# Design Principles for Vibration Test Fixtures

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# Outline

- Introduction
  - Problem Description and Approach
- Background Research
- Design Principles
- Analysis
  - Original Design
  - Design Iteration
- Recommendations for Future Work

# Project Overview

- **Problem:**
  - **Increased number of projects at the Lab requiring environmental testing**
  - **Engineers required to take on lead roles in tests like vibration qualification**
  - **New lead engineers often unfamiliar with complexities of vibration testing and vibration fixture design**

# Project Overview

- **Goals:**
  - **Develop design principles for vibration test fixtures**
  - **Validate principles through analysis**
- **Approach:**
  - **Literary search on important issues regarding test fixtures**
  - **Propose generic design principles for vibration test fixtures**
  - **Apply design principles and perform finite element analysis on test fixture to validate principles**

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# Background Research

- **Space Payload Vibration Environments**
  - **General Environmental Verification Standard (GEVS)**
  - **Military Standard 1540 Revision E (1540E)**

- **Other Vibration Environments**
  - **Department of Defense Test Method Standard for Environmental Engineering Considerations and Laboratory Tests (810F)**

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# Vibration Test Fixture

- **What is a vibration test fixture?**
  - **Mounts specific test specimen onto a vibration table**
  - **Transmits forces produced by vibration table to test specimen**
- **Properties to consider when designing a custom test fixture**
- **Why a proper design is important for testing**
  - **Dangers and complications**

    **of faulty fixture**

# Design Properties

- **Various materials can be used for fixture fabrication**
  - **Young's Modulus to density ratio determines natural frequency of material**
  - **Aluminum is most commonly used at the Lab**
  - **Theoretically, any material can be used**

| | Steel | Aluminum | Magnesium |
|---|---|---|---|
| Young's Modulus (E) $N/m^2$ | $20.7 \times 10^{10}$ | $6.9 \times 10^{10}$ | $4.14 \times 10^{10}$ |
| Density (ρ) $kg/m^3$ | 7840 | 2770 | 1800 |
| E/ρ N m/kg | $2.65 \times 10^7$ | $2.49 \times 10^7$ | $2.3 \times 10^7$ |

# Design Properties

- Minimize mechanical impedance from fixture
  - No natural frequency in test range
  - Less mass = smaller forces
  - Design fixture to be as rigid as possible

- Testing is performed in three orthogonal directional axes
  - Each axis isolated to provide control and standardization
  - Minimize movement in other axes

# Design Properties

- **Control accelerometer usually attached on shaker table, test fixture, or test specimen**
  - **Typically placed on shaker table at Lincoln Laboratory**
- **Properties to consider when attaching accelerometers**
  - **C.G. of part**
  - **Natural frequency of specimen**
  - **Other points of interest**

    **(i.e. sensitive electronics)**

# Design Principles

- **Fixture should be designed to have the least mass possible**
  - **Weight limits on shaker table**
- **Fixture should be designed to be as stiff as possible**
  - **No unnecessary vibrations**
- **Ensure natural frequency of fixture is not within test range**
  - **Do not amplify vibration loads to natural frequency**

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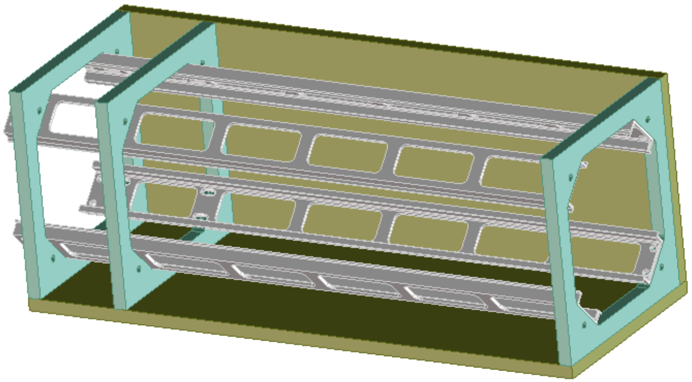
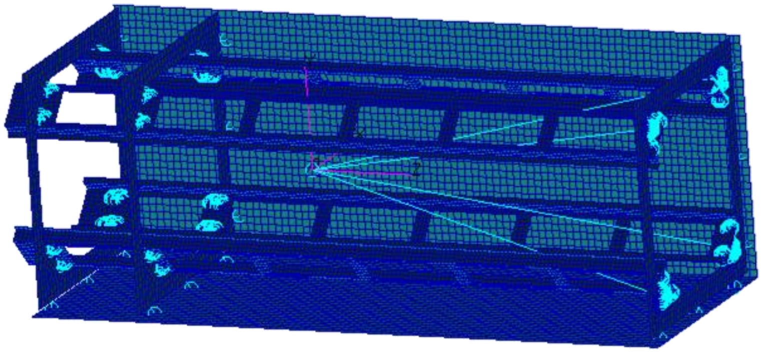
# Original Fixture



