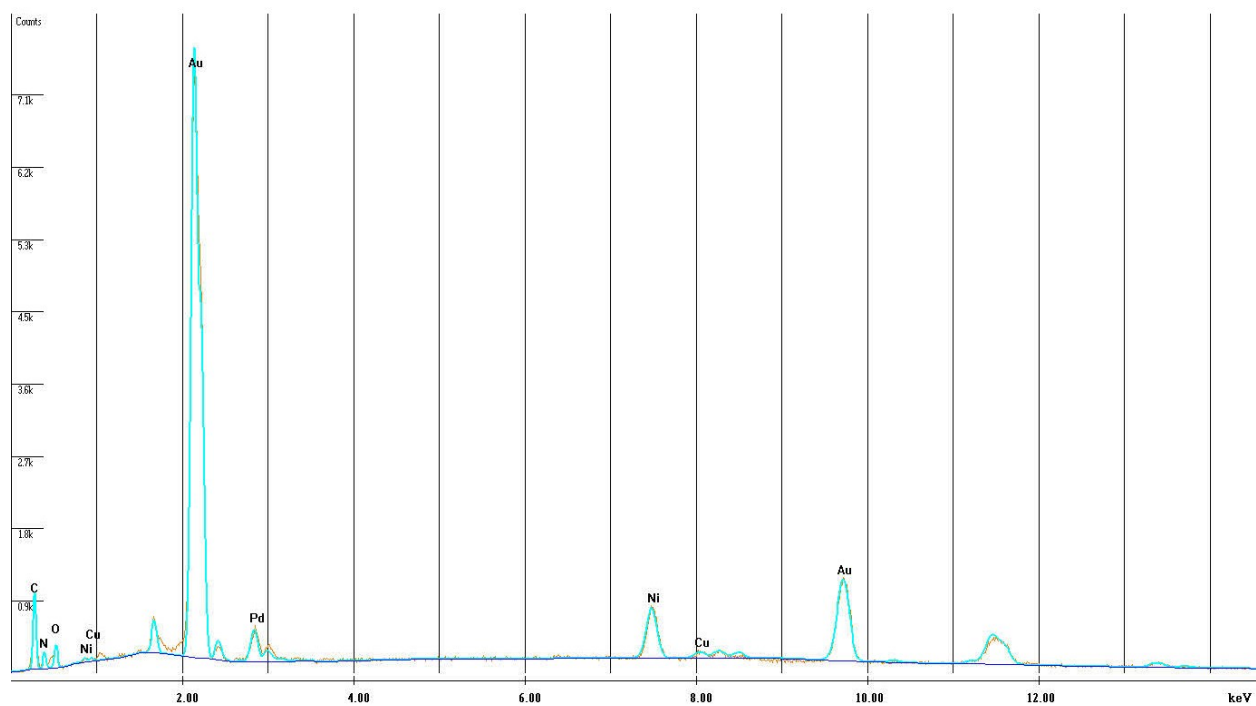


Figure 11.15: Male Power Blade #1 EDX Analysis Worn Region (Leading Edge) Spot #2

