Electric Propulsion Thruster Random Vibration Test with FEM Predicted Isolation System

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June 4–6, 2019

The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Government sponsorship acknowledged.

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Assuring Mission Success

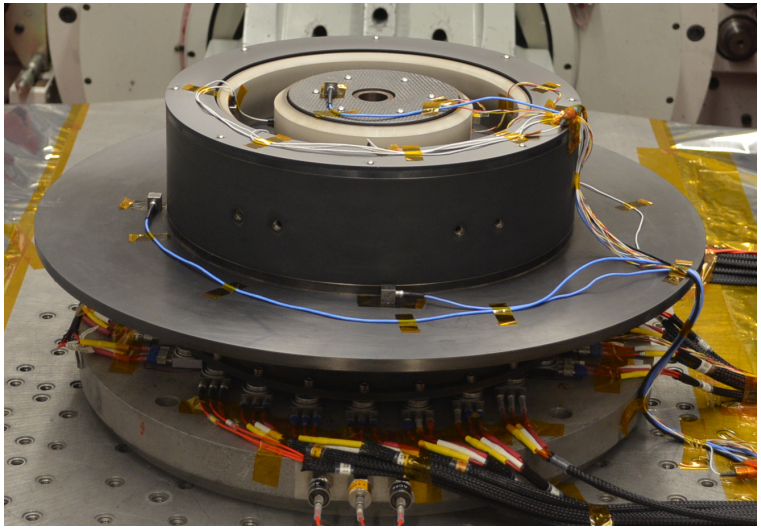
Overview

- Background
- Problem Statement
- Method
  - *Finite Element Model Updates*
  - *Analytical Response Limit Derivation*
- TDU-2 Environmental Testing
- Results
- Summary

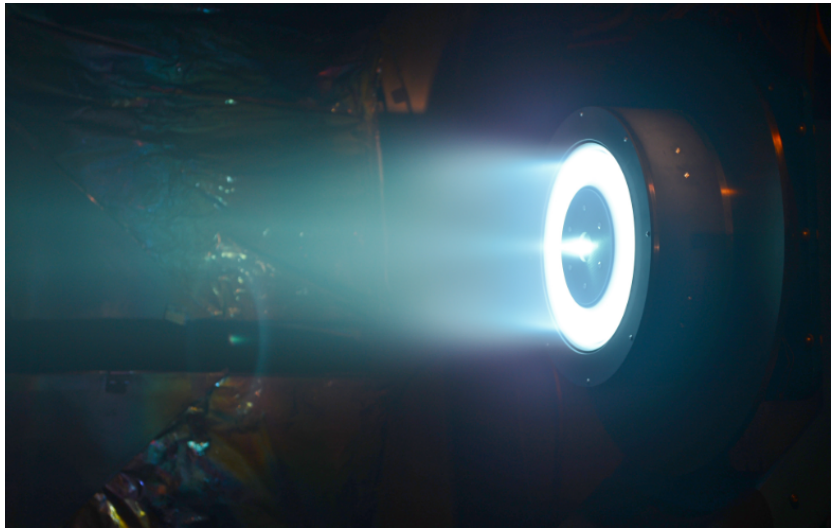
Background

HERMeS TDU-2 Hall Thruster

- The Hall Effect Rocket with Magnetic Shielding (HERMeS) is a 12.5 kW magnetically shielded Hall thruster currently under development for deep-space missions
- Technology Development Unit-2 (TDU-2) underwent environmental testing in both 2016 & 2017



TDU-2 (2017) on shaker



TDU-2 (2016) functional test

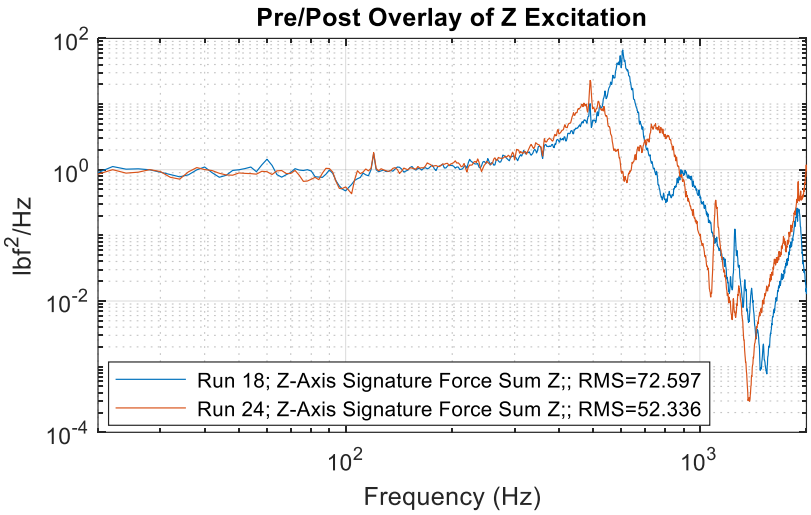
Background

2016 Random Vibration Test

- In July 2016 the HERMeS thruster underwent RV testing at JPL Environmental Test Lab (ETL)
- TDU-2 did not successfully survive vibration testing
  - *Particulate emission from thruster during -6 dB and higher runs*
  - *Significant shifts of structural modes seen in all three excitation axes*
  - *Post vibration magnetic mapping of coils showed significant differences*

