Team SAVI

Satellite Active Vibration Inverter

Wasseem Bel  Joseph Schmitz
Patrick Byrne  Justin Tomasetti
Blake Firner  Jackson Vlay
Corey Hyatt  Benjamin Zatz
CDR Overview

- Project Purpose
- Design Solution and Requirements
- Software
- Electrical
- Mechanical
- Simulink
- Error Analysis
- Verification and Validation
- Risk Assessment
- Project Planning
Problem Statement

Develop a Satellite Active Vibration Inverter (SAVI) mount system that will identify and cancel low frequency vibrations from a cryocooler that cause image smearing on a telescopic camera.
Project Background

Cryocoolers create Exported Forces and Torques (EFTs)
- Frequencies dynamically range from 40 to 60 Hz
- Amplitudes on the order of 20 microns (twice the thickness of a sheet of paper)

Simulated Telescoping Camera Payload
- 22 kg mass
- 1 \( \mu \)rad Pixel Resolution

Image Smearing
- Pixel Movement
  - Angular Displacements from EFTs

These EFTs will cause up to 150 pixel smear

1- Cryocooler
2- Simulated camera payload
3- SAVI system
CONOPS

1- Cryocooler
2- Simulated camera payload
3- SAVI system
As a camera experiences rotation the image seen by a single pixel may change to another pixel while the shutter is open, causing a smeared image.

On the left shows a single pixel smear. A set of pixels (1, 2, 3) is rotated by $\theta$, the object seen by pixel2 is then also seen briefly by pixel1 while the shutter is open.
System Overview

SAVI
- Top/base plate
- 2 actuating legs
- 1 solid leg
- 5 flexures
- 5 sensors
- 2 drivers

Test Stand
- Top/base plate
- 1 actuating leg
- 2 solid legs
- 4 flexures
- 1 driver

ITLL Lab Station Computer
NI cDAQ

Mass
SAVI and Test Stand Details

- Flexures placed on top and bottom of actuating legs to avoid shear stresses in piezoelectric actuators.
- Flexures placed on top of solid leg to allow for plate rotation.
- Accelerometers placed on top plate next to each leg and on bottom plate next to the two actuating legs.
Simulated EFT causes SAVI to rotate about one point resulting in pixel smear from the tip and tilt motion of top plate.
Accelerometer Inputs

Data taken from top sensor located next to solid leg and bottom sensors located next to either or both of the actuating legs.

The data from the sensors will output voltage and time.

\[ Data_{\text{Solid}} = \]

\[ Data_{\text{Act}} = \]
The Solution

- Send Data to Matlab
- FFT to find Amplitude and Frequency
- Cross Correlation to find Phase
- Construct Analytical Acceleration Sinusoid
- Calculate corresponding displacement
- Compare Solid Leg and Actuating Leg Displacements to Find Needed Actuation

**Solid Leg Displacement**

**Actuating Leg Displacement**

**Needed Actuation Displacement**
The Solution

Voltage needed is calculated from desired displacement and sent to actuator.

Actuating leg applies a displacement such that the top plate will not tip or tilt.
Design Objectives

Tier 1

- Pixel smear reduced by 60% to about 60 pixels of smear

Tier 2

- Pixel smear reduced by 80% so that about 30 pixels or fewer are smeared
- Signal frequency has dwell time of 2 seconds

Tier 3

- The system dimensions will not exceed 20 cm x 20 cm x 10 cm
- The system mass will not exceed 5 kg
- The system will use no more than 10 W of power
# Design Requirements

<table>
<thead>
<tr>
<th>DRS.1</th>
<th>Control system must be a predictive feed forward system</th>
</tr>
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<td>Software and electronics elements should be verified and validated</td>
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## Abbreviations
- **DRS**: Design Requirements
- **DRE**: Electrical Requirements
- **DRM**: Mechanical Requirements
- **DRT**: Testing Requirements
- **DRS-**: Software
- **DRE-**: Electrical
- **DRM-**: Mechanical
- **DRT-**: Testing
Critical Software Elements

• Data Input and Output from MATLAB Interface
  • NI CompactDAQ
    • Capable of communicating with MATLAB
  • Queued data I/O directly into MATLAB
    • For maintaining a processing speed to mitigate output signal phase error

• Characterize 20 μm EFT Vibration [DRS.4]
  • Find frequency \( f \), amplitude \( A \) and phase \( \theta \) from noisy accelerometer data
    • Collected errors in frequency, phase and amplitude must meet residual requirements
Software Design Requirements

DRS.1  Control system must be a predictive feed forward system
   • Customer Requirement

DRS.2  Dwell time will be to 2 seconds at each frequency
   • Customer Requirement

DRS.3  Total residual error is less than 20% of desired amplitude
   • To exceed 1\textsuperscript{st} level tier

DRS.4  Create prediction of EFT vibration
   • Need for predictive feed-forward
EFT Amplitude and Frequency Determination

- Frequency Resolution \( (df) \) of FFT is:
  \[
  df = \frac{1}{T} = \frac{1}{\text{time sampled}} = \frac{1}{0.25 \text{ s}} = 4 \text{ [Hz]}
  \]

- Due to low frequency resolution, peak in frequency domain is spread among many frequencies
  - Summation of amplitudes \( (A_i) \) around the peak \( (j) \) gives the actual amplitude prediction \( (A) \)
    \[
    A = \sum_{i=j-3}^{i=j+3} A_i
    \]
    - Accuracy \( \approx 2\% \) Error
  - Amplitude \( (A_j) \) weighted average of frequencies \( (F_i) \) around the peak in spectrum to find frequency prediction \( (F) \)
    \[
    F = \frac{\sum_{i=j-3}^{i=j+3} A_i \times F_i}{\sum_{i=j-3}^{i=j+3} A_i}
    \]
    - Accuracy \( \approx 0.05 \text{ [Hz]} \)

Amplitude and Frequency Determined from FFT output using averages and summations
EFT Phase Determination

• Phase of FFT is not an accurate method to find phase, so alternative method required

• Cross correlation between accelerometer data and predicted acceleration wave with no phase offset
  • Find maximum correlation between data and predicted wave

• Use to find number of points \( n \) prediction lags the measurements
  • \( \theta = \frac{2\pi fn}{F_s} \)

\( f \equiv \text{Frequency [Hz]} \)
\( F_s \equiv \text{Sampling Frequency [Hz]} \)
\( \theta \equiv \text{Phase Offset [rad]} \)

Phase determined using Cross Correlation between data and predicted wave with no phase offset
EFT Determination Result