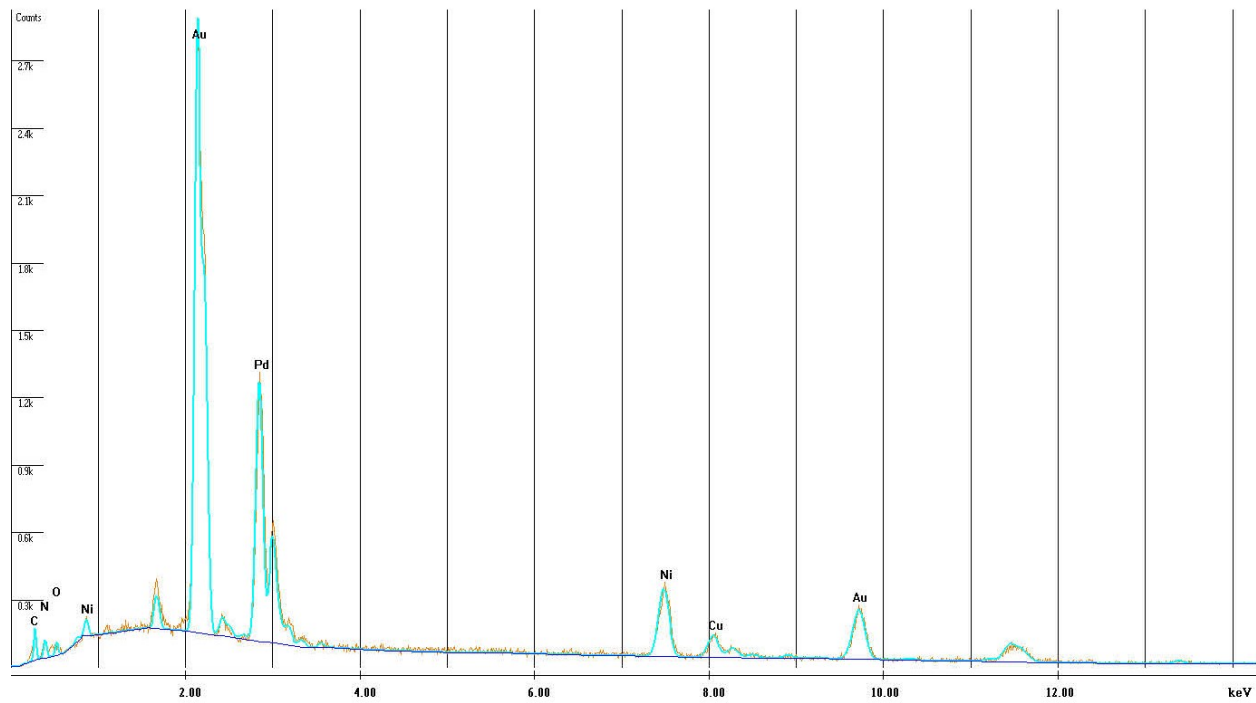


Figure 11.16: Male Power Blade #1 EDX Analysis Unworn Region Spot #3



Figure 11.17: Male Power Blade #2 Regions Tested for EDX

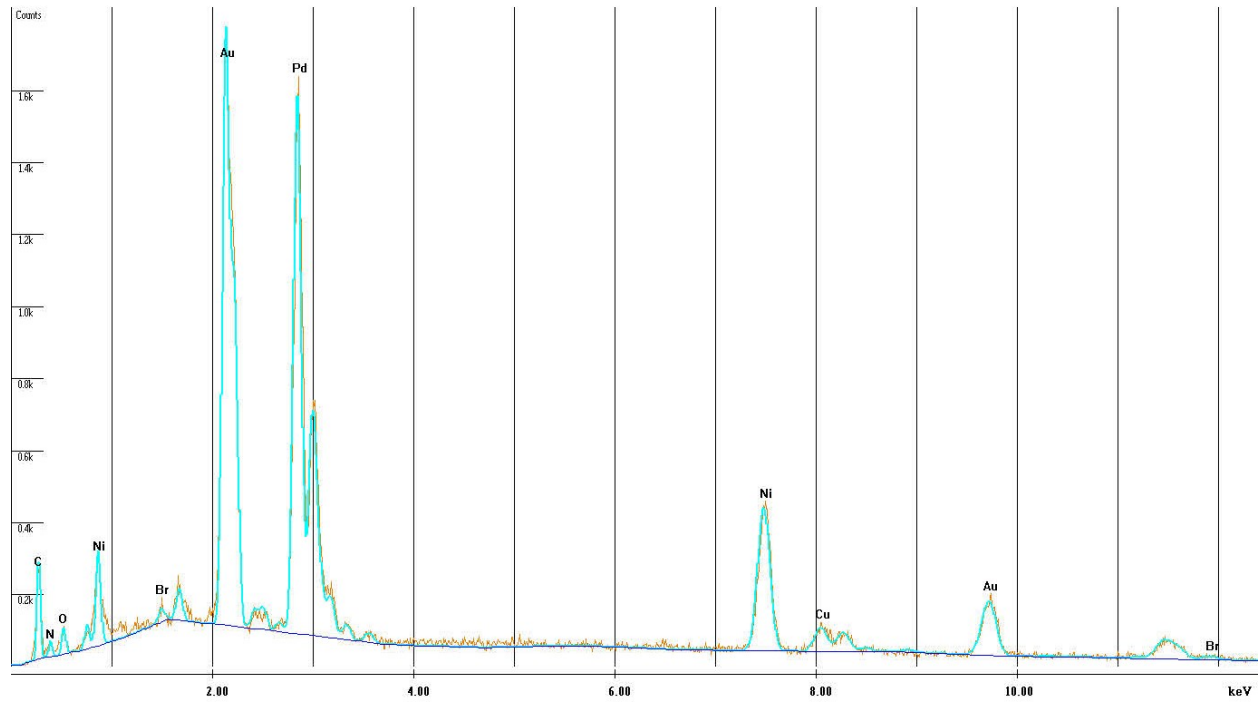


Figure 11.18: Male Power Blade #2 EDX Analysis Worn Region Spot #1

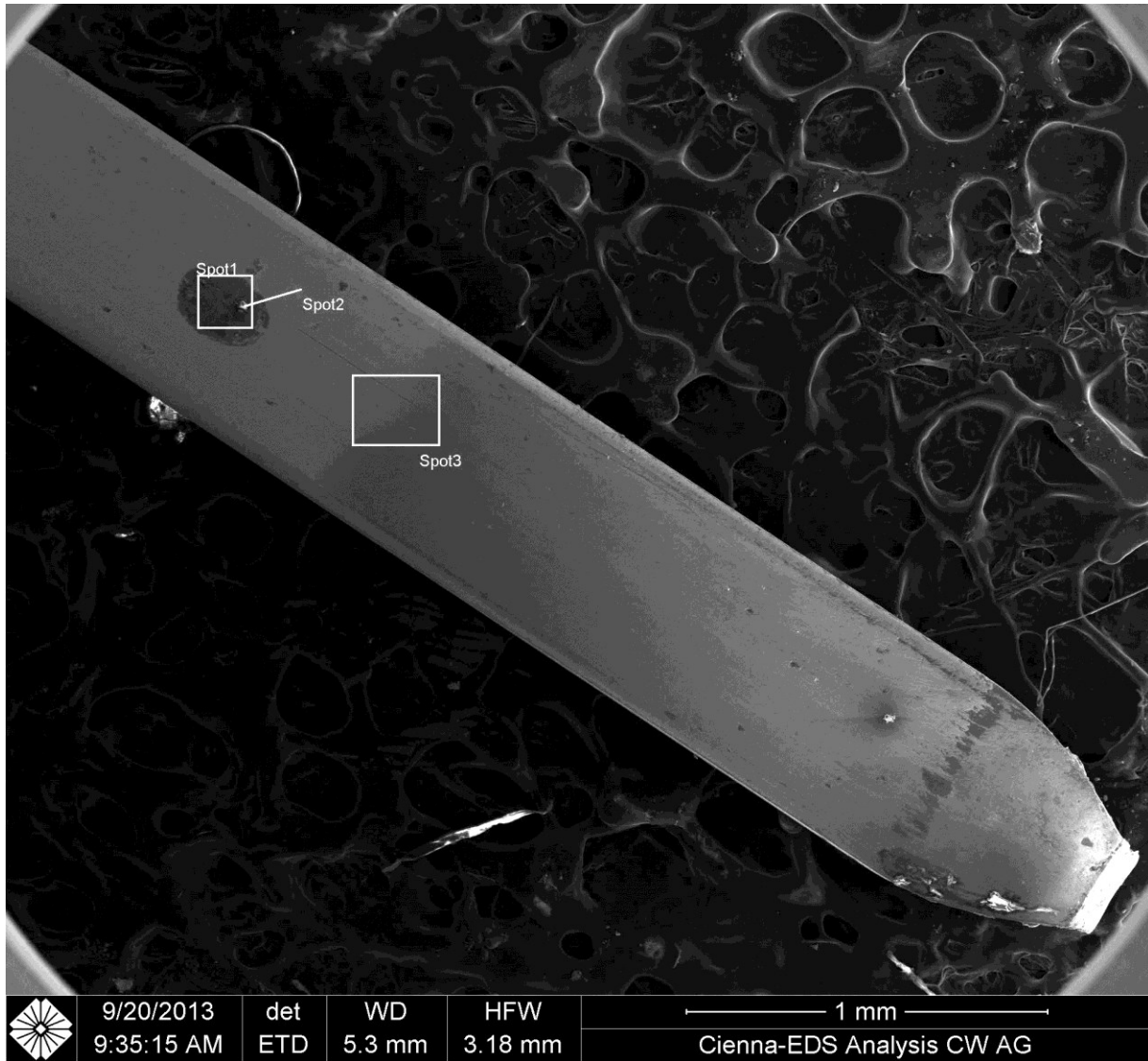


Figure 11.19: Male Signal Pin Contact #1 Regions Tested for EDX

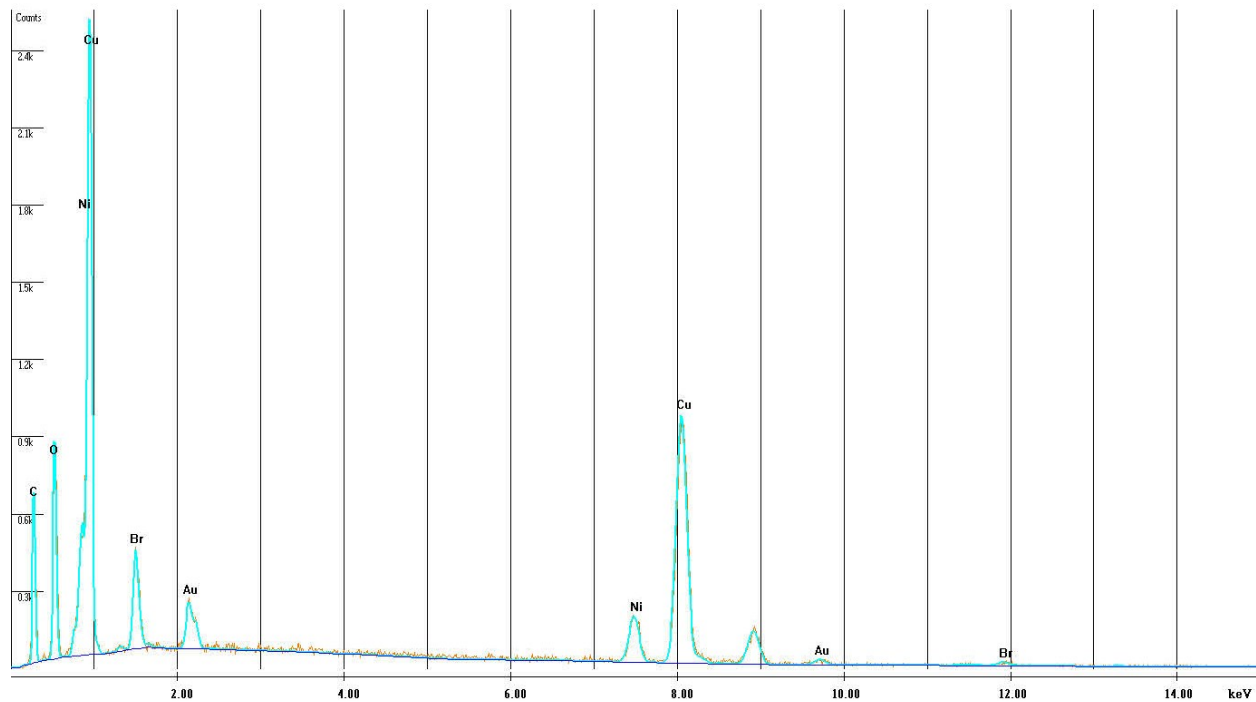


Figure 11.20: Male Signal Pin Contact #1 EDX Analysis Worn Region Spot #1

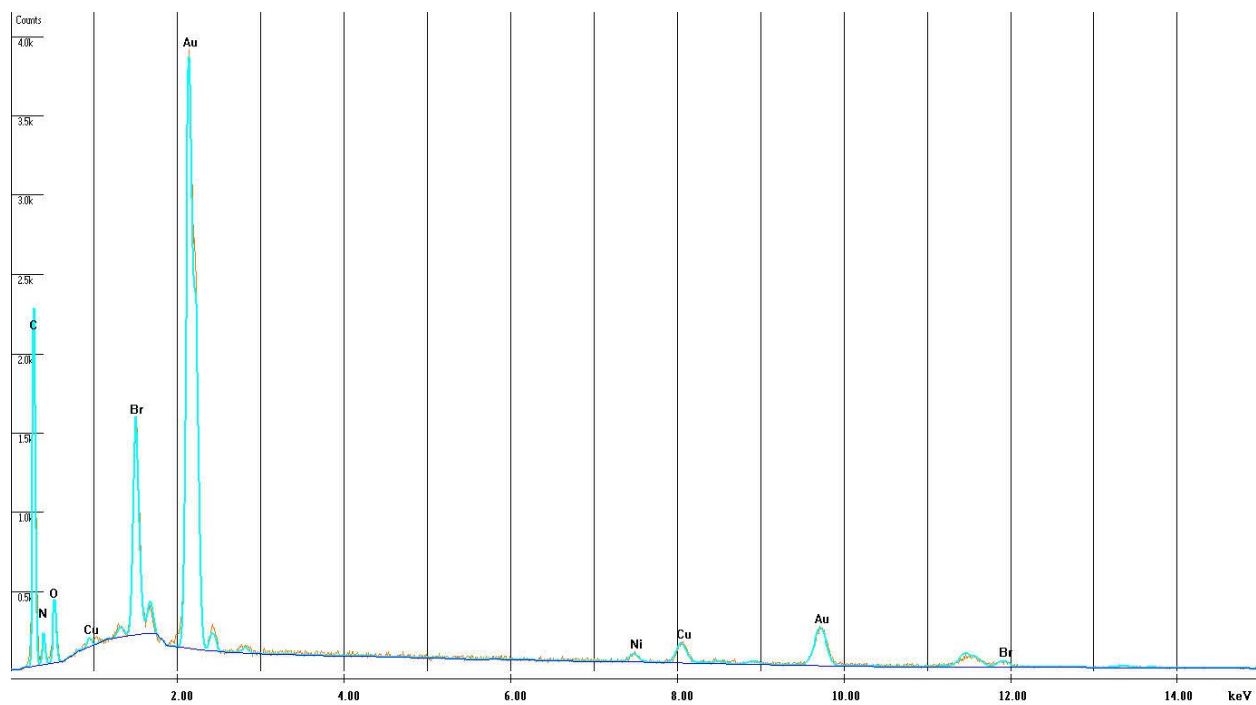


Figure 11.21: Male Signal Pin Contact #1 EDX Analysis Worn Region Focused Spot #2