Qualification Level Random Vibration Spectrum

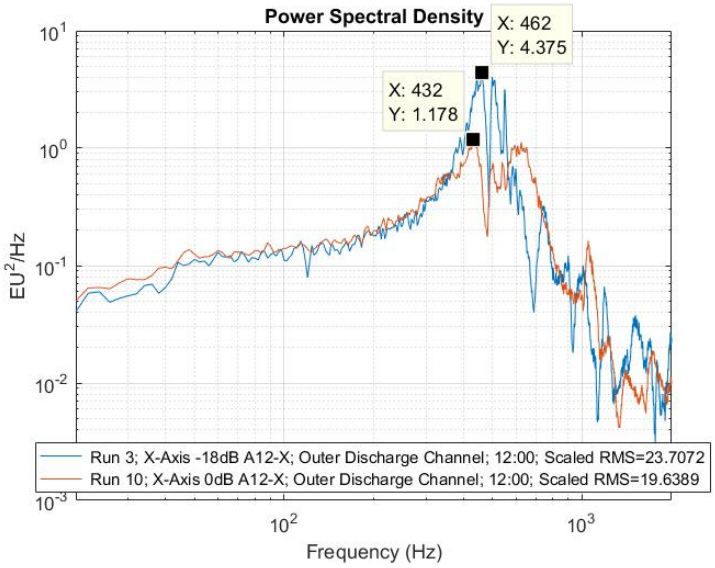
Frequency (Hz)	PF/Qual Level (G^2/Hz)
20	0.052
50	0.13
600	0.13
2000	0.012
Overall	11.4 GRMS
Duration	120 Seconds

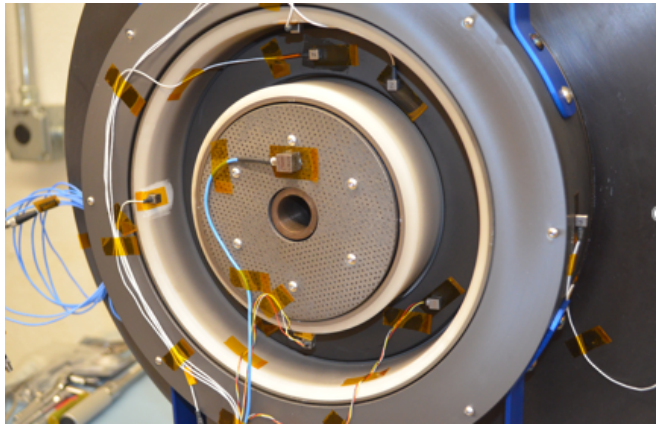


Background

TDU-2 Discharge Channel

- The TDU-2 discharge channel was the component of most concern going into dynamic testing
- No damage to the ceramic discharge channel was found following the test
- Excessive damping was observed in test due to structural failures and discharge channel did not see qualification levels





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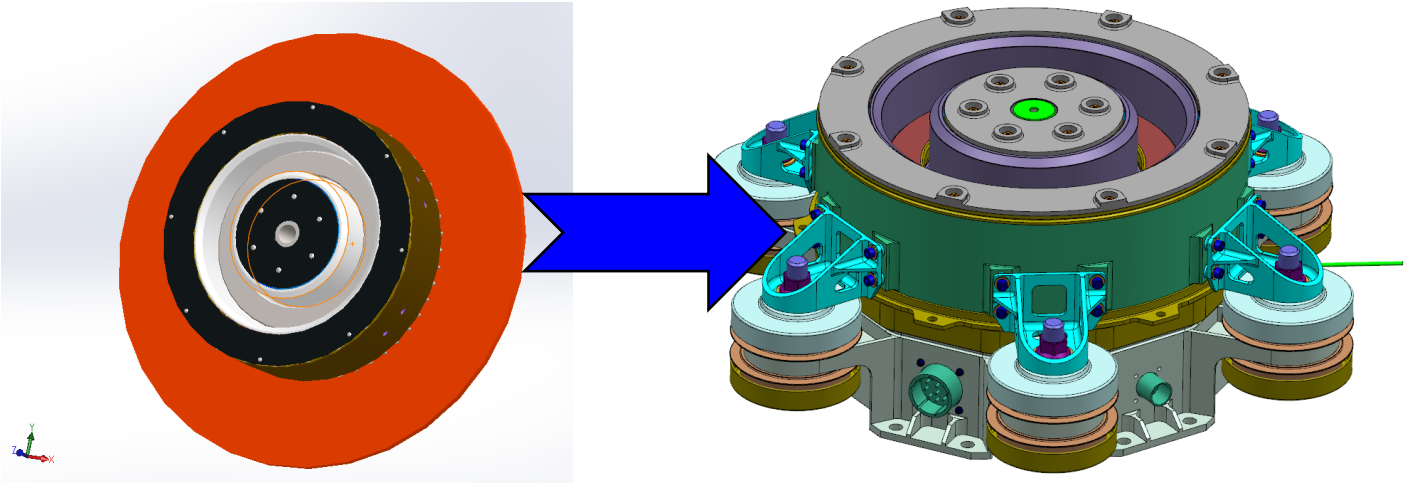
Problem Statement

- TDU-2 underwent several design changes including the addition of a shock isolation system



- **Problem Statement: Design and execute a test to expose discharge channel to predicted isolated qualification random vibration levels using TDU-2 hardware with no isolators**