Defeatured CAD
model in Co-Create.



FEA model in Patran.

## Material Properties

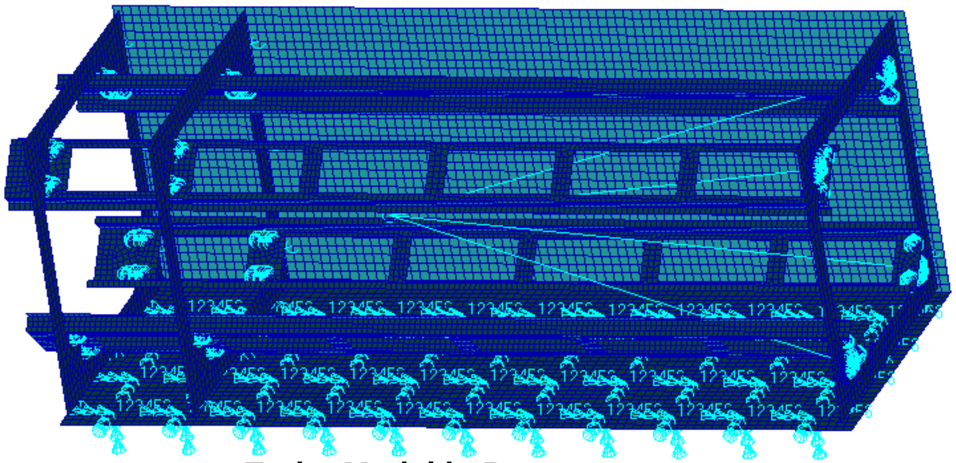
| Assumed Material Properties of Aluminum | |
|---|---|
| Elastic Modulus | $10^7$ psi |
| Poisson Ratio | 0.33 |
| Density | 0.098 lb/in$^3$ |

## Mass Properties

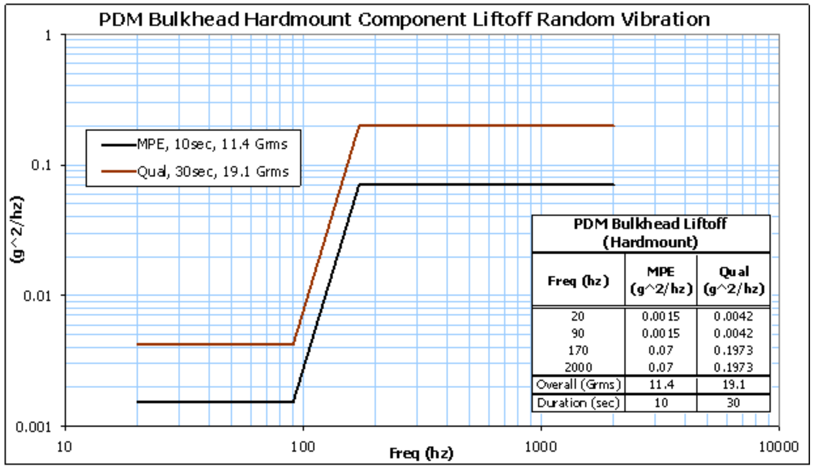
| Mass Moment of Inertia | X | Y | Z |
|---|---|---|---|
| X | 2235 | - | - |
| Y | - | 2236 | - |
| Z | - | - | 157 |