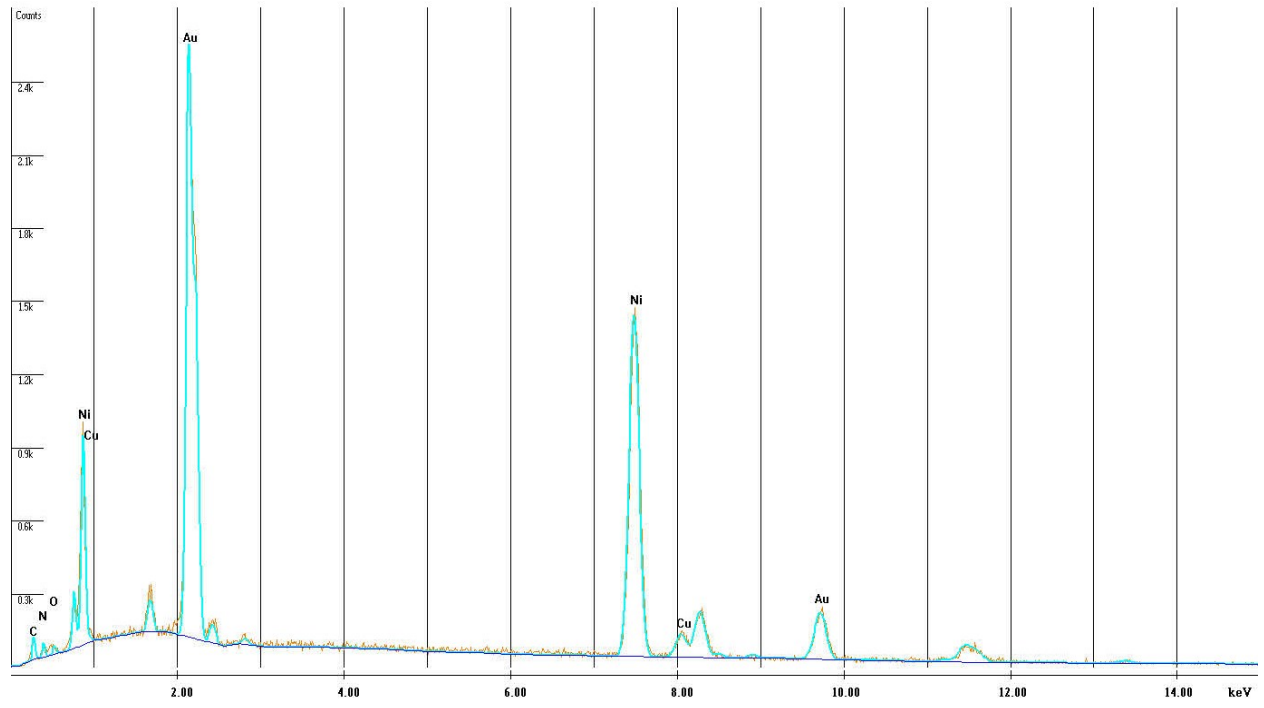


Figure 11.22: Male Signal Pin Contact #1 EDX Analysis Worn Region (Wear Track) Spot #3

Chapter 12 Appendix D: Tolerance Analyses

Fan Unit to Shelf Mating Tolerance Analysis – Connector Wipe

This tolerance analysis takes many factors into consideration. Due to the nature of the shelf and fan construction, it was unclear as to where the fan unit was bottoming out on the shelf as a hard stop. All possible tolerances loops and hard stops were investigated.

Table 12.1: GEN1 Fan Unit to Shelf Tolerance Analysis Summary [inches]

Z-Axis Crash and Pin Wipe [in]							
		Process Sigma	PCB Spacing for Zero Wipe	Nominal PCB Spacing	Nominal Wipe	Pin Wipe at 6σ	Probability of Zero Wipe
UFU Mated to Shelf							
Gasket as Hard Stop	6.8247 σ	0.011	0.788	0.711	0.107	0.0091	0.000000%
Washer as Hard Stop	8.2087 σ	0.011	0.788	0.698	0.120	0.0238	0.000000%
Ducting as Hard Stop	12.198 σ	0.010	0.788	0.666	0.152	0.0613	0.000000%
Latch as Hard Stop	6.3076 σ	0.011	0.788	0.692	0.126	0.0035	0.000000%
Front Latch as Hard Stop	10.609 σ	0.011	0.788	0.648	0.170	0.0507	0.000000%
LFU Mated to Shelf							
Gasket as Hard Stop	4.5685 σ	0.011	0.788	0.736	0.082	(0.0159)	0.000135%
Washer as Hard Stop	5.8930 σ	0.011	0.788	0.723	0.095	(0.0012)	0.000000%
Ducting as Hard Stop	9.6702 σ	0.010	0.788	0.691	0.127	0.0363	0.000000%
Latch as Hard Stop	4.1313 σ	0.011	0.788	0.717	0.101	(0.0215)	0.000000%
Front Latch as Hard Stop	8.3356 σ	0.011	0.788	0.673	0.145	0.0257	0.000000%
Nominal Connector Gap							
Front Latch	0.0072 in						
Latch	0.0514 in						
Duct	0.0250 in						

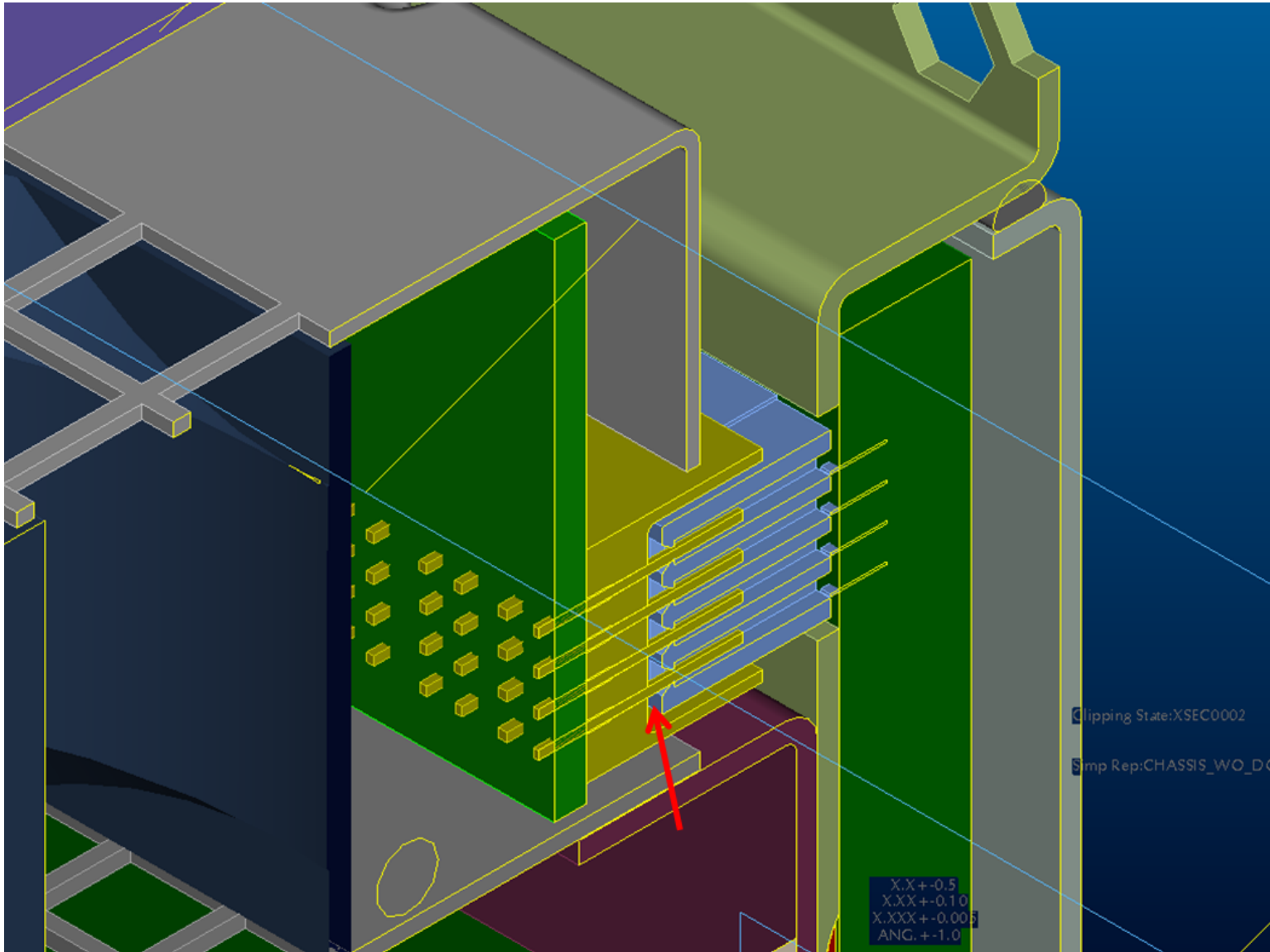


Figure 12.1: GEN1 Fan Unit to Shelf Tolerance Analysis - Connector Gap Section View