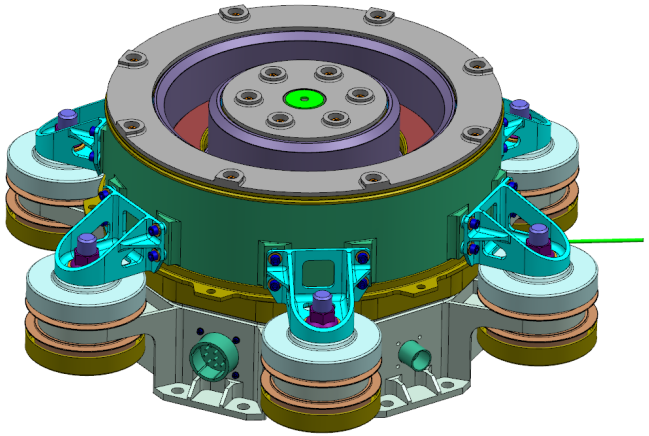
Method

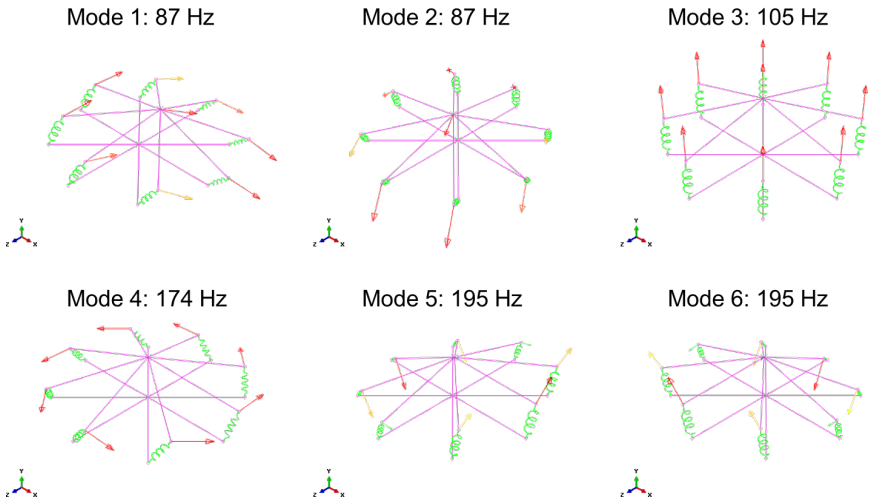
- Update TDU-2 FEM to include notional isolation system
- Perform force limited Qual RV analysis of isolated TDU-2 FEM
- Use original & isolated TDU-2 analysis results to develop response limit at accelerometer locations between spool mount and thruster
- Develop margin predictions and not to exceed limits for RV test
- Perform RV test
- Evaluate success of test and testing methodology

Update TDU-2 FEM

Isolation System

- The isolation system consists of 6 spring dampers between the thruster mounting ring and the thruster stackup
- An Abaqus mass-spring model was used to predict fundamental modes of the isolation system
- This simplified model was provided to JPL to use for FEM updates





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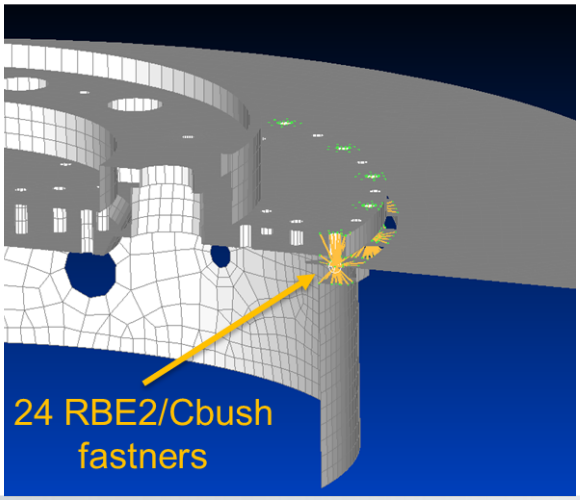
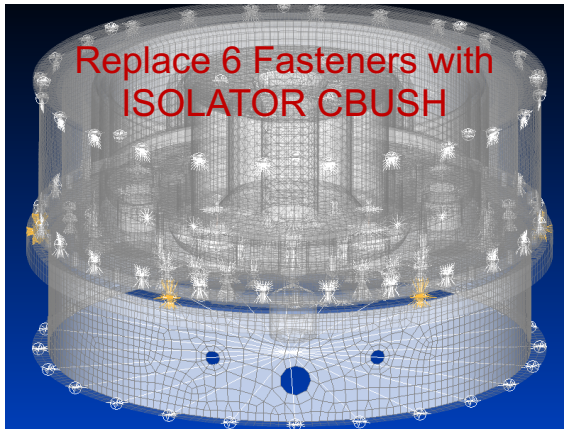
Update TDU-2 FEM

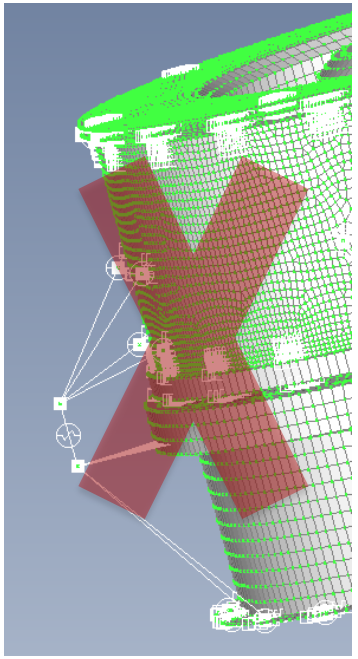
- The TDU-2 FEM attaches the mounting ring to the radiator and the radiator to the thruster backplate at 24 locations – Remove all
- Remove Radiator
- Create 6 Isolator CBUSH elements
  - *Looked at two methods of implementing CBUSH*
  - *Simplest method worked best*