**Assumed Lumped Mass: 26.5 lb**
**CG Location: 13.9" in from Front Support Panel**

# Boundary Conditions



Entire Model in Patran

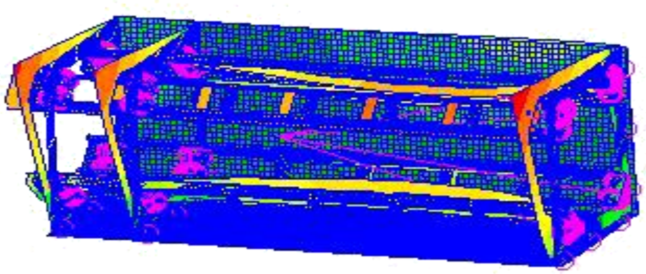



| PDM Bulkhead Liftoff (Hardmount) | | |
|---|---|---|
| Freq (hz) | MPE (g^2/hz) | Qual (g^2/hz) |
| 20 | 0.0015 | 0.0042 |
| 90 | 0.0015 | 0.0042 |
| 170 | 0.07 | 0.1973 |
| 2000 | 0.07 | 0.1973 |
| Overall (Grms) | 11.4 | 19.1 |
| Duration (sec) | 10 | 30 |

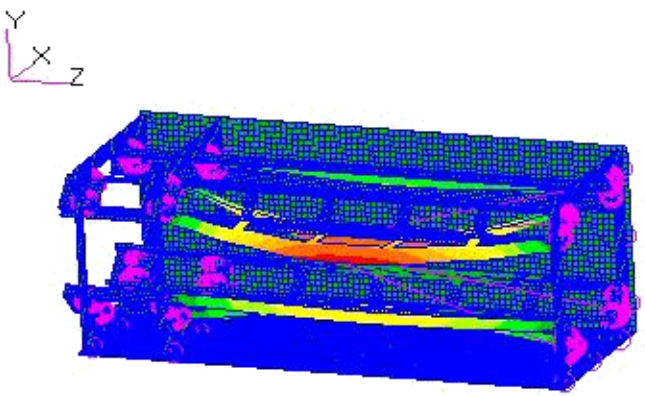
PSD Curve Used

- 44 SPCs assumed as connection points to table
- The 24 bolt holes were modeled as RBE2s
- 3 RBE2s per support block were used to connect the blocks to the side and bottom panels connecting the support blocks to the panels.
- 4 bolt holes on front plate modeled as RBE2s, and one RBE3 used to connect the lumped mass to the 4 bolts on the front block.

# Model with Lumped Mass: Normal Modes



Mode 1, Frequency 7.498 Hz



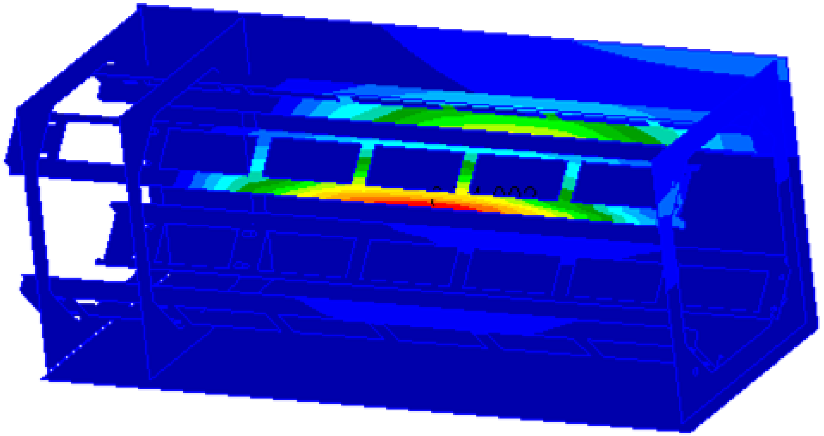

Mode 4, Frequency 216.17 Hz

| Mode | Frequency (Hz) |
|---|---|
| 1 | 7.50 |
| 2 | 11.20 |
| 3 | 37.25 |
| 4 | 216.17 |
| 5 | 217.51 |
| 6 | 218.18 |
| 7 | 218.64 |
| 8 | 246.31 |
| 9 | 262.08 |
| 10 | 264.17 |

**Modes 1-3 affect the front support block the mass is attached to, among other sections. Modes 4-10, in the testing range, affect the long section of rails that is unsupported.**

**Videos not to scale.**

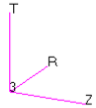
# Model with Lumped Mass: Random Vibration Test Results



Screenshot of Displacement in the X Direction due to Vibration in the X Direction

Screenshot of Displacement in the Z Direction due to Vibration in the Z direction