Case #1: Assume washer as hard stop in tolerance loop:

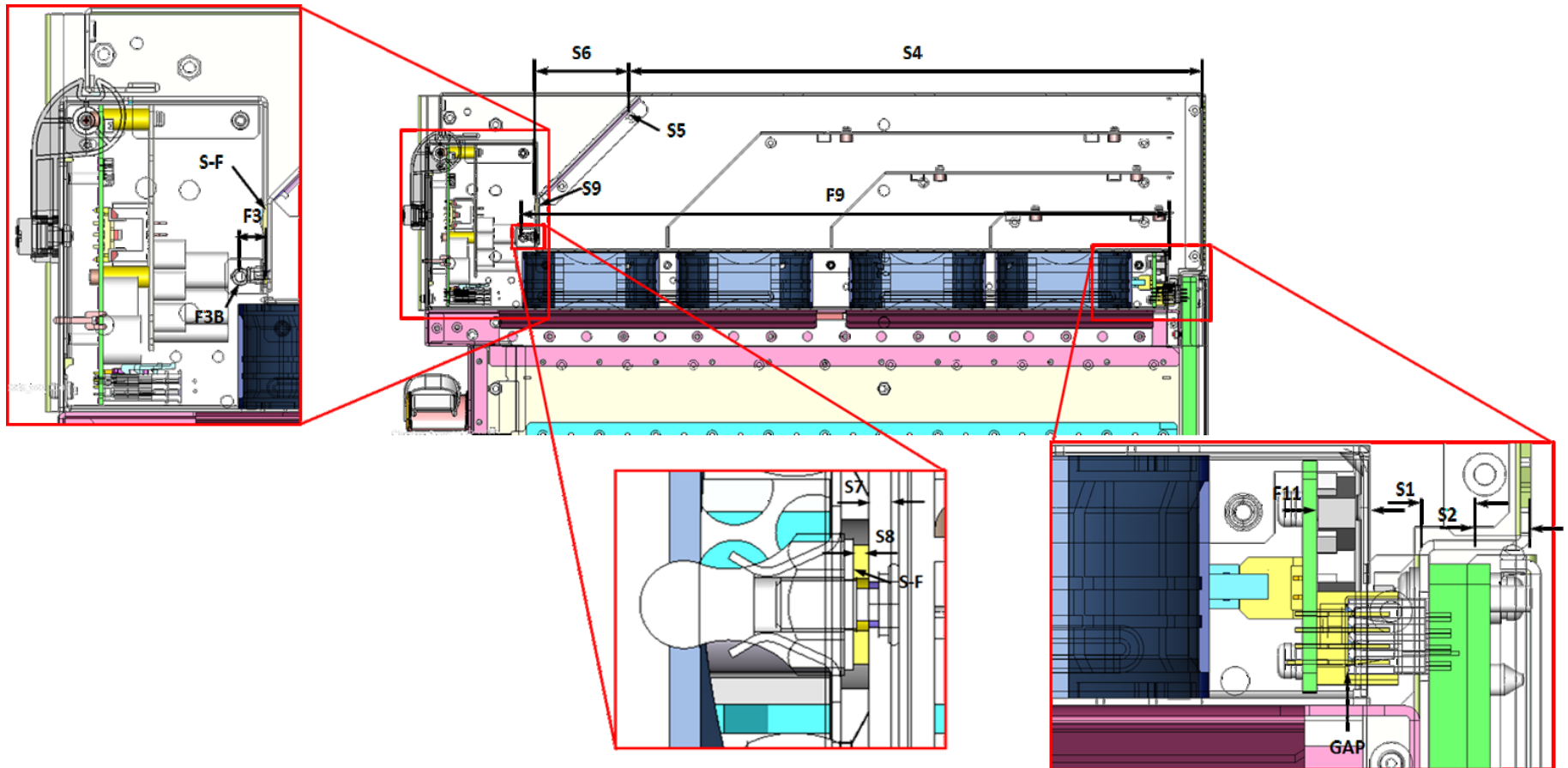


Figure 12.2: Tolerance Loop – GEN1 Fan Unit to Shelf - Washer Hard Stop

Assumptions:

1. $C_p = 1.0$ for all parts
2. $C_{PK} = 0.5$ for all parts
3. Hole-Hole tolerance within a PCB is ± 0.003 in

Table 12.2: Tolerance Loop – GEN1 Fan Unit to Shelf - Washer Hard Stop

Dimension	Part/Assembly	Feature/Joint Type	Slop (±mm)	Slop (±in)	Tolerance (±mm)	Tolerance (±in)	σ ² (mm ²)	Reference/Notes
S1	Chassis Sheetmetal	Sheetmetal bend			0.381	0.015	0.0161	Estimate, complex part geometry
S2	Chassis Sheetmetal	Sheetmetal bend			0.381	0.015	0.0161	Estimate, complex part geometry
S4	Chassis Sheetmetal	Sheetmetal bend to hole			0.254	0.010	0.0072	From Ciena Mechanical Spec. (CMS)
S5	Riveted Connection	Countersunk Connect			0.025	0.001	0.0001	Estimate
S6	Chassis Sheetmetal	Sheetmetal bend to hole			0.254	0.010	0.0072	From CMS
S7	Chassis Sheetmetal	Thickness			0.127	0.005	0.0018	From CMS
S8	#6 Type A Flat Washer	Thickness			0.330	0.013	0.0121	From CMS
F3	Fan Chassis Sheetmetal	Sheetmetal bend to hole			0.254	0.010	0.0072	From CMS
F3B	Screwed Connection	Countersunk screwed connection	0.035	0.001				Estimate
F9	Fan Chassis Sheetmetal	Sheetmetal hole to bend			0.254	0.010	0.0072	From CMS
F11	PEM SO	Length			0.051	0.002	0.0003	Penn Engineering
		Total Stack Up	0.035	0.001	2.311	0.091		
		Pooled Variance of Tolerances					0.0752	
		Process Sigma of Tolerances			0.274	0.011		
		6× Process Sigma (σ)			1.645	0.065		
		6× Process Sigma + Slop (σ+S)	1.680	0.066				
		Nominal Spacing BP to BP CAD	18.364	0.723				Minimum nominal offset from CAD models
		Nominal Spacing BP to BP Spec	16.916	0.666				Minimum nominal offset from FCI Spec
		Nominal Offset (NO)	1.448	0.057				
		Pin Wipe	3.861	0.152				Taken from interconnect specification.
		Effective Pin Wipe (EPW)	3.099	0.122				To ensure good pin contact (oxide removal, etc.)
		EPW - NO - Slop - (6 × σ)	-0.029	-0.001				< 0 means signal loss occurs below six sigma
		(EPW - NO - Slop)/σ	5.893	5.893				n × Process Sigma for Signal Loss
		Crash at 6 × σ	0.198	0.008				(Nominal Offset - 6 × Process Sigma) × (-1)
		Expected 6 x σ with Extended Fan Design	8.209	8.209				

Case #2: Assume EMI gasket as hard stop in tolerance loop:

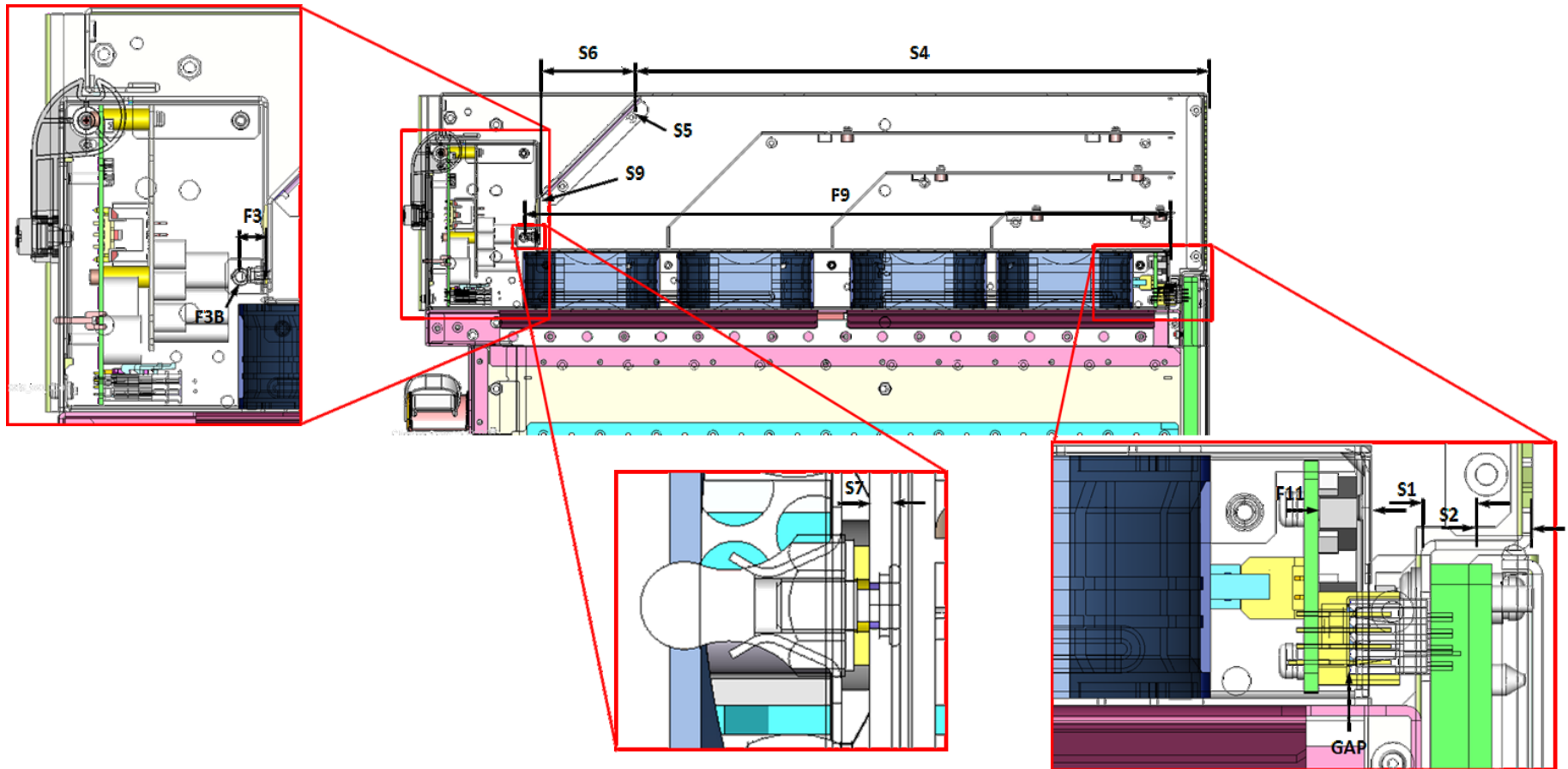


Figure 12.3: Tolerance Loop – GEN1 Fan Unit to Shelf - EMI Gasket Hard Stop

Assumptions:

1. $C_P = 1.0$ for all parts
2. $C_{PK} = 0.5$ for all parts
3. Hole-Hole tolerance within a PCB is ± 0.003 in

Table 12.3: Tolerance Loop – GEN1 Fan Unit to Shelf - EMI Gasket Hard Stop

Dimension	Part/Assembly	Feature/Joint Type	Slop (±mm)	Slop (±in)	Tolerance (±mm)	Tolerance (±in)	σ ² (mm ²)	Reference/Notes
S1	Chassis Sheetmetal	Sheetmetal bend			0.381	0.015	0.0161	Estimate, complex part geometry
S2	Chassis Sheetmetal	Sheetmetal bend			0.381	0.015	0.0161	Estimate, complex part geometry
S4	Chassis Sheetmetal	Sheetmetal bend to hole			0.254	0.010	0.0072	From CMS
S5	Riveted Connection	Countersunk Connect			0.025	0.001	0.0001	Estimate
S6	Chassis Sheetmetal	Sheetmetal bend to hole			0.254	0.010	0.0072	From CMS
S7	Chassis Sheetmetal	Thickness			0.127	0.005	0.0018	From CMS
S9	EMI Gasket	Thickness			0.381	0.015	0.0161	Estimate
F3	Fan Chassis Sheetmetal	Sheetmetal bend to hole			0.254	0.010	0.0072	From CMS
F3B	Screwed Connection	Countersunk screwed connection	0.035	0.001				Estimate
F9	Fan Chassis Sheetmetal	Sheetmetal hole to bend			0.254	0.010	0.0072	From CMS
F11	PEM SO	Length			0.051	0.002	0.0003	Penn Engineering
		Total Stack Up	0.035	0.001	2.362	0.093		
		Pooled Variance of Tolerances					0.0792	
		Process Sigma of Tolerances			0.281	0.011		
		6 × Process Sigma (σ)			1.689	0.066		
		6 × Process Sigma + Slop (σ+S)	1.724	0.068				
		Nominal Spacing BP to BP CAD	18.694	0.736				Minimum nominal offset from CAD models
		Nominal Spacing BP to BP Spec	16.916	0.666				Minimum nominal offset from FCI Spec
		Nominal Offset (NO)	1.778	0.070				
		Pin Wipe	3.861	0.152				Taken from interconnect specification.
		Effective Pin Wipe (EPW)	3.099	0.122				To ensure good pin contact (oxide removal, etc.)
		EPW - NO - Slop - (6 × σ)	-0.403	0.016				< 0 means signal loss occurs below six sigma
		(EPW - NO - Slop)/σ	4.569	4.569				n × Process Sigma for Signal Loss
		Crash at 6 × σ	-0.089	0.004				(Nominal Offset - 6 × Process Sigma) × (-1)
		Expected 6 x σ with Extended Fan Design	6.825	6.825				

Case #3: Assume duct as hard stop in tolerance loop:

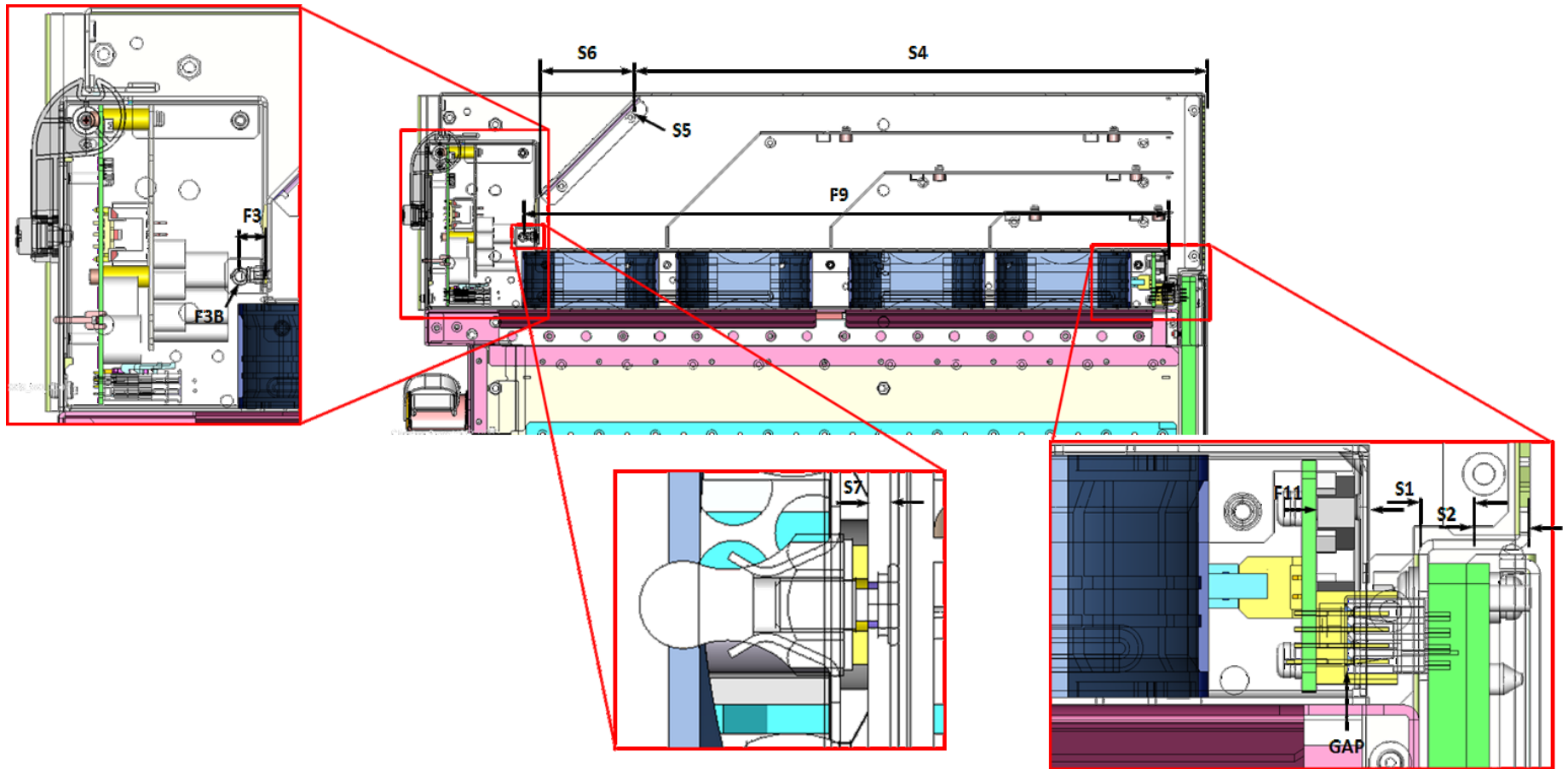


Figure 12.4: Tolerance Loop – GEN1 Fan Unit to Shelf - Duct Hard Stop

Assumptions:

1. $C_p = 1.0$ for all parts
2. $C_{PK} = 0.5$ for all parts
3. Hole-Hole tolerance within a PCB is ± 0.003 in