TDU-2 FEM





Create offset isolator using rbe2 and cbush elements



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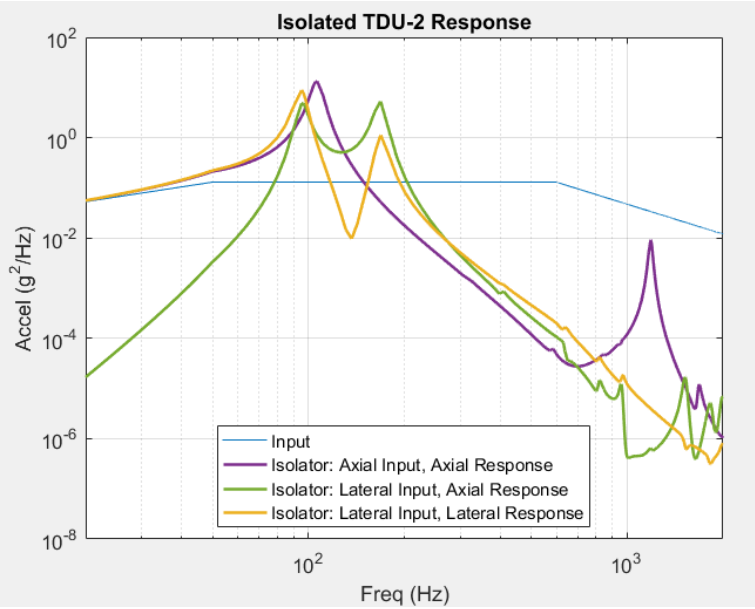
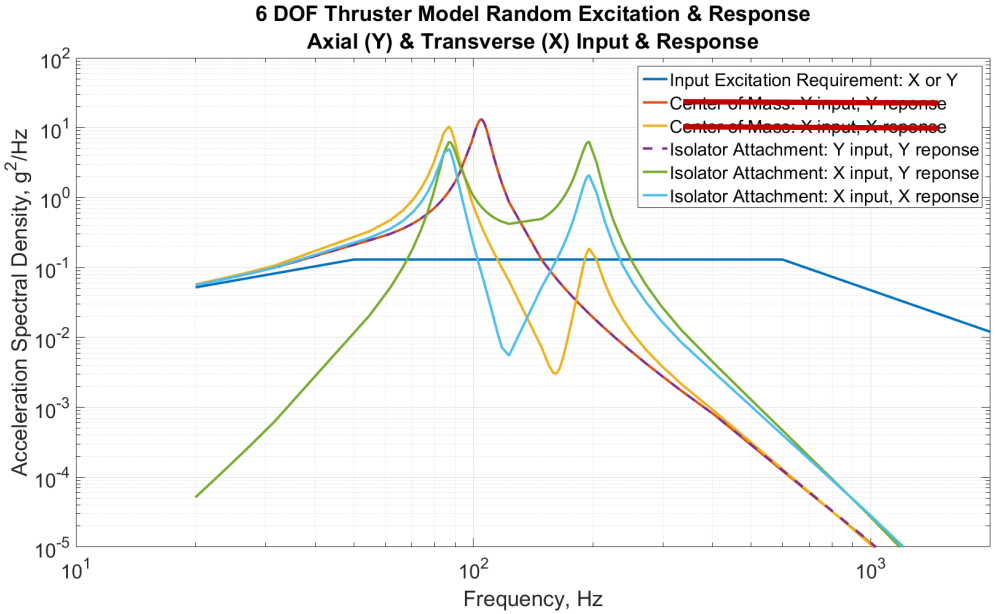
Update TDU-2 FEM

Probably Remove

- Responses from simpler isolation FEM and provided CBUSH stiffness and damping are similar to provided rigid body response





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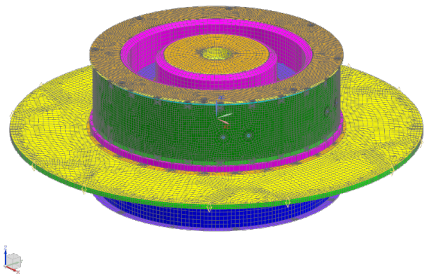
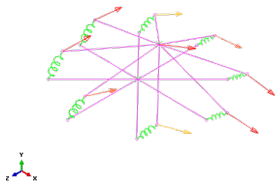
Perform RV Analysis

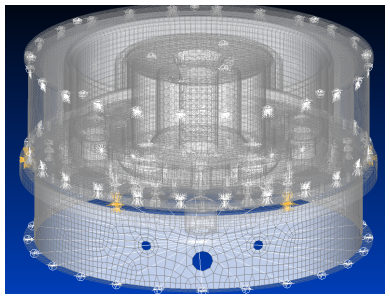
Interface Force Comparison

Original FEM



Isolated FEM





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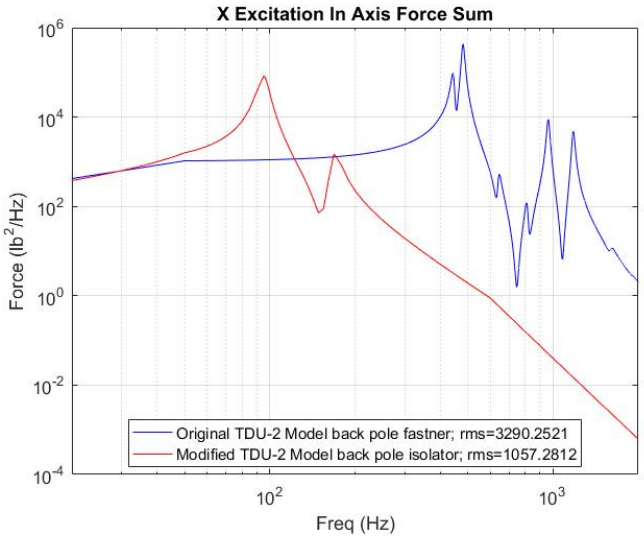