- Noisy accelerometer data
  - FFT to find amplitude \(A\) and frequency \(f\)
  - Cross Correlation to find phase \(\theta\)
- Acceleration Prediction \(\ddot{x}\)
  - \(\ddot{x} = A \sin(2\pi ft - \theta)\)
  - Double integration of \(\ddot{x}\) to find displacement \(x\):
    - \(x = \frac{A}{(2\pi f)^2} \sin(2\pi ft - \theta)\)

*Analytical Displacement* found using noisy accelerometer data
Time Budget

- Based on dwell time requirement and maximizing cancellation period
  - Data Collection: ≈ 250 ms
  - Computation: ≈ 10 ms
  - Actuate: ≈ 125 ms

1.74 seconds of Mitigated Pixel Smearing for a dwell time of 2 seconds
Critical Electronics Elements

- **Accelerometers**
  - PCB C65 – Piezoelectric accelerometer
    - Must be able to measure system level vibrations [DRE. 1]

- **Actuators**
  - PI 820.2 – Piezoelectric actuator
    - Must be able to have submicron resolution while under the payload [DRE. 2]

- **Actuator Driver**
  - PDm200 – Voltage amplifier and signal conditioner
    - Must be able to run actuator within specifications
    - Must be compatible with DAQ system

- **NI CompactDAQ with modules**
  - NI 9205 – Analog to digital voltage measurement
    - Must be able to sample system level vibrations
  - NI 9263 – Digital to analog voltage output
    - Must be able to provide input voltage to PDm200
Electronic Design Requirements

DRE.1 System cancels EFT vibrations between 40 and 60 Hz
   • Range at which cryocoolers vibrate

DRE.2 Vibrations have a maximum amplitude of 20μm
   • Maximum amplitude of cryocooler vibrations

DRE.3 DAQ resolution must be high enough to measure incoming EFT’s
   • Needed in order to meet software speed requirements

DRE.4 Electrical components can consume up to 10 W of power
   • Customer Requirement

DRE.5 DAQ must have voltage range of 0-10 V
Sensor Requirements

• Range 40 to 60 Hz or larger \[^{[DRE.1]}\]

• Resolution \(\leq 0.869\) mg
  • Resolution \(\leq \ddot{x}_{min} = -4\pi^2 A_{min} f_{nmin}^2 \cos(2\pi f_{nmin} t)/g\)

• For one pixel, sensitivity \(\geq 35 \frac{mV}{g}\)
  • \textit{sensitivity} \(\geq \frac{Bin}{\ddot{x}_{min}}\)

• Requires a signal conditioner to operate

\(\ddot{x}_{min}\) = maximum acceleration for one pixel change \([g]\)
\(A_{min} = 0.135\) \(\mu m\)[26]
\(f_{nmin} = 40\) Hz = minimum frequency \(^{[DRE.1]}\)
\(\ddot{x}_{min}\) is at \(\cos(2\pi f_n t) = -1\)
\(Bin = 0.0305\) mV = DAQ step size

Chose PCB 352C65 Accelerometer
Actuator Requirements

Stroke ≥ 20μm \textsuperscript{DRE.2}

Response time peak-to-peak in ≤ 16.7 ms

\[
\text{Response Time} = \frac{1}{f_{n_{\text{max}}}}
\]

Resolution ≤ 0.135 μm

Resolution ≤ \( A_{\text{min}} = \theta_{\text{min}} \times L \)

Force ≥ 31.267 N

\( f_{n_{\text{max}}} = 60 \text{ Hz} = \text{maximum frequency}^{\text{DRE.1}} \)

\( \theta_{\text{min}} = 1\mu\text{rad} = 1 \text{ pixel resolution}^{\text{DRM.3}} \)

\( L = 13.5 \text{ cm} = \text{shortest distance between legs}^{[73]} \)

\( A_{\text{min}} = \text{maximum amplitude for a change in 1 pixel} \)

Chose P-820.20 Piezoelectric Actuator
Driver Requirement

- Driver must be capable of operating with P-820.20 actuator
- Capable of outputting $100\,V_{pp}$ signal at 60 Hz with $< 20\,V_{pp}$ input
  - At capacitive load $\approx 0.7\mu F$ from actuator
  - Power bandwidth must exceed SAVI operational frequencies

PDm200 was chosen which has a Power Bandwidth of $> 750\,[Hz]$
Power Budget

- Power budget for electronics equipment meets design requirement when excluding computer system.

<table>
<thead>
<tr>
<th>Item</th>
<th>Power per Item</th>
<th>Quantity</th>
<th>Total Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDm200/P-820.2</td>
<td>1.893 W</td>
<td>2</td>
<td>3.79 W</td>
</tr>
<tr>
<td>PCB C65</td>
<td>0.6 W</td>
<td>3</td>
<td>1.8 W</td>
</tr>
<tr>
<td>NI 9205</td>
<td>0.625 W</td>
<td>1</td>
<td>0.625 W</td>
</tr>
<tr>
<td>NI 9263</td>
<td>0.625 W</td>
<td>1</td>
<td>0.625 W</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td><strong>6.84 W</strong></td>
</tr>
</tbody>
</table>

Predicted Power Consumption less than 10 W not including computer.
Critical Mechanical Elements

• Structural
  • Flexure
    • Longitudinally rigid and laterally flexible to allow flexibility and mitigate shear stresses
  • Base/top plate and solid leg
    • Sufficient stiffness to be approximated as a rigid element

• Electronic components
  • Electronic mounting capability

• Connections
  • Materials compatible with epoxy chosen

• Analysis
  • Modeled in CAD (SolidWorks)
    • Able to produce force and vibration analysis
    • Able to confirm flexure deflection with system loads
Mechanical Design Requirements

DRM.1 Structure must fit in a 20x20x10 cm space
   • Customer Requirement

DRM.2 Structure must have a mass less than or equal to 5kg
   • Customer Requirement

DRM.3 System designed to a camera that has a resolution of 1 μrad per pixel
   • Smallest resolution found for cameras that are suitable for SAVI

DRM.4 System designed to a camera that has a mass of 22 kg
   • Largest camera mass found suitable for SAVI
Cylindrical Dumbbell Flexure

- Acrylonitrile-butadiene-styrene (ABS) plastic rod
  - Density: 1.04 g/cc
  - Yield Strength: 44 MPa
- Easy to machine with High Speed Steel (HSS) tooling
- Designed with #23 gauge (3.9116 mm) unthreaded hole for epoxy connection to actuators
- 2 DOF bending to accommodate tip and tilt
  - Longitudinally stiff

Flexure Provides 2 DOF Bending and longitudinal stability
Main Structure Material