Table 12.4: Tolerance Loop – GEN1 Fan Unit to Shelf - Duct Hard Stop

Dimension	Part/Assembly	Feature/Joint Type	Slop (±mm)	Slop (±in)	Tolerance (±mm)	Tolerance (±in)	σ ² (mm ²)	Reference/Notes
S1	Chassis Sheetmetal	Sheetmetal bend			0.381	0.015	0.0161	Estimate, complex part geometry
S2	Chassis Sheetmetal	Sheetmetal bend			0.381	0.015	0.0161	Estimate, complex part geometry
S4	Chassis Sheetmetal	Sheetmetal bend to hole			0.254	0.010	0.0072	From CMS
S5	Riveted Connection	Countersunk Connect			0.025	0.001	0.0001	Estimate
S6	Chassis Sheetmetal	Sheetmetal bend to hole			0.254	0.010	0.0072	From CMS
S7	Chassis Sheetmetal	Thickness			0.127	0.005	0.0018	From CMS
S-F	Duct to Fan Faceplate	Mate	0.000	0.000				Estimate
F3	Fan Chassis Sheetmetal	Sheetmetal bend to hole			0.254	0.010	0.0072	From CMS
F3B	Screwed Connection	Countersunk screwed connection	0.035	0.001				Estimate
F9	Fan Chassis Sheetmetal	Sheetmetal hole to bend			0.254	0.010	0.0072	From CMS
F11	PEM SO	Length			0.051	0.002	0.0003	Penn Engineering
		Total Stack Up	0.035	0.001	1.981	0.078		
		Pooled Variance of Tolerances					0.0631	
		Process Sigma of Tolerances			0.251	0.010		
		6× Process Sigma (σ)			1.507	0.059		
		6× Process Sigma + Slop (σ+S)	1.542	0.061				
		Nominal Spacing BP to BP CAD	17.551	0.691				Minimum nominal offset from CAD models
		Nominal Spacing BP to BP Spec	16.916	0.666				Minimum nominal offset from FCI Spec
		Nominal Offset (NO)	0.635	0.025				
		Pin Wipe	3.861	0.152				Taken from interconnect specification.
		Effective Pin Wipe (EPW)	3.099	0.122				To ensure good pin contact (oxide removal, etc.)
		EPW - NO - Slop - (6 × σ)	0.922	0.036				< 0 means signal loss occurs below six sigma
		(EPW - NO - Slop)/σ	9.670	9.670				n × Process Sigma for Signal Loss
		Crash at 6 × σ	0.872	0.034				(Nominal Offset - 6 × Process Sigma) × (-1)
		Expected 6 x σ with Extended Fan Design	12.199	12.199				

Case #4: Assume latch as hard stop in tolerance loop:

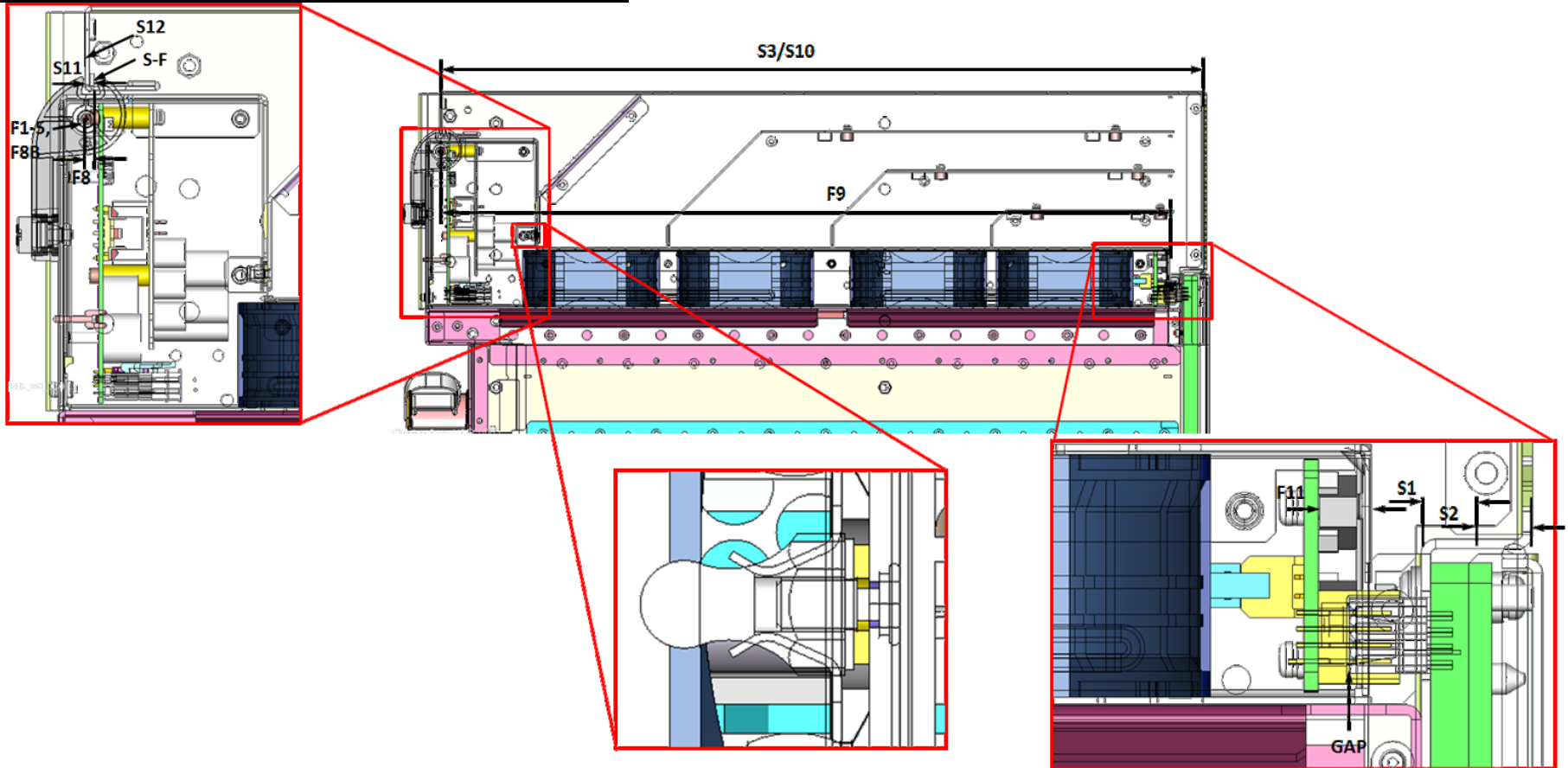


Figure 12.5: Tolerance Loop – GEN1 Fan Unit to Shelf - Latch Hard Stop

Assumptions:

1. $C_p = 1.0$ for all parts
2. $C_{PK} = 0.5$ for all parts
3. Hole-Hole tolerance within a PCB is ± 0.003 in

Table 12.5: Tolerance Loop – GEN1 Fan Unit to Shelf - Latch Hard Stop

Dimension	Part/Assembly	Feature/Joint Type	Slop (±mm)	Slop (±in)	Tolerance (±mm)	Tolerance (±in)	σ ² (mm ²)	Reference/Notes
S1	Chassis Sheetmetal	Sheetmetal bend			0.381	0.015	0.0161	Estimate, complex part geometry (CPG)
S2	Chassis Sheetmetal	Sheetmetal bend			0.381	0.015	0.0161	Estimate, CPG
S3	Chassis Sheetmetal	Sheetmetal bend			0.381	0.015	0.0161	Estimate, CPG
S10	Chassis Sheetmetal	Sheetmetal bend			0.381	0.015	0.0161	Estimate, CPG
S11	Chassis Sheetmetal/Latch	Thickness x 2			0.254	0.010	0.0072	From CMS
S12	Chassis Sheetmetal	Bowing	0.025	0.001			0.0000	Estimate
S-F	Front Chassis to Latch	Mate	0.000	0.000			0.0000	Estimate
F8	Fan Latch	Feature to hole			0.127	0.005	0.0018	Estimate
F1	Fan Latch	Radial Tolerance of Hole			0.127	0.005	0.0018	Estimate
F2	Fan Latch-Bushing	Radial Slop	0.225	0.009			0.0000	CAD Model
F3	Fan Latch Bushing	Radial Tolerance			0.127	0.005	0.0018	Estimate
F4	Fan Latch Bushing-Screw	Radial Slop	0.303	0.012			0.0000	CAD Model - Marks' SHME
F5	Screw	Radial Tolerance			0.075	0.003	0.0006	ANSI/ASME B1.1
F8B	Screwed Connection	Countersunk screwed connection	0.035	0.001			0.0000	Estimate
F9	Fan Chassis Sheetmetal	Sheetmetal hole to bend			0.254	0.010	0.0072	From CMS
F11	PEM SO	Length			0.051	0.002	0.0003	Penn Engineering
		Total Stack Up	0.588	0.023	2.539	0.100		
		Pooled Variance of Tolerances					0.0851	
		Process Sigma of Tolerances			0.292	0.011		
		6× Process Sigma (σ)			1.751	0.069		
		6× Process Sigma + Slop (σ+S)	2.338	0.092				
		Nominal Spacing BP to BP CAD	18.222	0.717				Minimum nominal offset from CAD models
		Nominal Spacing BP to BP Spec	16.916	0.666				Minimum nominal offset from FCI Spec
		Nominal Offset (NO)	1.306	0.051				
		Pin Wipe	3.861	0.152				Taken from interconnect specification.
		Effective Pin Wipe (EPW)	3.099	0.122				To ensure good pin contact (oxide removal, etc.)
		EPW - NO - Slop - (6 × σ)	-0.545	-0.021				< 0 means signal loss occurs below six sigma
		(EPW - NO - Slop)/σ	4.131	4.131				n × Process Sigma for Signal Loss
		Crash at 6 × σ	0.445	0.018				(Nominal Offset - 6 × Process Sigma) × (-1)
		Expected 6 x σ with Extended Fan Design	6.308	6.308				