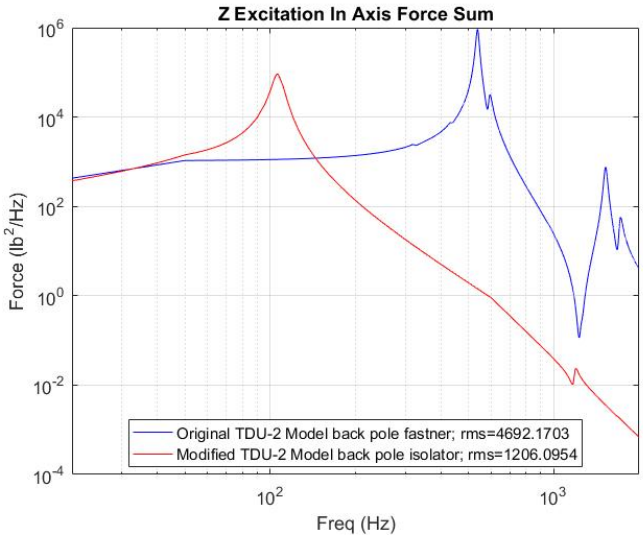

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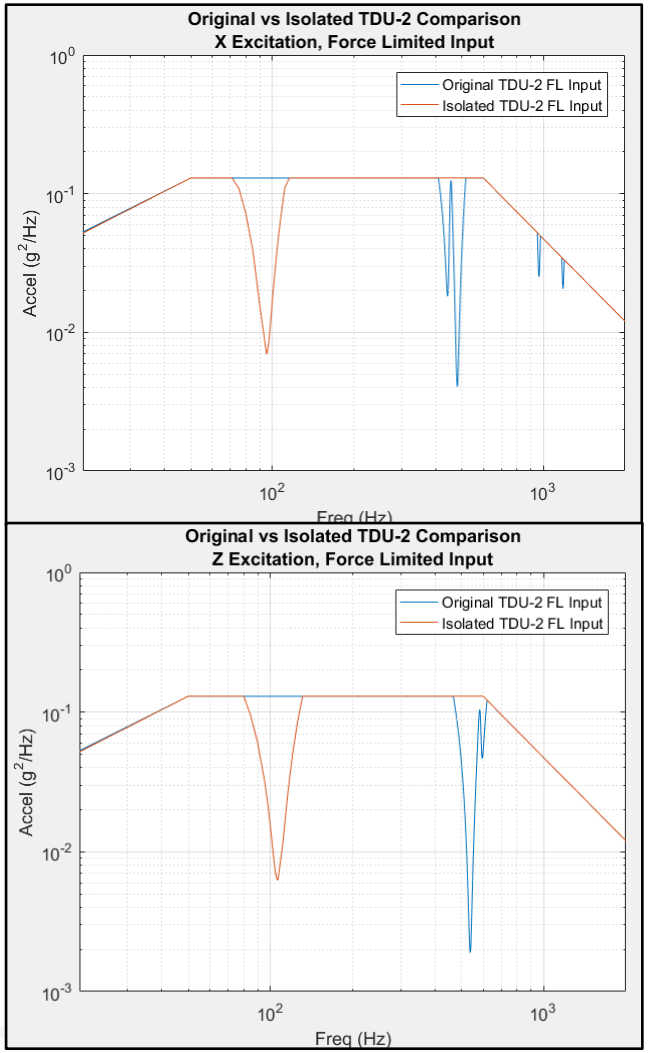
Perform RV Analysis

Force Limiting

- Apply force limiting to all accelerometers
- Use nodes at corresponding accelerometer locations to find isolated thruster predictions

Accel #	Location	Node #
1	Radiator Top +Y	124086
2	Radiator Top -X	139155
3	Front Pole Cover	30845
4	Outer Core +X	222468
5	Anode +Y	186532
6	Anode -X	187117
7	Anode +X	186994
8	Anode Middle	186725
9	Propellant isolator bracket	N/A
10	Cathode Mount Flange	280278
11	Radiator Bot -X	134407
12	Outer Discharge Channel +Y	151684
13	Outer Discharge Channel -X	157922
14	Inner Discharge Channel -Y	153347



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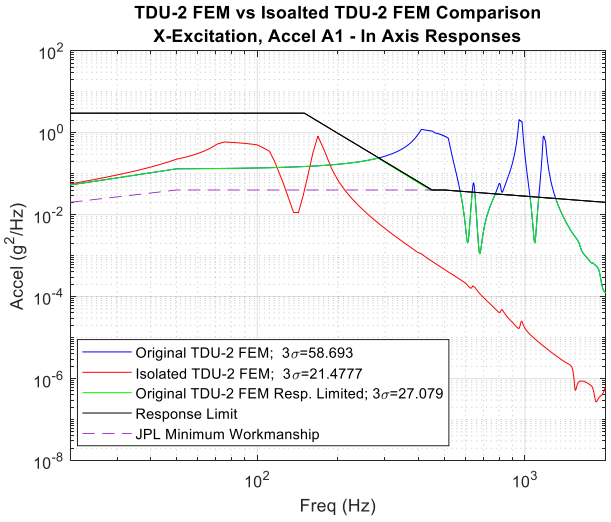
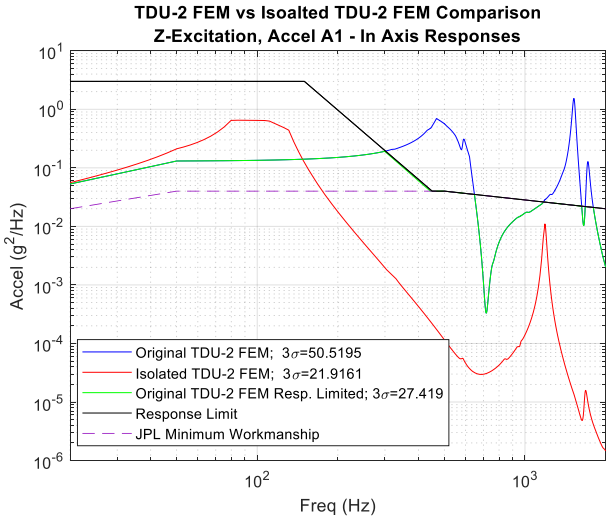
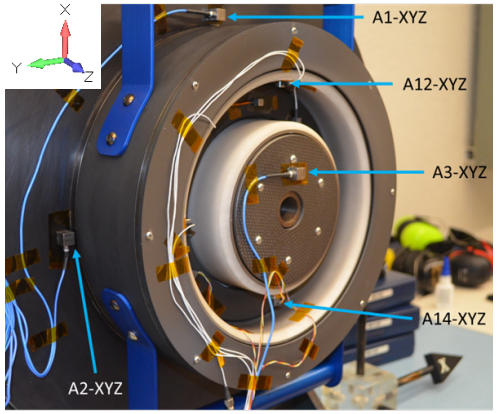
Perform RV Analysis