**Coordinate Frame 0 for Displacement of Two Panels, Three Support Blocks and Vibration Direction**




**Coordinate Frame 1, Cylindrical Coordinate Frame for Displacement of Rails. Located at C.G. of part.**

| Vibration Direction | 3σ Displacement (inches) | | | 3σ Von-Mises Stress (psi) |
|---|---|---|---|---|
| | X | Y | Z | |
| X | **0.196** | 0.168 | 0.048 | 41100 |
| Affected Part | Rails | Rails | Rail/Corners of Support Blocks | Rails |
| Y | 0.0498 | **0.0528** | 0.0097 | 36600 |
| Affected Part | Rails | Rails | Rail/Corners of Support Blocks | Mass Support Block to Panel |
| Z | **0.1137** | 0.084 | 0.0789 | 41100 |
| Affected Part | Rails | Rails | Rail/Corners of Support Blocks | Rails to Support Block |

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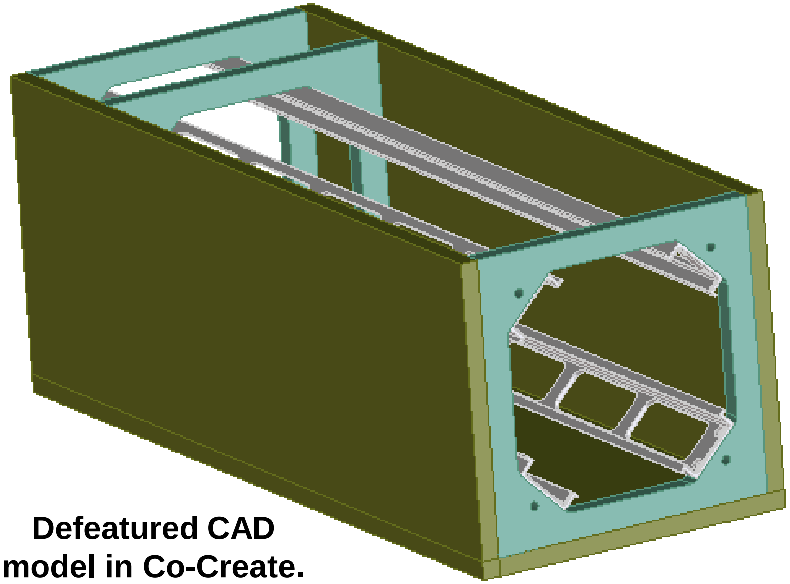
# Model with Lumped Mass and Third Panel



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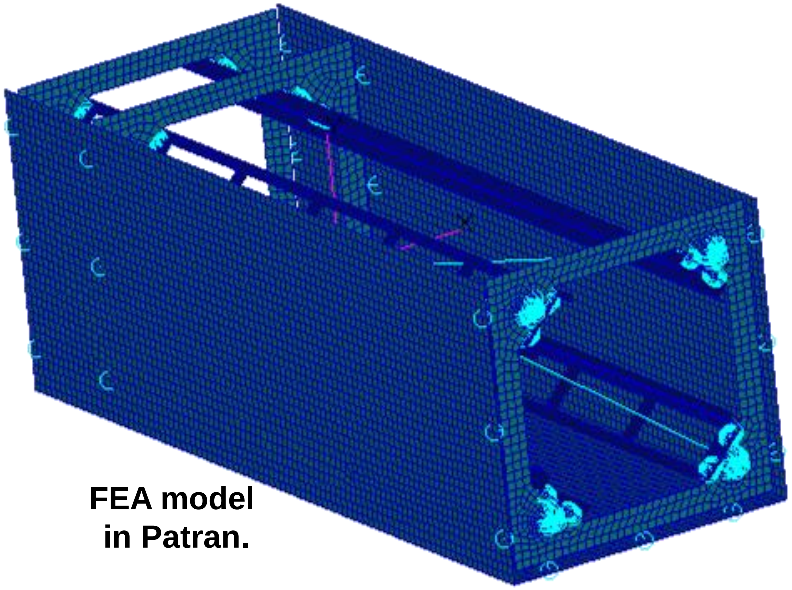


FEA model in Patran.