- **Aluminum 6061**
  - Widely used in space applications
    - Density: 2.7 g/cc
    - Modulus of Elasticity: 68.9 GPa
    - Ultimate Tensile Strength: 310 MPa
  - High stiffness
    - Ability to model as a rigid body
  - Widely available
    - Low cost: ($15.00 / plate)
  - Easy to machine

Aluminum Components
- 1.27 cm diameter solid legs (x 3)
- 20 cm diameter, 0.64 cm thick plates (x 4)
- 3 kg mass of 20 cm diameter and 3.8 cm thick
Epoxy Requirements

- Able to bond
  - ABS to Stainless Steel
  - ABS to Al 6061
  - Al 6061 to Al 6061
- Removable
- Cure time < 1 hour

Chosen: Cyberbond Apollo 2150

Note: Since Epoxy Layer is thin, deformation due to strain is negligible
Simulink Simulation

• Goal: Model system performance for cancelling EFT vibrations and predict residual cancellation performance
  • Simulated and measured noise taken into account
  • Physical systems (piezo actuator and accelerometers) modeled
  • Preliminary software implemented and checked for performance
• Piezo actuator
  • Characteristics of piezo actuator specified from P-820.20 Datasheet

• Institute of Electronics and Electrical Engineers (IEEE) standard on piezoelectricity model
  • No hysteresis modeling

Piezo Actuator Model using IEEE standard with Voltage Input Control
Accelerometer Model

- Properties set based on datasheet for C65 accelerometers
- Accelerometer dynamics included

Accelerometer Model based on C65 datasheet
Noise Added to simulate measured noise
Embedded MATLAB: Data Handling

• DAQ: Simulates data logging
• `sin_analysis()` performs calculations to find $A, f, \theta$ based on FFT and cross correlation
• `sin_calc()` computes the shifted displacement wave for piezo control

Preliminary *Software Implemented* in Simulink simulation to determine analytical response
Voltage Control

- Piezo drive voltage ($V_{\text{drive}}$) from linear relationship to desired stack displacement ($x$)
  - $\frac{\partial x}{\partial V_{\text{drive}}} = \frac{30 \mu m}{100 V} = 0.3 \frac{\mu m}{V}$
  - $V_{\text{drive}} = x \left(\frac{\partial x}{\partial V_{\text{drive}}}\right)^{-1}$

**Voltage Control** from desired piezo actuator displacement
Simulation Results

• Simulated system performance using above methods

• Maximum error \( (E_{\text{max}}) \approx 0.75\mu m \) during cancellation
  • Readjust signal 8 times a second
  • Always using last 0.25 seconds data
  • Responds to a jump in frequency in \(< 0.25 \) seconds

Simulated performance yields
\[ \text{Maximum Error} \approx 0.75\mu m \]
Software Error

• Software errors due to errors in phase, frequency, and amplitude of the prediction from actual input
  
  \[ E_{tot} = A \sin(2\pi ft + \theta) - (A + \Delta_A) \sin \left(2\pi (f + \Delta_f)t + (\theta + \Delta\theta) \right) \]

Simulated performance yields

*Maximum Error* \( \approx 0.75\mu m \)
Additional Electrical Error

- **NI 9263 D/A Converter**\(^1\)
  - Gain: 0.35%, Offset: 0.75% (Voltage)
    - Approximately 1.1 V error \(\approx 0.33\ \mu m\)

- **P820.20 Actuators**
  - 0.3 nm Resolution\(^2\)
  - Creep <2% of command amplitude \(\approx 0.6\ \mu m\)
    - Only occurs for continuous command for over 3 hours
    - Not relevant for SAVI
  - Hysteresis causes 2-15% error

- **U352C65 Accelerometers**
  - Error from 100 mV/g imperfection
    - Removed with calibration

- **PDm200 Driver**
  - Noise: 0.72 mV, much less than 1 micron\(^3\)

Total Electrical Error \(\approx 1\ \mu m\) (excluding hysteresis)

1\(^1\)Calibrated at -40 to 70 °C
2\(^2\)Unloaded Value
3\(^3\)Low Noise Channel
Hysteresis

Largest Source of Error
• Imperfections in elastic contraction
• Generally 2-15% of command amplitude
• Worst at middle of sine wave
• Has a greater impact on contraction than expansion
• Can be mitigated with closed loop driver
  • If needed, voltage biasing can be implemented in control

Hysteresis Error ≈ 0.4μm to 3μm
Total Errors

- **Worst Case Errors:**
  - Hysteresis: 3μm
  - Software: 0.75μm
  - Additional electronic error: 1μm

- Errors exceed tier 2 level of success at worst case
  - Would have to account for hysteresis in voltage control to reduce error

Total **Worst Case Error** ≈ 4.75 μm, corresponding to **76.25% Reduction on Residual**
Critical Test Elements

• Verification and Validation of Elements
  • Electronic component tests
    • Accelerometer
    • Piezo driver
    • Actuator
  • Software test
    • Input output phase
  • Integrated software and electronics test
    • Will be used to validate the software

• Verification and Validation of System
  • Full system test
    • Environmental noise test
• DRT.1 Testing must simulate 0-g loading
  • SAVI would be operating in space
• DRT.2 Environmental noise will have negligible effects on the SAVI system
  • Minimize software error to satisfy DRS.3
• DRT.3 Software and electronics elements should be verified and validated
  • Required for SAVI to be verified and validated
  • Results must be directly related to software, electrical and mechanical requirements
Full System Test

• Location:
  • ITLL basement, late at night

• Equipment:
  • Computer, simulated mass, SAVI, test stand, passive damping system
Preliminary ITLL Noise Testing

• Purpose is to identify noise within SAVI operation range

• Conducted from 11:20 PM to midnight to minimize noise from other students
  • All trials ran on NI CompactDAQ 9174 chassis
    • NI 9205 analogue input
      • Channel 1
        • BNC cable2
        • Accelerometer #13264

ITLL is Not a Viable Testing Facility without environmental isolation
Preliminary Noise Damping

• Mass spring damper
  • $k \equiv$ spring constant $\approx 35 \frac{N}{m}$
  • $c \equiv$ damping ratio
  • $m \equiv$ mass $\approx 17$ kg

• Transfer Function
  • $\frac{X(s)}{F(s)} = \frac{1}{ms^2 + cs + k}$

$\approx 100$dB Attenuation Between 40 – 60 Hz
Damped Noise Results

- Approximately 1 mV\textsubscript{pp} of noise
- Produced results an order of magnitude less than undamped trials
- Removed peaks in 40-60 Hz range
- Remaining noise is likely electrical
- Results can be improved before final testing