Develop Response Limit

- FEM nodes near A1 & A2 were used to develop the response limit that will be used to implement the potential isolation system
- The response limit envelopes the TDU-2 Isolated FEM response and JPL minimum workmanship







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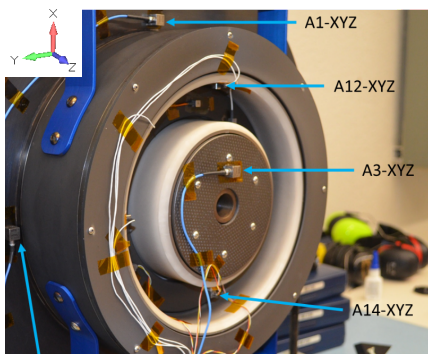
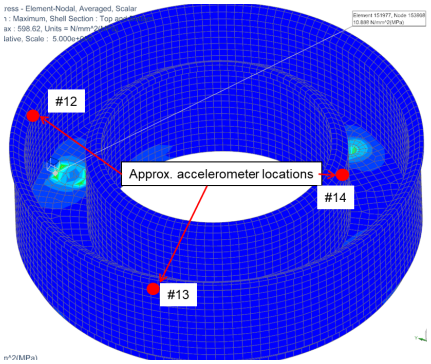
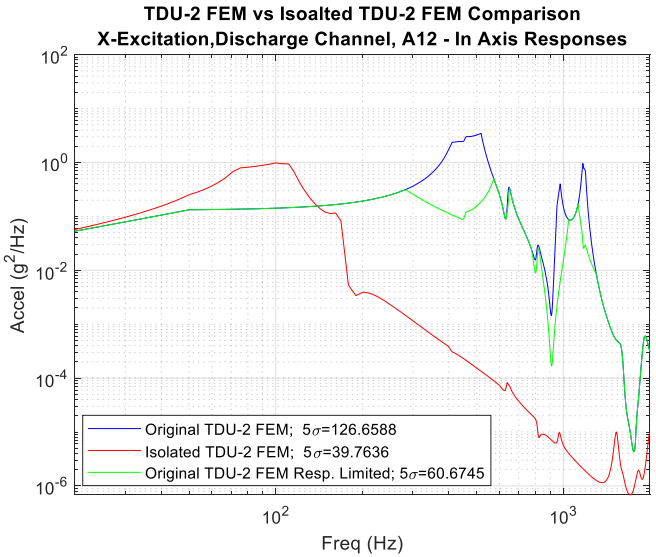
Perform RV Analysis

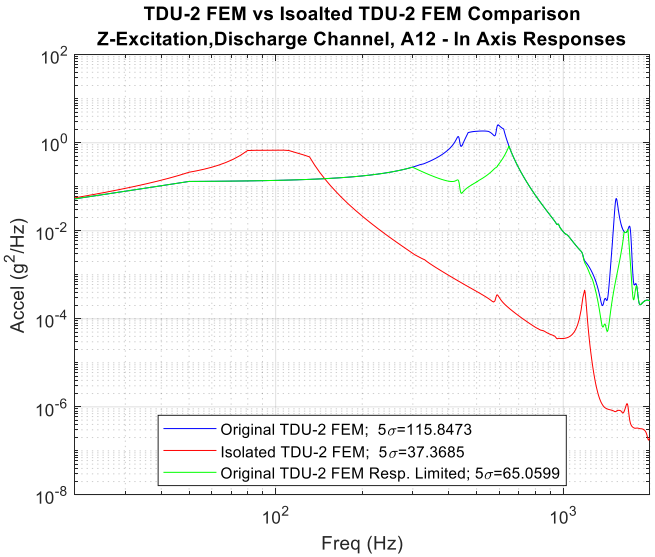
Ceramic Channel Response

- Accels on tip of ceramic channel used to monitor peak stresses at base of ceramic
- Predicted Responses are well below NTE limits from 2016 test