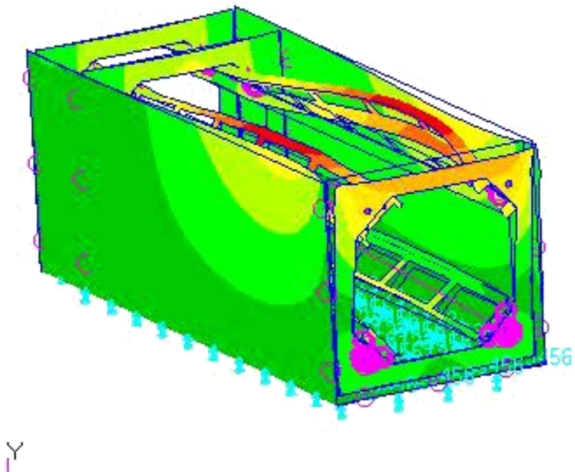
•Initial properties of Aluminum assumed

•Initial MPCS and lumped mass kept constant

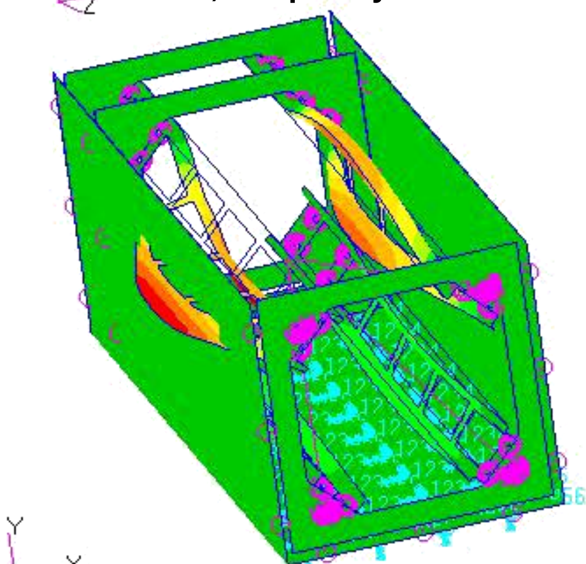
•Initial PSD Curve used

•Added 9 RBE2s to connect the third panel to the three support blocks

# Model with Lumped Mass and Third Panel: Normal Modes



**Mode 1, Frequency 12.297 Hz**



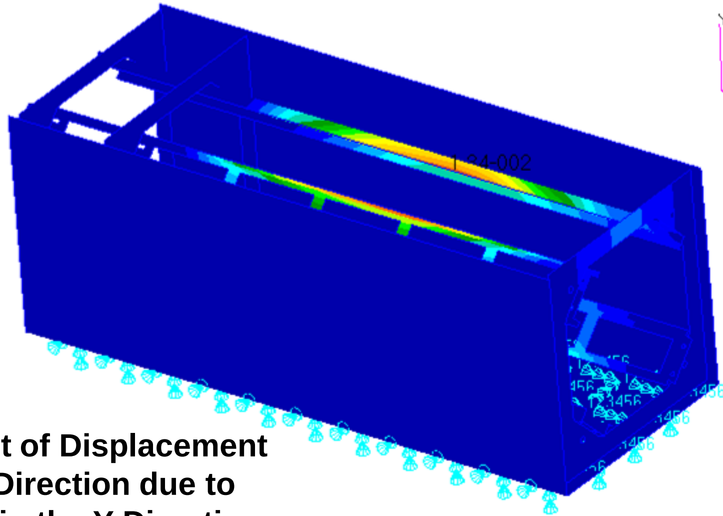
**Mode 5, Frequency 218.13 Hz**

| Mode | Frequency (Hz) |
|---|---|
| 1 | (7.498) 12.297 |
| 2 | (11.2) 14.245 |
| 3 | (37.246) 55.931 |
| 4 | (216.17) 217.46 |
| 5 | (217.51) 218.13 |
| 6 | (218.18) 218.73 |
| 7 | (218.64) 218.77 |
| 8 | (246.31) 261.85 |
| 9 | (262.08) 263.16 |
| 10 | (264.17) 266.61 |