ITLL is a Sufficient Testing Location when passive damping is incorporated
Full System Test

• How it works:
  • Test stand will apply a 20 μm peak-to-peak displacement between 40 and 60 Hz
    • SAVI and test stand will have 6 distinct configurations to test tip and tilt
    • Tests will be performed with varying dwell times all greater than 2 seconds [DRS.2]
  • SAVI system will respond to the test stand’s EFT
    • SAVI actively mitigates tip and tilt

• Measurements made:
  • Record residual accelerations and calculate sinusoidal displacements
    • Quantification of tip and tilt by comparison with solid leg response

• Key Issues:
  • Signal to noise ratio too low, hysteresis cannot be mitigated, test stand incapable of creating EFT with specified amplitude and frequency
## Risk Assessment

### Consequence

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<tr>
<th>Likelihood</th>
<th>Insignificant</th>
<th>Minor</th>
<th>Moderate</th>
<th>Major</th>
<th>Severe</th>
</tr>
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<tr>
<td>Almost Certain</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>RSK.10</strong></td>
</tr>
<tr>
<td>Likely</td>
<td></td>
<td><strong>RSK.2</strong></td>
<td><strong>RSK.8</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Possible</td>
<td></td>
<td><strong>RSK.5</strong></td>
<td><strong>RSK.3</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unlikely</td>
<td><strong>RSK.9</strong></td>
<td><strong>RSK.6</strong></td>
<td><strong>RSK.1</strong></td>
<td><strong>RSK.4</strong></td>
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<tr>
<td>Rare</td>
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### Risk

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<td>RSK.3</td>
<td>Flexure manufacturability with accessible machines</td>
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<tr>
<td>RSK.4</td>
<td>Electronic failure during vibration testing</td>
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<tr>
<td>RSK.5</td>
<td>Borrowed electronics have error due to previous use</td>
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<td>RSK.6</td>
<td>40-60 Hz resonance modes</td>
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<td>Test structure does not reproduce EFT vibrations</td>
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<td>RSK.8</td>
<td>Software cannot meet necessary clock speed</td>
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<td>RSK.9</td>
<td>New electronics have unforeseen error</td>
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<td>RSK.10</td>
<td>Error due to hysteresis</td>
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### Electrical Risks

- RSK.2: Unable to control ambient noise
- RSK.3: Flexure manufacturability with accessible machines
- RSK.4: Electronic failure during vibration testing
- RSK.5: Borrowed electronics have error due to previous use
- RSK.6: 40-60 Hz resonance modes
- RSK.7: Test structure does not reproduce EFT vibrations
- RSK.8: Software cannot meet necessary clock speed
- RSK.9: New electronics have unforeseen error
- RSK.10: Error due to hysteresis

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### Project Purpose

- Design Solution & Reqs.
- Software
- Electrical
- Mechanical
- Simulink
- Errors
- Verification & Validation
- Risks
- Project Planning

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<th>Mitigation</th>
<th>Off Ramp</th>
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<td>RSK.1</td>
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<td>Testing at different times to reduce noise</td>
<td>New testing method</td>
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<tr>
<td>RSK.2</td>
<td>Unable to control ambient noise</td>
<td>Use of vibration isolation through passive damping structure or optics bench</td>
<td>New testing site</td>
</tr>
<tr>
<td>RSK.3</td>
<td>Flexure manufacturability with accessible machines</td>
<td>Design flexures based on available machine capabilities</td>
<td>Send flexure designs to outside machining facility</td>
</tr>
<tr>
<td>RSK.4</td>
<td>Electronic failure during vibration testing</td>
<td>Purchase of electronics capable of withstanding expected vibrations</td>
<td>Purchase additional electronics</td>
</tr>
<tr>
<td>RSK.5</td>
<td>Borrowed electronics have error due to previous use</td>
<td>Recalibrate</td>
<td>Buy new electronics or borrow different ones</td>
</tr>
<tr>
<td>RSK.6</td>
<td>Resonance modes frequencies between 40-60 Hz</td>
<td>SolidWorks modal analysis of complete design</td>
<td>Different size/shape of top and bottom plates</td>
</tr>
<tr>
<td>RSK.7</td>
<td>Test structure does not reproduce EFT vibrations</td>
<td>Perform analysis and make modifications to the test structure</td>
<td>New testing method</td>
</tr>
<tr>
<td>RSK.8</td>
<td>Software cannot meet necessary clock speed</td>
<td>Decrease precision therefore increasing speed</td>
<td>Readjust allowable dwell time or rewrite MATLAB code</td>
</tr>
<tr>
<td>RSK.9</td>
<td>New electronics have unforeseen error</td>
<td>Calibrate</td>
<td>Contact electronics provider</td>
</tr>
<tr>
<td>RSK.10</td>
<td>Error due to hysteresis</td>
<td>Voltage biasing in control</td>
<td>Purchase additional electronics</td>
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</tbody>
</table>
Work Breakdown Structure

SAVI

**Mechanical Systems**
- Materials Purchased
  - Parts Machined
  - System Constructed

**Electrical Systems**
- Electronics Purchased
  - Electronics Integrated
    - Actuators, Piezo-Drivers
    - Actuators Installed
    - Accelerometers Installed

**Software Systems**
- Basic Model
  - Baseline Control
  - Electronic Integration
  - System Integration
  - Accelerometers, Actuators
  - Software Tested with Accelerometers and Actuators in 1-D

**Testing Systems**
- Electronics Functionality Checklist
  - Full System Tested
  - Software Tested with Accelerometers and Actuators in 1-D
## Work Plan

### Projects

<table>
<thead>
<tr>
<th>Project Purpose</th>
<th>Design Solution &amp; Reqs</th>
<th>Software</th>
<th>Electrical</th>
<th>Mechanical</th>
<th>Simulink</th>
<th>Errors</th>
<th>Verification &amp; Validation</th>
<th>Risks</th>
<th>Project Planning</th>
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</table>