Case #5: Assume front of latch as hard stop in tolerance loop:

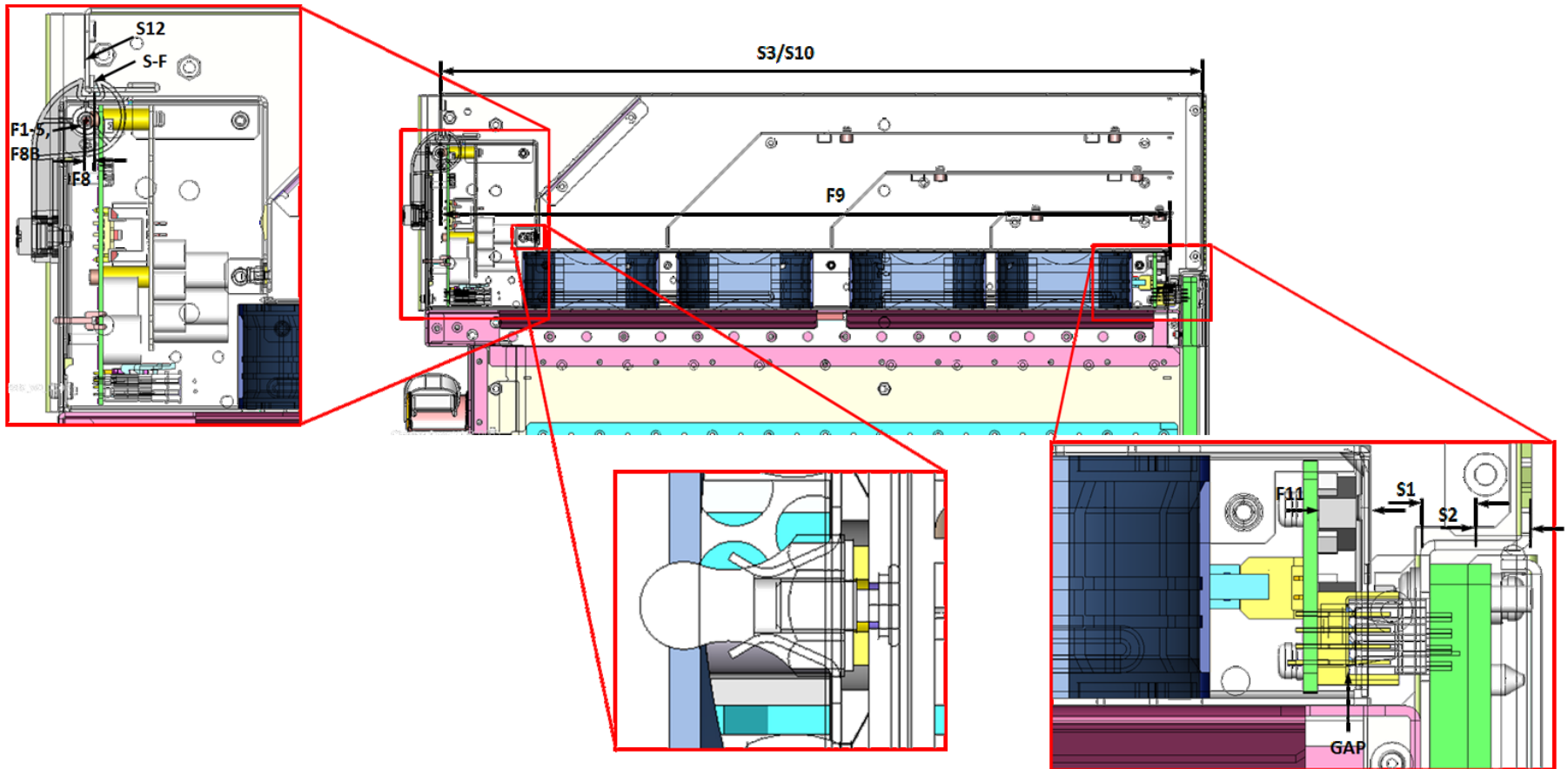


Figure 12.6: Tolerance Loop – GEN1 Fan Unit to Shelf - Latch Front Hard Stop

Assumptions:

1. $C_p = 1.0$ for all parts
2. $C_{PK} = 0.5$ for all parts
3. Hole-Hole tolerance within a PCB is ± 0.003 in

Table 12.6: Tolerance Loop – GEN1 Fan Unit to Shelf - Latch Front Hard Stop

Dimension	Part/Assembly	Feature/Joint Type	Slop (±mm)	Slop (±in)	Tolerance (±mm)	Tolerance (±in)	σ ² (mm ²)	Reference/Notes
S1	Chassis Sheetmetal	Sheetmetal bend			0.381	0.015	0.0161	Estimate, CPG
S2	Chassis Sheetmetal	Sheetmetal bend			0.381	0.015	0.0161	Estimate, CPG
S10	Chassis Sheetmetal	Sheetmetal bend			0.381	0.015	0.0161	Estimate, CPG
S10B	Chassis Sheetmetal	Sheetmetal bend			0.381	0.015	0.0161	Estimate, CPG
S12	Chassis Sheetmetal	Bowing	0.025	0.001			0.0000	Estimate
S-F	Front Chassis to Latch	Mate	0.000	0.000			0.0000	Estimate
F8	Fan Latch	Feature to hole			0.127	0.005	0.0018	Estimate
F1	Fan Latch	Radial Tolerance of Hole			0.127	0.005	0.0018	Estimate
F2	Fan Latch-Bushing	Radial Slop	0.225	0.009			0.0000	CAD Model
F3	Fan Latch Bushing	Radial Tolerance			0.127	0.005	0.0018	Estimate
F4	Fan Latch Bushing-Screw	Radial Slop	0.303	0.012			0.0000	CAD Model - Marks' SHME
F5	Screw	Radial Tolerance			0.075	0.003	0.0006	ANSI/ASME B1.1
F8B	Screwed Connection	Countersunk screwed connection	0.035	0.001			0.0000	Estimate
F9	Fan Chassis Sheetmetal	Sheetmetal hole to bend			0.254	0.010	0.0072	From CMS
F11	PEM SO	Length			0.051	0.002	0.0003	PEM
		Total Stack Up	0.588	0.023	2.285	0.090		
		Pooled Variance of Tolerances					0.0780	
		Process Sigma of Tolerances			0.279	0.011		
		6× Process Sigma (σ)			1.675	0.066		
		6× Process Sigma + Slop (σ+S)	2.263	0.089				
		Nominal Spacing BP to BP CAD	17.100	0.673	Minimum nominal offset from CAD models			
		Nominal Spacing BP to BP Spec	16.916	0.666	Minimum nominal offset from FCI Spec			
		Nominal Offset (NO)	0.183	0.007				
		Pin Wipe	3.861	0.152	Taken from interconnect specification.			
		Effective Pin Wipe (EPW)	3.099	0.122	To ensure good pin contact (oxide removal, etc.)			
		EPW - NO - Slop - (6 × σ)	0.652	0.026	< 0 means signal loss occurs below six sigma			
		(EPW - NO - Slop)/σ	8.336	8.336	n × Process Sigma for Signal Loss			
		Crash at 6 × σ	1.492	0.059	(Nominal Offset - 6 × Process Sigma) × (-1)			
		Expected 6 x σ with Extended Fan Design	10.610	10.610				

Fan Internal Tolerance Analysis

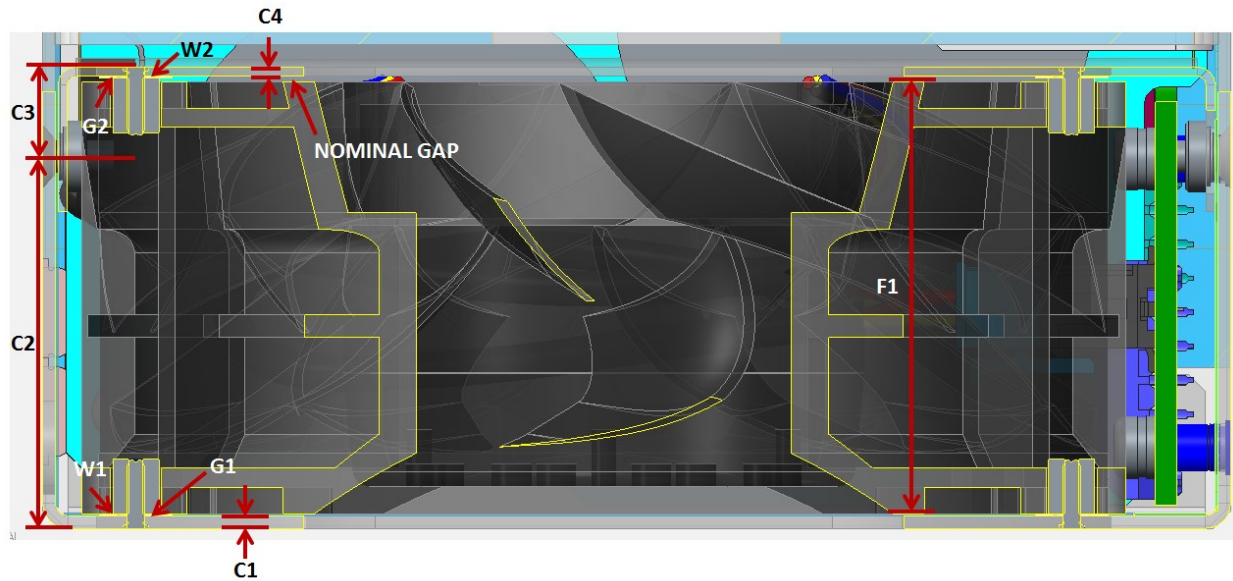


Figure 12.7: GEN1A/GEN2A Fan Unit Vertical Tolerance Analysis

Table 12.7: GEN1A/GEN2A Fan Unit Vertical Tolerance Analysis [mm]