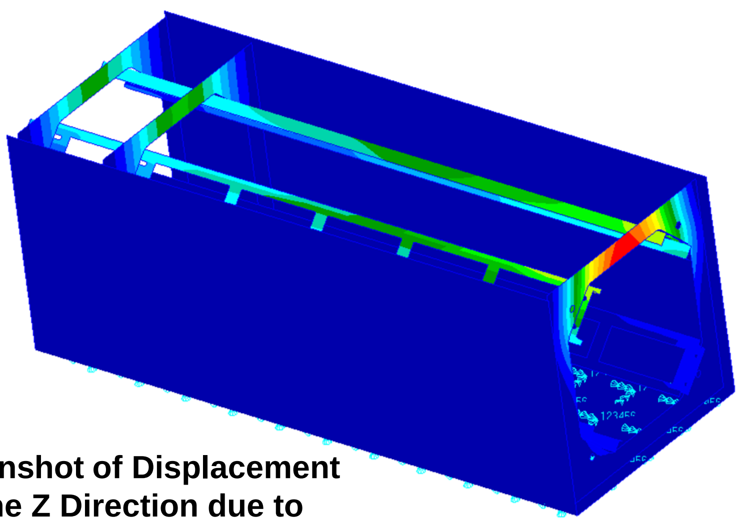
**Modes 1-3 affect the front support block the mass is attached to, among other sections. Modes 4-10, in the testing range, affect the long section of rails that is unsupported.**

**Videos not to scale.**

# Model with Lumped Mass and Third Panel: Random Vibration Test Results

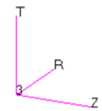


Screenshot of Displacement in the Y Direction due to Vibration in the Y Direction



Screenshot of Displacement in the Z Direction due to Vibration in the Z direction

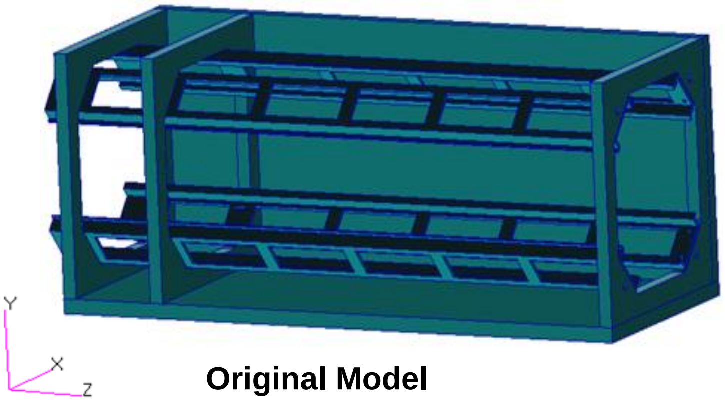

Coordinate Frame 0 for Displacement of Two Panels, Three Support Blocks and Vibration Direction



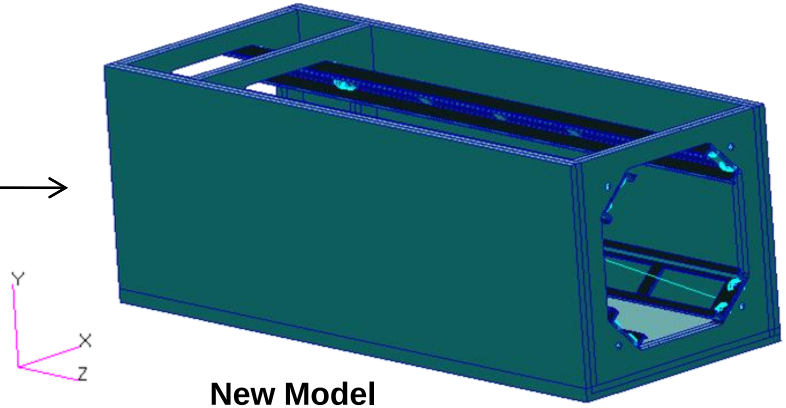

Coordinate Frame 1, Cylindrical Coordinate Frame for Displacement of Rails. Located at C.G. of part.

| Vibration Direction | 3σ Displacement (inches) | | | 3σ Von-Mises Stress (psi) |
|---|---|---|---|---|
| | X | Y | Z | |
| X | (0.1962) 0.1989 | **(0.17) 0.21** | (0.048) 0.005 | (41100) 47100 |
| Affected Part | Rails | Rails | Rail/Tops of Support Blocks | Rails |
| Y | (0.0498) 0.0378 | **(0.053) 0.040** | (0.0097) 0.0082 | (36600) 20700 |
| Affected Part | Rails | Rails | Rails/Panel Sides/ Tops Supports | Mass Support Block to Panel |
| Z | (0.114) 0.023 | (0.084) 0.018 | **(0.079) 0.026** | (41100) 31800 |
| Affected Part | Rail/Side Panels | Rails | Rail/Tops of Support Blocks | Rails to Support Block |