### Work Plan Table

<table>
<thead>
<tr>
<th>Tasks and Milestones</th>
<th>Staffing</th>
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<tr>
<td>Fall Final Report</td>
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<tr>
<td>Define Accelerometer Function</td>
<td>Corey</td>
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<tr>
<td>Define Actuator Function</td>
<td>Corey</td>
</tr>
<tr>
<td>Define Piezo Driver Function</td>
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<tr>
<td>Describe Software Input</td>
<td>Joseph</td>
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<td>Describe Software Processing</td>
<td>Joseph</td>
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<tr>
<td>Describe Software Output</td>
<td>Joseph</td>
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<tr>
<td>Model Base and Top Plates</td>
<td>Justin</td>
</tr>
<tr>
<td>Model Flexures</td>
<td>Jackson</td>
</tr>
<tr>
<td>Model Solid Strut</td>
<td>Justin</td>
</tr>
<tr>
<td>Outline Full System Test</td>
<td>Ben</td>
</tr>
<tr>
<td>Outline Plan for Full System Test</td>
<td>Ben</td>
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<tr>
<td>Outline Additional Test Cases</td>
<td>Ben</td>
</tr>
<tr>
<td>Outline Accelerometer Test</td>
<td>Blake</td>
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<tr>
<td>Outline Actuator Test</td>
<td>Blake</td>
</tr>
<tr>
<td>Outline Software and Electronics Integration Test</td>
<td>Ben</td>
</tr>
<tr>
<td>Create Budget Estimate</td>
<td>Patrick</td>
</tr>
<tr>
<td>Purchase Actuators</td>
<td>Blake</td>
</tr>
<tr>
<td>Purchase Piezo Driver</td>
<td>Blake</td>
</tr>
<tr>
<td>Purchase Base, Top Plate and Solid Strut Materials</td>
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### December

<table>
<thead>
<tr>
<th>W15</th>
<th>W16</th>
<th>Finals</th>
<th>Win</th>
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# Work Plan

## Tasks and Milestones

<table>
<thead>
<tr>
<th>Task</th>
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<tbody>
<tr>
<td>Manufacturing Status Review</td>
<td>Wasseem</td>
</tr>
<tr>
<td>Write Manufacturing Safety Plan</td>
<td>Wasseem</td>
</tr>
<tr>
<td>Receive and Validate Materials</td>
<td>Justin</td>
</tr>
<tr>
<td>Validate Actuators and Drivers</td>
<td>Corey</td>
</tr>
<tr>
<td>Validate Accelerometers</td>
<td>Corey</td>
</tr>
<tr>
<td>Draft Manufacturing Plans for Flexures</td>
<td>Justin</td>
</tr>
<tr>
<td>Draft Manufacturing Plans for Struts</td>
<td>Justin</td>
</tr>
<tr>
<td>Draft Manufacturing Plans for Base and Top Plates</td>
<td>Jackson</td>
</tr>
<tr>
<td>Consult Matt Rhode about Manufacturing Plans</td>
<td>Jackson</td>
</tr>
<tr>
<td>Revise Manufacturing Parts</td>
<td>Jackson</td>
</tr>
<tr>
<td>Draw Circuit Diagram</td>
<td>Patrick</td>
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<tr>
<td><strong>Manufacture Parts</strong></td>
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</tr>
<tr>
<td>Manufacture Struts</td>
<td>Wasseem</td>
</tr>
<tr>
<td>Manufacture Flexures</td>
<td>Jackson</td>
</tr>
<tr>
<td>Manufacture Base and Top plates</td>
<td>Justin</td>
</tr>
<tr>
<td><strong>Construct SAVI</strong></td>
<td></td>
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<tr>
<td>Construct Test Apparatus</td>
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</tr>
<tr>
<td>Integrate SAVI and Test Apparatus</td>
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<tr>
<td>Integrate Electronics</td>
<td></td>
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## Project Purpose

- **Objective:**
- **Scope:**
- **Timeline:**
- **Budget:**
- **Resources:**

## Project Planning

<table>
<thead>
<tr>
<th>Month</th>
<th>December</th>
<th>January</th>
<th>February</th>
<th>March</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>W15</td>
<td>W16</td>
<td>Winter Break</td>
<td>W1</td>
</tr>
<tr>
<td></td>
<td>W2</td>
<td>W3</td>
<td>W4</td>
<td>W5</td>
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<td>W6</td>
<td>W7</td>
<td>W8</td>
<td>W9</td>
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<tr>
<td></td>
<td>W10</td>
<td>Break</td>
<td>W11</td>
<td>W12</td>
</tr>
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</table>

## Risks

- Design Integration
- Manufacturing Delays
- Electrical Interference
- Simulation Failures

## Verification & Validation

- System Testing
- Component Testing
- Interface Testing

## Errors

- Design Flaws
- Manufacturing Errors
- Electrical shorts

## Simulink

- Model Development
- Model Verification
- Model Validation

## Mechanical

- Structural Analysis
- Thermal Analysis
- Fluid Dynamics

## Electrical

- Power Electronics
- Control Systems
- Signal Processing

## Software

- Data Analysis
- Algorithm Development
- Interfaces
# Financial Break Down

<table>
<thead>
<tr>
<th>Category</th>
<th>Item</th>
<th>Cost</th>
<th>Amount (#)</th>
<th>Estimated Shipping</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronics</td>
<td>Accelerometers and Driver (PCB C65/482C series)</td>
<td>$0.00 Borrowed from Trudy</td>
<td>5</td>
<td>$0.00</td>
<td>$0.00</td>
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<tr>
<td></td>
<td>Actuators (PI P820.20)</td>
<td>$646.00</td>
<td>3</td>
<td>$7.00 + $9.00 (insurance)</td>
<td>$1,954.00</td>
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<tr>
<td></td>
<td>Driver (PDm200)</td>
<td>$230.00</td>
<td>3</td>
<td>$80.00 + $4.00 (insurance)</td>
<td>$774.00</td>
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<tr>
<td></td>
<td>D/A Converter</td>
<td>$404.00</td>
<td>1</td>
<td>$3.00 + $3.00 (insurance)</td>
<td>$410.00</td>
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<tr>
<td>Mechanical / Testing</td>
<td>Flexure Material (ABS)</td>
<td>$1.00/foot</td>
<td>1 foot</td>
<td>$3.00 + $0.00 (insurance)</td>
<td>$4.00</td>
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<tr>
<td></td>
<td>Solid Leg Material (AL6061)</td>
<td>$6.00/foot</td>
<td>1 foot</td>
<td>$7.00 + $0.00 (insurance)</td>
<td>$13.00</td>
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<tr>
<td></td>
<td>Top/Bottom Plate Material (AL6061)</td>
<td>$15.00</td>
<td>4</td>
<td>$10.00 + $2.00 (insurance)</td>
<td>$72.00</td>
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<tr>
<td></td>
<td>Epoxy/Remover (Apollo 2150/ UNDO 6020)</td>
<td>Epoxy - $8.00/ ounce Remover -</td>
<td>8 ounces</td>
<td>$15.00 + $2.00 (insurance)</td>
<td>$91.00</td>
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<tr>
<td></td>
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<td>$10.00/ ounce</td>
<td>1 ounce</td>
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<tr>
<td></td>
<td>Heavy Mass (AL6061)</td>
<td>$0.00 Borrowed</td>
<td>1</td>
<td>$0.00</td>
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<td></td>
<td>Styrofoam Base</td>
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<td>$0.00 + $0.00 (insurance)</td>
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<td>Simulated Mass (AL6061)</td>
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<td>1</td>
<td>$6.00 + $2.00 (insurance)</td>
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<td>Total</td>
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<td>$3,443.00</td>
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<tr>
<td>Buffer</td>
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<td></td>
<td>$1,557.00</td>
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</table>

All values rounded up to the nearest dollar, or whole number.