Parameter		Slop	Tolerance (+/-)	σ^2	Source
W2	Washer Thickness	0	0.0381	0.00016129	Seastrom 5612-32-10
G2	Glue Film Thickness	0	0.05	0.000277778	Ideal Bond Gap - Loctite 4205
C4	Chassis Thickness	0	0.0762	0.00064516	Document 008-0000-009
C3	Edge to Hole	0	0.127	0.001792111	Document 008-0000-009
C2	Edge to Hole	0	0.127	0.001792111	Document 008-0000-009
C1	Chassis Thickness	0	0.0762	0.00064516	Document 008-0000-009
G1	Glue Film Thickness	0	0.05	0.000277778	Ideal Bond Gap - Loctite 4205
W1	Washer Thickness	0	0.0381	0.00016129	Seastrom 5612-32-10
F1	Fan Thickness	0	0.5	0.027777778	Fan Data Sheets Files

Sum	0	1.0826	0.033530456
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n ↓	Process Sigma (tol)	0.18311323
3	Sigma	0.54933969
3	Sigma + Slop	0.54933969

Nominal Gap (CAD Models – D Fan)	0.9000998
Nominal Gap (CAD Models – N Fan)	0.7000998
Gap - slop - (n Sigma) [Delta]	0.35076011
Gap - slop - (n Sigma) [Delta]	0.15076011

Chapter 13 Appendix E: Fan Unit Inspection Data

Table 13.1: GEN1 Fan Unit Connector Inspection Ottawa Carling Labs

Shelf DOM	Fan Rev	Fan DOM Mo.-Year	Fan Slot	Latch Screwed Down?	Signal Pin Corrosion	Notes	Test #
Jan-11	15	May-12	N/A	N/A	YES - fretting	All signal pins	1
Jan-11	15	May-12	N/A	N/A	YES - fretting onset	Bottom pins	2
Jan-11	15	May-12	N/A	N/A	YES - fretting onset	Bottom pins	3
Jan-11	15	May-12	N/A	N/A	YES - fretting	All pins top side	4
Jan-11	15	May-12	N/A	N/A	YES - fretting	All pins bottom side	5
Jan-11	15	May-12	N/A	N/A	YES - fretting	All signal pins	6
Jan-11	11	Mar-11	N/A	N/A	YES - fretting onset	All signal pins	7
Jan-11	3	Jan-10	N/A	No	Probable fretting	Some signal pins	8
Jan-11	11	Jan-10	N/A	N/A	YES - fretting	All signal pins	9
N/A	3	Jan-10	N/A	N/A	YES - wear & tracks	No apparent gold through wear	10
Dec-09	3	Dec-09	N/A	Yes	YES - fretting	All signal pins	11
Dec-09	3	Jan-10	N/A	Yes	YES - fretting	All signal pins (3 distinct locations)	12
Dec-09	3	Jan-10	N/A	Yes	YES - fretting	All signal pins significant	13
Dec-09	3	Dec-09	N/A	Yes	YES - fretting	All signal pins	14
Dec-09	3	Jan-10	N/A	Yes	YES - fretting	All signal pins (2 distinct locations)	15
Dec-09	3	Dec-09	N/A	Yes	YES - fretting	All signal pins	16
Dec-09	3	Jan-10	N/A	Yes	YES - fretting	All signal pins	17
Dec-09	3	Dec-09	N/A	Yes	YES - fretting onset	All signal pins	18
Dec-09	10	Jun-09	N/A	Yes	YES - fretting	All signal pins	19
Dec-09	3	Dec-09	N/A	Yes	YES - fretting	All signal pins significant	20
N/A	3	Jan-10	N/A	N/A	YES - fretting	All signal pins	21
Jan-11	12	Aug-09		No	YES - fretting	All signal pins	22
Jan-11	?	Sep-09?			YES - fretting onset	All signal pins	23
Jan-11	3	Jan-10			YES - fretting	Bottom and top signal rows	24
Jan-11	12	Aug-09			YES - fretting	Bottom signal row	25

Jan-11	3	Jan-10			YES - fretting onset	All signal pins, slight onset	26
Jan-11	6	Mar-09			NO fretting	Possibly on one pin only?	27
Jan-11	6	Mar-09			YES - fretting	Bottom signal row	28
Jan-11	6	Mar-09			YES - fretting	Bottom and top signal rows	29
Jan-11	6	Mar-09			YES - fretting onset	All signal pins, slight onset	30
Jan-11	6	Mar-09			YES - fretting	All signal pins significant	31
Jan-11	6	Mar-09			YES - fretting	All signal pins significant	32
Jan-11	6	Mar-09			YES - fretting	All signal pins	33
Jan-11	6	Mar-09			YES - fretting	All signal pins	34
Jan-11	6	Mar-09			YES - fretting	All signal pins	35
N/A	9	Nov-10	N/A	Yes	YES - fretting onset	All signal pins, slight onset	36
N/A	9	Nov-10	N/A	Yes	YES - fretting	Bottom and top signal rows	37
N/A	9	Nov-10	N/A	Yes	YES - fretting onset	All signal pins, slight onset	38
N/A	9	Nov-10	N/A	Yes	YES - fretting	All signal pins	39
Feb-11	11	Feb-11	1	Yes	YES - fretting onset	All signal pins	40
Feb-11	11	Feb-11	2	Yes	YES - fretting onset	Bottom and top signal rows, slight	41
Feb-11	11	Feb-11	3	Yes	YES - fretting onset	All signal pins	42
Feb-11	11	Feb-11	4	Yes	NO fretting	Possibly on one pin only?	43
May-11	11	Apr-11	1	Yes	YES - fretting	All signal pins	44
May-11	11	Apr-11	2	Yes	YES - fretting	All signal pins	45
May-11	11	Apr-11	3	Yes	YES - fretting	All signal pins	46
May-11	11	Apr-11	4	Yes	YES - fretting	All signal pins	47
May-11	11	Feb-11	4	Yes	YES - fretting onset	All signal pins	48
May-11	11	Apr-11	3	Yes	YES - fretting onset	All signal pins	49
May-11	11	Apr-11	2	Yes	YES - fretting onset	All signal pins	50
May-11	11	Feb-11	1	Yes	YES - fretting	All signal pins	51
Mar-10	6	May-10	5A		YES - fretting	All signal pins	52
Mar-10	6	May-10	4A		YES - fretting	All signal pins	53
Mar-10	6	May-10	3A		YES - fretting	All signal pins	54
Mar-10	6	May-10	2A		YES - fretting	All signal pins	55

Mar-10	6	May-10	1A		YES - fretting	All signal pins	56
Mar-10	6	May-10	5B		YES - fretting	Bottom and top signal rows	57
Mar-10	6	May-10	4B		YES - fretting	All signal pins	58
Mar-10	6	May-10	3B		YES - fretting	Half signal pins, half onset	59
Mar-10	6	May-10	2B		YES - fretting	All signal pins	60
Mar-10	6	May-10	1B		YES - fretting	All signal pins significant	61
May-11	11	Apr-11	4	No	YES - fretting onset	All signal pins	62
May-11	11	Apr-11	3	No	YES - fretting onset	All signal pins	63
May-11	11	Apr-11	2	No	YES - fretting onset	All signal pins, slight onset	64
May-11	11	Apr-11	1	No	YES - fretting onset	All signal pins, slight onset	65
Mar-10	3	Jan-10	5A		YES - fretting	All signal pins	66
Mar-10	3	Jan-10	4A		YES - fretting	All signal pins	67
Mar-10	12	Aug-09	3A		YES - fretting onset	All signal pins	68
Mar-10	5	Mar-10	2A		YES - fretting	All signal pins	69
Mar-10	5	Mar-10	1A		YES - fretting	All signal pins	70
Mar-10	3	Dec-09	5B		YES - fretting	All signal pins significant	71
Mar-10	3	Jan-10	4B		YES - fretting	Half signal pins, half onset	72
Mar-10	7	Jun-09	3B		YES - fretting	All signal pins significant	73
Mar-10	5	Mar-10	2B		YES - fretting	All signal pins significant	74
Mar-10	5	Mar-10	1B		YES - fretting	All signal pins	75
Unknown	4	Dec-09			YES - fretting	All signal pins significant	76
Unknown	7	May-10			YES - fretting	All signal pins significant	77
Unknown	3	Jan-10			YES - fretting	All signal pins significant	78