# Comparison




Original Model




New Model

| Vibration Direction | Random Vibration Displacement Ratio<br>Design Iteration Results<br>Original Design Results | | | Von-Mises Stress Ratio<br>Design Iteration Results<br>Original Design Results |
|---|---|---|---|---|
| | Displacement Direction | | | |
| | X | Y | Z | |
| X | 1.01 | 1.25 | 0.0975 | 1.146 |
| Y | 0.76 | 0.76 | 0.85 | 0.57 |
| Z | 0.20 | 0.21 | 0.32 | 0.77 |

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# Future Work

**Our Future Work:**

- **Publish MQP Report**
- **Tutorial**

**Future Work at the Laboratory:**

- **Discussion with Sponsor**
- **Fabrication**
- **Real Vibration Testing**

# Questions?

Special thanks to: Dave Freeman, Professor Gatsonis, Grace Kessenich, Baoqing Yu, Sultan Chowdhry, Dave Costa, Jesse Mills, Jeremy Coombs, Anne Vogel, Mike Mastovich, Nicholas Leathe and Team Co-op.

# Background Slides

# Vibration Test Procedure

1. FEA
   1. Test fixture
   2. Test part
   3. Combination of fixture and part
2. Shake fixture
3. Shake fixture and mass mock-up of test part
4. Low level shake fixture and test part
5. Specified vibration test
6. Repeat low level shake fixture and test part

# Comparison

| | GEVS | 1540E |
|---|---|---|
| **Vibration Test Required** | Sine Sweep Testing | Random Vibration Testing |
| | **Prototype Qualification Test / Qualification Test** | |
| **Level** | Limit Level x 1.25 | Acceptance Level + 6 dB |
| **Duration** | ~1.5 min/axis<br>2 octaves/min from 5 – 50 Hz | 3 min/axis<br>20 – 2000 Hz |
| | **Protoflight Qualification Test / Protoqualification Test** | |
| **Level** | Limit Level x 1.25 | Acceptance Level + 3 dB |
| **Duration** | ~1 min/axis<br>4 octaves/min from 5 – 50 Hz | 2 min/axis<br>20 – 2000 Hz |
| | **Acceptance Test** | |
| **Level** | Limit Level | Acceptance Level |
| **Duration** | ~1 min/axis<br>4 octaves/min from 5 – 50 Hz | 1 min/axis<br>20 – 2000 Hz |

**The terms "Limit Level" and "Acceptance Level" are taken directly from the corresponding standards. Though the terms used are different, the meaning is the same: the maximum expected/predicted environment.**

# Fixture Analysis

| ***Fixture*** | | **Random Vibration Displacement (inches)** | | | | **3-Sigma Values** | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Displacement Direction | | | | Displacement Direction | | |
| **Modes (Hz)** | | | *x* | *y* | *z* | | *x* | *y* | *z* |
| 1 | 211.7 | *x* | 0.0252 | 0.0225 | 0.00516 | *x* | 0.0756 | 0.0675 | 0.01548 |
| 2 | 214.75 | *Location* | Rail | Rail | Rail/Corners | | | | |
| 3 | 216.51 | *y* | 0.0106 | 0.0121 | 0.00169 | *y* | 0.0318 | 0.0363 | 0.00507 |
| 4 | 217.91 | *Location* | Rail | Rail | Rail/Corners | | | | |
| 5 | 239.41 | *z* | 0.00646 | 0.00578 | 0.0107 | *z* | 0.01938 | 0.01734 | 0.0321 |
| 6 | 257.02 | *Location* | Rail | Rail | Rail/Corners | | | | |
| 7 | 262.15 | | **Von Mises Stress (psi)** | | | | **3-Sigma Values** | | |
| 8 | 265.1 | | *x* | 11100 | | | *x* | 33300 | |
| 9 | 272.47 | | *y* | 4040 | | | *y* | 12120 | |
| 10 | 287.45 | | *z* | 5150 | | | *z* | 15450 | |