All manufacturing can be done in house, no cost associated.

D/A converter may be able to be borrowed.
# Test Plan

<table>
<thead>
<tr>
<th>Tasks and Milestones</th>
<th>December</th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
<th>May</th>
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<tbody>
<tr>
<td>Test Readiness Review</td>
<td>W15</td>
<td>W16</td>
<td>W1</td>
<td>W2</td>
<td>W3</td>
<td>W4</td>
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<tr>
<td>Define Accelerometer Test</td>
<td>W5</td>
<td>W6</td>
<td>W7</td>
<td>W8</td>
<td>W9</td>
<td>W10</td>
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<td>Plan Accelerometer Test</td>
<td>W11</td>
<td>W12</td>
<td>W13</td>
<td>W14</td>
<td>W15</td>
<td>W16</td>
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<td>Revise Accelerometer Test</td>
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<tr>
<td>Perform Accelerometer Test</td>
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<tr>
<td>Record and Report on Accelerometer Test</td>
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<tr>
<td>Define Noise Test</td>
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<td>Revise Noise Test</td>
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<tr>
<td>Perform Noise Test</td>
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<td>Define Input Output Phase Test</td>
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<td>Plan Input Output Phase Test</td>
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<td>Define Piezo Driver Test</td>
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<tr>
<td>Plan Piezo Driver Test</td>
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<tr>
<td>Revise Piezo Driver Test</td>
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<tr>
<td>Perform Piezo Driver Test</td>
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<tr>
<td>Record and Report on Piezo Driver Test</td>
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<td>Revise Integrated Software and Electronics Test</td>
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<tr>
<td>Perform Integrated Software and Electronics Test</td>
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<tr>
<td>Record and Report on Integrated Software and Electronics Test</td>
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<tr>
<td>Define Full System Test</td>
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<td>Record and Report on Full System Test</td>
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<tr>
<td>Design SAVI</td>
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</tr>
<tr>
<td>Construct Test Apparatus</td>
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</tr>
<tr>
<td>Integrate SAVI and Test Apparatus</td>
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<td>W17</td>
<td>W18</td>
<td>W19</td>
<td>W20</td>
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<td>W23</td>
<td>W24</td>
<td>W25</td>
<td>W26</td>
<td>W27</td>
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**Project Purpose**

- Design Solution & Reqs.
- Software
- Electrical
- Mechanical
- Simulink
- Errors
- Verification & Validation
- Risks

**Project Planning**

- W15: Winter Break
- W16: Finals
Backup Slide Table of Contents

• Problem
  • Pixel Smear (61)

• Software
  • EFT Amplitude Determination (62)
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  • EFT Phase Determination (64)
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  • PCB Piezotronics – Accelerometer (66)
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  • Lateral Flexure Force Calculation (77)
  • Flexure Lateral Motion (78)
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  • Calculating Mass in One g (80)
  • Material Evaluation Criteria (81)
  • Material Trade Study (82)
  • Cyberbond Apollo 2150 (83)
Pixel Smear

\[ \kappa_{\text{max}} = \frac{\theta_{\text{max}}}{\lambda} \]

\[ \kappa_{\text{max}} = 148.15 \text{ [Pixels]} \]

\[ \kappa_{60\% \text{reduction}} = \kappa_{\text{max}} \times 40\% = 59.24 \text{ [Pixels]} \]

\[ \theta_{40\%} = 0.00005926 \text{ rad} \]

\[ \kappa_{80\% \text{reduction}} = \kappa_{\text{max}} \times 20\% = 29.62 \text{ [Pixels]} \]

\[ \theta_{20\%} = 0.00002963 \text{ rad} \]

\( \kappa = \text{amount of pixel smear} \)

\( \theta_{\text{Max}} = 0.00014815 \text{ rad} = \text{deflection of plate, [74]} \)

\( \lambda = 1\mu\text{rad} = \text{Pixel resolution, [DRM.3]} \)
EFT Amplitude Determination

• FFT of accelerometer data to find amplitude ($A$).
  • To improve amplitude accuracy, Flat Top Windowing used. [BS #]
  • The amplitude of the singular frequency in the domain is spread between nearby frequency bins.

• Summation of Amplitudes around the peak ($j$) gives the actual amplitude prediction.
  • $A = \sum_{i=j-3}^{i=j+3} A_i$

Amplitude Determined Using Flat Top Windowing and Summation of Amplitudes in surrounding bins
EFT Frequency Determination

• Frequency Resolution of FFT is:
  • \( df = \frac{1}{T} = \frac{1}{\text{time sampled}} \)
  • Would have to sample too long to achieve high enough Frequency resolution.
  • Need a way to find frequency accurately with a low frequency resolution.
    • \( df = \frac{1}{0.5\text{s}} = 2\text{[Hz]} \)

• Amplitude Weighted Average of Frequencies around the peak in spectrum
  • \( F = \frac{\sum_{i=j-3}^{i=j+3} A_i \times F_i}{\sum_{i=j-3}^{i=j+3} A_i} \)
  • Find Frequency with accuracy
EFT Phase Determination

• Phase of FFT is not an accurate method to find phase.
  • Alternative method is required to find phase.

• Cross Correlation between accelerometer data and predicted acceleration wave with no phase offset.
  • Find maximum correlation between data and predicted wave. [BS #]
  • Use to find # of points \( n \) prediction lags the measurements.
  • \( \theta = \frac{2\pi fn}{F_s} \)

Phase Determined Using Cross Correlation between data and predicted wave with no phase.
Computation Time Calculations

- Duration of Code highly dependent on # of samples in data segment.
  - FFT most efficient in powers of 2.

*Time to Run is much less than 10 ms*
PCB Piezotronics – 352C65 Accelerometer

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>100 mV/g</td>
</tr>
<tr>
<td>Range</td>
<td>±50g</td>
</tr>
<tr>
<td>Resonance Frequency</td>
<td>17 kHz</td>
</tr>
<tr>
<td>Broadband Resolution</td>
<td>0.16 mg RMS</td>
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<tr>
<td>Spectral Noise</td>
<td>10, 100, 1k Hz</td>
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<tr>
<td>Dimensions</td>
<td>9.5 mm Hex x14 mm</td>
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</tbody>
</table>

Lower Sensitivity was Deemed Acceptable.

2 Pixel Resolution.

3-channel 480B21 sensor signal conditioner
4-channel 482C series sensor signal conditioner
Physik Instrumente – P820.20 Actuator

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Range</td>
<td>0 to 100 V</td>
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<tr>
<td>Resolution</td>
<td>0.15 nm</td>
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<tr>
<td>Force Capacity</td>
<td>Push: 50 N</td>
</tr>
<tr>
<td></td>
<td>Pull: 10 N</td>
</tr>
<tr>
<td>Unloaded Resonant Frequency</td>
<td>12 kHz</td>
</tr>
<tr>
<td>Mass</td>
<td>11 g</td>
</tr>
</tbody>
</table>

• Flexures are designed for epoxy bonding to either top or bottom of actuator
Actuator Driver Specifications

• **PDm200 Operational Range**

<table>
<thead>
<tr>
<th>Input Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Supply Voltage (differential)</td>
<td>Vs</td>
</tr>
<tr>
<td>Positive Output Voltage Range Vhv+</td>
<td></td>
</tr>
<tr>
<td>Negative Output Voltage Range Vhv-</td>
<td></td>
</tr>
<tr>
<td>Load Capacitance (effective) C</td>
<td>C</td>
</tr>
<tr>
<td>Output Voltage (peak to peak) Vpp</td>
<td>f</td>
</tr>
<tr>
<td>Frequency</td>
<td></td>
</tr>
</tbody>
</table>

• **PDm200 Capabilities**

<table>
<thead>
<tr>
<th>Results</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required Average Output Current Iav</td>
<td>0.004 A</td>
</tr>
<tr>
<td>Available Average Output Current Iav, max</td>
<td>0.080 A</td>
</tr>
<tr>
<td>Required Input Power Pin</td>
<td>1.893 W</td>
</tr>
<tr>
<td>Required Supply Current Iin</td>
<td>0.079 A</td>
</tr>
<tr>
<td>Small Signal Bandwidth Fbw</td>
<td>22.68 kHz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Maximum Frequency (Power Bandwidth)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sine Wave</td>
<td>1143 Hz</td>
</tr>
<tr>
<td>Triangle Wave</td>
<td>1143 Hz</td>
</tr>
<tr>
<td>Square Wave</td>
<td>571 Hz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Maximum Freq. at Full Range</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sine Wave</td>
<td>1143 Hz</td>
</tr>
<tr>
<td>Triangle Wave</td>
<td>1143 Hz</td>
</tr>
<tr>
<td>Square Wave</td>
<td>571 Hz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Maximum Freq. with Minimum Load</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sine Wave</td>
<td>63694 Hz</td>
</tr>
<tr>
<td>Triangle Wave</td>
<td>100000 Hz</td>
</tr>
<tr>
<td>Square Wave</td>
<td>500000 Hz</td>
</tr>
</tbody>
</table>
Driver Calculations

• Required Input Power:
  • \( P_{in} = 1.33V_{out}(0.001 + I_{av}) \)

• Maximum Frequency
  • \( f_{max} = \frac{20 \times 10^6}{\pi V_{L(p-p)}} \)

• Power Bandwidth with a Capacitive Load
  • \( f_{pwr} = \frac{I_{av}}{V_{L(p-p)}C_{L}} \)

\( V_{L(p-p)} = \) Configured Voltage Output = 100Vpp
\( f_{max} = 63 \text{ kHz for Unloaded Operation} \)
\( C_{L} = \) Capacitive Load = 0.7 \( \mu \text{F} \)
\( f_{pwr} \approx 750 - 1100 \text{ Hz} \)
### PiezoDrive - PDm200 miniature Piezo Driver

<table>
<thead>
<tr>
<th>Specification</th>
<th>Specification Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Range</td>
<td>-30 to 200 V</td>
</tr>
<tr>
<td>Peak Output Current</td>
<td>300 mA</td>
</tr>
<tr>
<td>Gain</td>
<td>20 V/V</td>
</tr>
<tr>
<td>Input Impedance</td>
<td>200k</td>
</tr>
<tr>
<td>Noise</td>
<td>&lt;1 mV RMS</td>
</tr>
<tr>
<td>Dimensions</td>
<td>7.1 X 3.9 X 2.9</td>
</tr>
</tbody>
</table>
Data Flow

Incoming Vibrations

- Accelerometer
  - NI-9205 DAQ
    - 64 Bit Computer
      - NI-9263
        - 0 to +5V
  - NI-9205 DAQ
    - <30 mVpp
- Piezo Driver PDm200
  - Piezo Actuators PI P-820
    - 0 to +100V
  - Piezo Driver PDm200
    - 0 to +5V
- 64 Bit Computer
  - 0 to +5V
- 0 to +100V
- <30 mVpp
Wiring

1: Accelerometers -> Charge Amplifier -> DAQ -> Computer
2: Computer Output -> D/A Output -> Actuator Drivers
3: Actuator Drivers -> Actuators
Accelerometer Validation

• Apply a 1 g acceleration by dropping accelerometer from one hand to the other.
• Divide voltage output by g’s
• Compare to data sheet for actual sensitivity
Actuator and Driver Validation

• Stationary Test
  • Connect actuator and driver to DAQ
  • Collect data with system stationary
  • Use signal as resolution
  • Compare the resolution with the data sheet
• Plate is considered rigid, therefore the plate can only pivot at one of the three legs

\[ L_{\text{min}} = 13.5 \text{ cm} \]
\[ L_{\text{max}} = 15.59 \text{ cm} \]
Calculating Maximum Deflection Angle

\[ \sin(\theta) = \frac{20 \mu m}{13.5 \text{ cm}} = 0.00014815 \text{ rad} \]
Lateral Flexure Force Calculation

\[ m_{\text{plate}} = \pi r_{\text{plate}}^2 t_{\text{plate}} \rho_{\text{plate}} = 0.53 \text{ kg} \]

\[ F_{\text{plate}} = m_{\text{plate}} g = 5.28 \text{ N} \]

\[ F_{\text{mass}} = F_{\text{plate}} + F_{\text{camera}} = 36.55 \text{ N} \]

\[ F_1 = \ddot{x}_{\text{max}} \frac{2}{3} \frac{(F_{\text{mass}})}{g} = 3.53 \text{ N} \]

\[ M_1 = F_1 L_1 = 0.477 \text{ Nm} \]

\[ F_{\text{simulate}} h_{\text{flexure}} = M_1 \Rightarrow F_{\text{simulate}} = \frac{M_1}{h_{\text{flexure}}} \]

\[ F_{\text{simulate}} = 23.83 \text{ N} \]