# Fixture and Lumped Mass Analysis

| ***Fixture + Lumped Mass*** | | **Random Vibration Displacement (inches)** | | | | **3-Sigma Values** | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Displacement Direction | | | | Displacement Direction | | |
| **Modes (Hz)** | | | *x* | *y* | *z* | | *x* | *y* | *z* |
| 1 | 7.498 | *x* | 0.0654 | 0.056 | 0.016 | *x* | 0.1962 | 0.168 | 0.048 |
| 2 | 11.2 | *Location* | Rail | Rail | Rail/Corners | | | | |
| 3 | 37.246 | *y* | 0.0166 | 0.0176 | 0.00323 | *y* | 0.0498 | 0.0528 | 0.00969 |
| 4 | 216.17 | *Location* | Rail | Rail | Rail/Corners | | | | |
| 5 | 217.51 | *z* | 0.0379 | 0.028 | 0.0263 | *z* | 0.1137 | 0.084 | 0.0789 |
| 6 | 218.18 | *Location* | Rail | Rail | Rail/Corners | | | | |
| 7 | 218.64 | | **Von Mises Stress (psi)** | | | | **3-Sigma Values** | | |
| 8 | 246.31 | | *x* | 13700 | | | *x* | 41100 | |
| 9 | 262.08 | | *y* | 12200 | | | *y* | 36600 | |
| 10 | 264.17 | | *z* | 13700 | | | *z* | 41100 | |

# Fixture and Third Panel Analysis

| *Fixture + Third Wall* | | Random Vibration Displacement (inches) | | | | 3-Sigma Values | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Displacement Direction | | | | Displacement Direction | | |
| Modes (Hz) | | | *x* | *y* | *z* | | *x* | *y* | *z* |
| 1 | 214.89 | *x* | 0.027 | 0.026 | 0.00153 | *x* | 0.081 | 0.078 | 0.00459 |
| 2 | 215.69 | *Location* | Rails | Rails | Rails/Tops Support Blocks | | | | |
| 3 | 217.96 | *y* | 0.0102 | 0.0114 | 0.000488 | *y* | 0.0306 | 0.0342 | 0.001464 |
| 4 | 218.08 | *Location* | Rails | Rails | Rail/Panel Sides/Tops Supports | | | | |
| 5 | 253.83 | *z* | 0.00135 | 0.00139 | 0.00492 | *z* | 0.00405 | 0.00417 | 0.01476 |
| 6 | 261.07 | *Location* | Rail/Sides of Panels | Rails/Tops Support Blocks | Rails/Tops Support Blocks | | | | |
| 7 | 265.49 | | **Von Mises Stress (psi)** | | | | **3-Sigma Values** | | |
| 8 | 265.54 | | *x* | 15200 | | | *x* | 45600 | |
| 9 | 281.49 | | *y* | 4080 | | | *y* | 12240 | |
| 10 | 357.4 | | *z* | 3110 | | | *z* | 9330 | |

# Fixture, Lumped Mass, and Third Panel Analysis

| ***Fixture + Mass +Wall*** | | **Random Vibration Displacement (inches)** | | | | **3-Sigma Values** | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Displacement Direction | | | | Displacement Direction | | |
| **Modes (Hz)** | | | *x* | *y* | *z* | | *x* | *y* | *z* |
| 1 | 12.297 | *x* | 0.0663 | 0.07 | 0.00156 | *x* | 0.1989 | 0.21 | 0.00468 |
| 2 | 14.245 | *Location* | Rails | Rails | Rails/Tops Support Blocks | | | | |
| 3 | 55.931 | *y* | 0.0126 | 0.0134 | 0.00274 | *y* | 0.0378 | 0.0402 | 0.00822 |
| 4 | 217.46 | *Location* | Rails | Rails | Rail/Panel Sides/Tops Supports | | | | |
| 5 | 218.13 | *z* | 0.00768 | 0.00594 | 0.00855 | *z* | 0.02304 | 0.01782 | 0.02565 |
| 6 | 218.73 | *Location* | Rail/Sides of Panels | Rails | Rails/Tops Support Blocks | | | | |
| 7 | 218.77 | | **Von Mises Stress (psi)** | | | | **3-Sigma Values** | | |
| 8 | 261.85 | | *x* | 15700 | | | *x* | 47100 | |
| 9 | 263.16 | | *y* | 6900 | | | *y* | 20700 | |
| 10 | 266.61 | | *z* | 10600 | | | *z* | 31800 | |