- \[ F_{\text{camera}} = 31.3 \text{ N} = \text{Force of camera, [78]} \]
- \[ \ddot{x}_{\text{max}} = 1.4212 \frac{m}{s^2} = \text{max acceleration, [78]} \]
- \[ \rho_{\text{plate}} = 2700 \frac{\text{kg}}{\text{m}^3} = \text{density of Al 6061} \]
- \[ r_{\text{plate}} = 10 \text{ cm} = \text{radius of plate, [DR. 6]} \]
- \[ L_1 = 13.5 \text{ cm}, [73] \]
- \[ t_{\text{plate}} = 0.635 \text{ cm} = \text{thickness of plate} \]
- \[ g = 9.81 \text{ m/s}^2 \]
- \[ h_{\text{flexure}} = 2 \text{ cm} \]
Lateral Motion

Force = 23.83 N in lateral direction

Minimum deflection needed = 2.96 \times 10^{-3} \text{ mm}

Deflection is great enough to provide necessary flexural displacement under full loading
Longitudinal Motion

*Force* = 15.7 N in downward direction

\[
FOS_{\text{longitudinal}} = \frac{44,000,000 \text{ Pa}}{1,165,281 \text{ Pa}}
\]

\[
FOS_{\text{longitudinal}} = 37.8
\]

\[
\delta_{\text{max}} = 5 \mu m
\]
Motion of the vibrating mass: \( x(t) = A \cos(2\pi f_n t) \)

\[
\begin{align*}
\dot{x}(t) &= -2\pi A f_n \sin(2\pi f_n t) \\
\ddot{x}(t) &= -4\pi^2 A f_n^2 \cos(2\pi f_n t) \\
\ddot{x}_{\text{max}} &= 1.4212 \text{ m/s}^2 \\
F_{\text{zero } g} &= m \ddot{x}_{\text{max}} = 31.267 \text{ N, [DR.5]} \\
m_{\text{one } g} &= \frac{F_{\text{zero } g}}{g} = 3.19 \text{ kg}
\end{align*}
\]

\( f_n = \frac{1}{T} = 60 \text{ Hz} \equiv \text{Natural Frequency, [DRE.1]} \\
A = 10\mu\text{m} \equiv \text{Amplitude, [DRE.2]} \\
m = 22 \text{ kg} \equiv \text{Mass of Camera, [DRM.4]} \\
g = 9.81 \text{m/s}^2 \equiv \text{Gravity} \\
t \equiv \text{time} \\
\ddot{x}_{\text{max}} \text{ is at } \cos(2\pi f_n t) = -1 \)
Material Evaluation Criteria

• Availability
  • Ease in which material can be acquired in necessary quantity

• Cost
  • Relative cost of each material

• Machinability
  • Ease in which material can be machined to desired dimensions and shapes

• Stiffness
  • Ability of material to be modeled as a rigid body

• Density
  • Relative weight comparison for each material

• Space Application
  • How often material is used for space missions
## Material Trade Study

<table>
<thead>
<tr>
<th></th>
<th>6061 Al</th>
<th>AZ91C Mg</th>
<th>B/Al</th>
<th>Ti 6Al-4V</th>
<th>17-4 PH Stainless</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Weight [%]</strong></td>
<td>NV</td>
<td>W</td>
<td>NV</td>
<td>W</td>
<td>NV</td>
</tr>
<tr>
<td><strong>Space Application</strong></td>
<td>5</td>
<td>9</td>
<td>0.45</td>
<td>9</td>
<td>0.45</td>
</tr>
<tr>
<td><strong>Density</strong></td>
<td>15</td>
<td>9</td>
<td>1.35</td>
<td>9</td>
<td>1.35</td>
</tr>
<tr>
<td><strong>Stiffness</strong></td>
<td>15</td>
<td>7</td>
<td>1.05</td>
<td>6</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>Machinability</strong></td>
<td>20</td>
<td>9</td>
<td>1.8</td>
<td>7</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>20</td>
<td>9</td>
<td>1.8</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td><strong>Availability</strong></td>
<td>25</td>
<td>8</td>
<td>2</td>
<td>3</td>
<td>0.75</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100</td>
<td>8.45</td>
<td>5.85</td>
<td>5.9</td>
<td>6.65</td>
</tr>
</tbody>
</table>

|                      | NV      | W        | NV   | W         | NV                | W |
| **Space Application**| 5       | 9        | 0.45 | 9         | 0.45              | 7 | 0.35 | 5 | 0.25 |
| **Density**          | 15      | 9        | 1.35 | 9         | 1.35              | 5 | 0.75 | 3 | 0.45 |
| **Stiffness**        | 15      | 7        | 1.05 | 6         | 0.9               | 5 | 0.75 | 9 | 1.35 |
| **Machinability**    | 20      | 9        | 1.8  | 7         | 1.4               | 8 | 1.6  | 9 | 1.8  |
| **Cost**             | 20      | 9        | 1.8  | 5         | 1                 | 5 | 1    | 4 | 0.8  |
| **Availability**     | 25      | 8        | 2    | 3         | 0.75              | 3 | 0.75 | 5 | 1.25 |
| **Total**            | 100     | 8.45     | 5.85 | 5.9       | 6.5               | 6.65 |
Cyberbond Apollo 2150

- Tensile Strength: 3400 psi
- Ability to bond metals and plastics
- Set time under 20 minutes for Aluminum and ABS
- Corresponding Remover: UNDO 6020
Electronic Mounting

• PDm200 – Driver
  • Mounted to baseplate with screws

• PI 820.20 – Actuator
  • Secured above and below flexures with thin layer of epoxy

• PCB C65 – Accelerometer
  • Secured to top/base plate of SAVI with a thin layer of epoxy
Preliminary Noise Damping

- $\approx 17$ kg plate

- $k$ is the spring constant, $m$ is the mass, and $\omega_0$ is the natural frequency of the spring oscillations

- $\omega_0 = 1.43486 \text{ rad/s} = 0.2284 \text{ Hz}$ for a Styrofoam support of $k = 35 \text{ N/m}$, and a mass of 17 kg on top

- Characteristic Equation:
  - $\zeta = 1$, critically damped system