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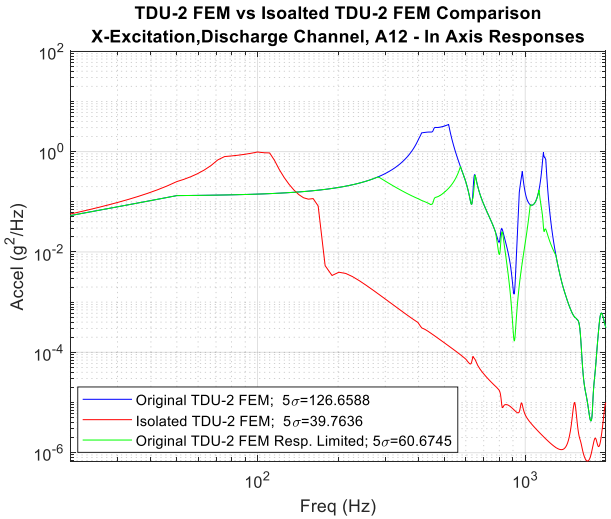
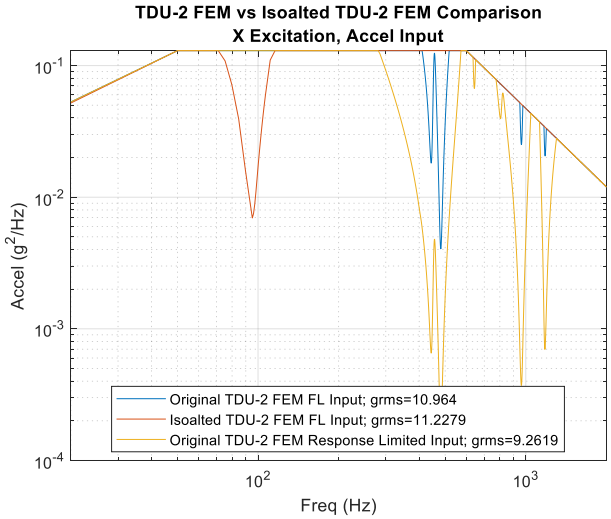
Perform RV Analysis

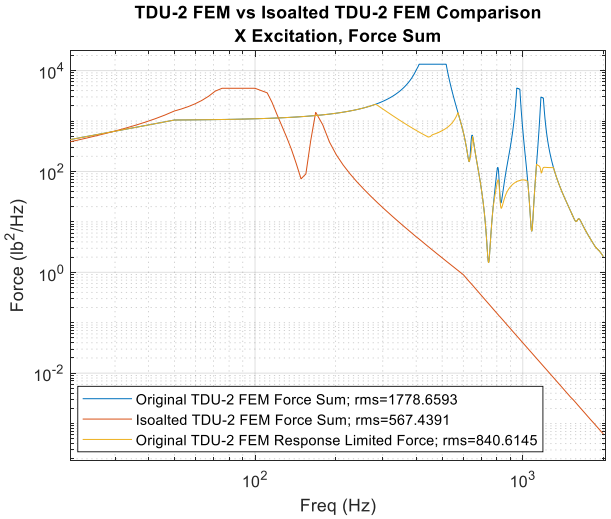
Lateral Excitation Predictions

Lateral Excitation:

FEM Model	Base Force (lb)	Ceramic Accel (5σ)
2016 TDU FEM w/ FL	1779	126
2017 TDU FEM w/ FL	567	39.8
2017 TDU FEMw/ Resp Lim & Min Workmanship @ Spool Mount	840	60.7







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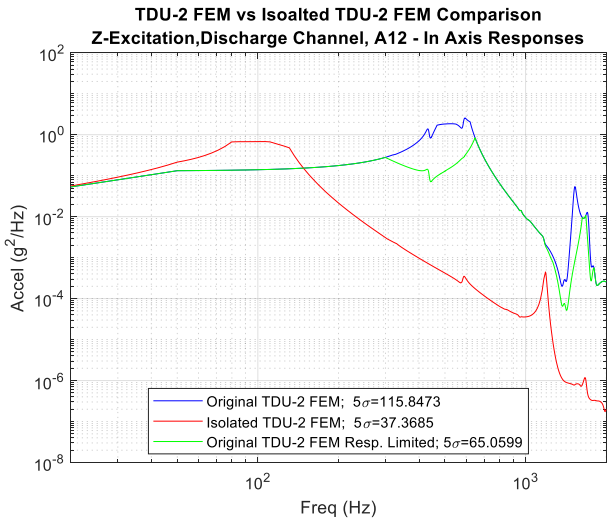
Perform RV Analysis

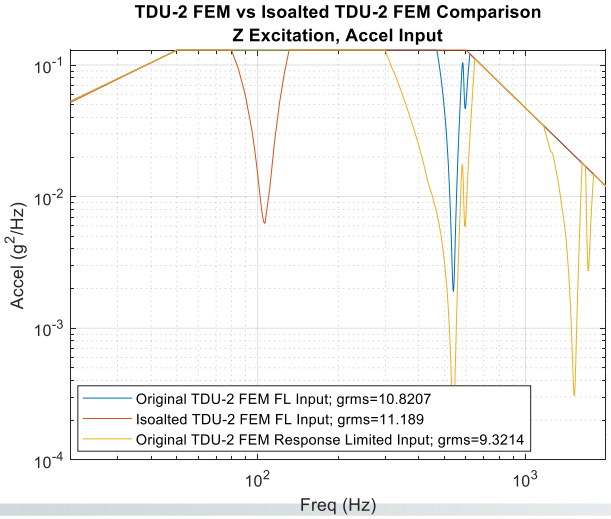
Axial Excitation Predictions

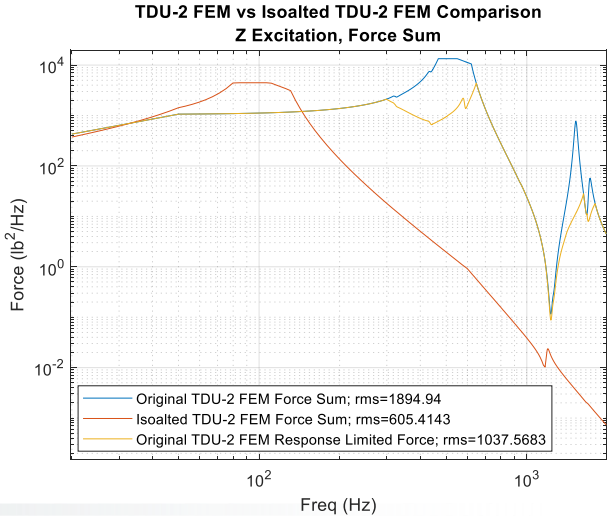
Axial Excitation:

FEM Model	Base Force (lb)	Ceramic Accel (5σ)
2016 TDU FEM w/ FL	1895	115.8
2017 TDU FEM w/ FL	605	37.4
2017 TDU FEMw/ Resp Lim & Min Workmanship @ Spool Mount	1037	65.1

Minimum Ceramic Chamber Stress Margin per 5σ Stress Results			
Worst Case direction is Z	Flexural Strength (Mpa)	Min. Margin	Note
2016 TDU w/ Resp Limit - Prediction	34	1.25	Will Not Slip







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Perform RV Test

Test Levels, Configuration, and Instrumentation

Qual Level Input

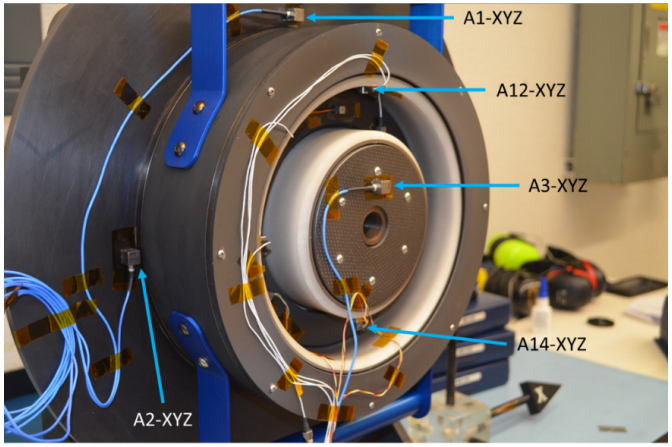
Frequency (Hz)	Qual Level (g^2/Hz)
20	0.052
50	0.13
600	0.13
2000	0.012
Overall	11.4 GRMS
Duration	120 Seconds

Response Limit applied at A1 & A2

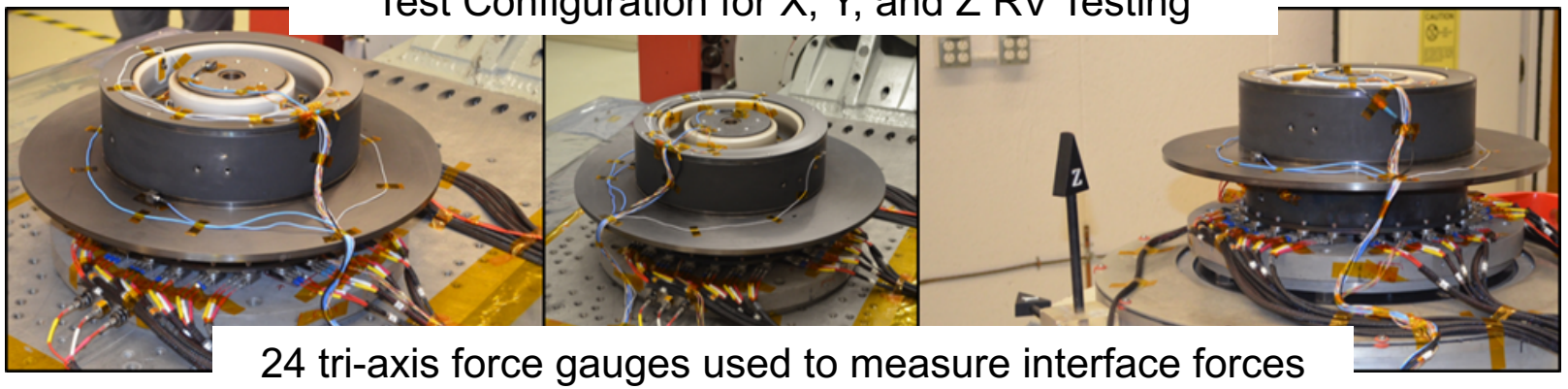
Frequency (Hz)	Response Limit (g^2/Hz)
20	3
150	3
450	0.04
500	0.04
2000	0.012

Maximum Ceramic Chamber Acceleration in Axis - 5σ (g's)			
	2016 TDU - Prediction	2016 RV Test	2016 TDU w/ Resp Limit - Prediction
X- Excitation	126	98	61
Y- Excitation	126	92	61
Z- Excitation	116	148	65

14 tri-axis accelerometers



Test Configuration for X, Y, and Z RV Testing



24 tri-axis force gauges used to measure interface forces

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Perform RV Test

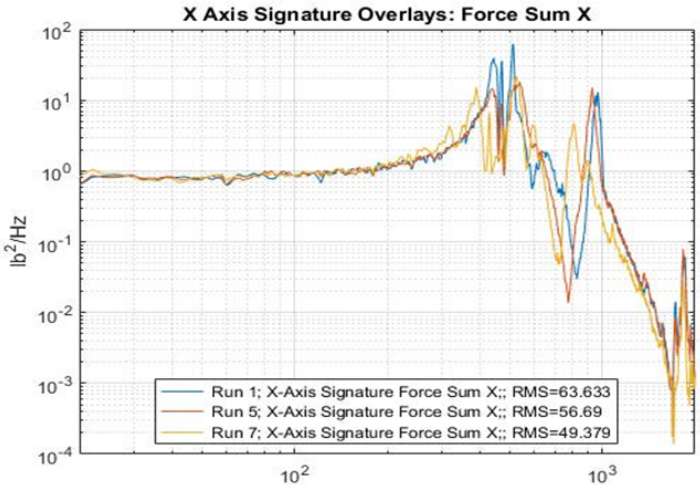
Test Flow

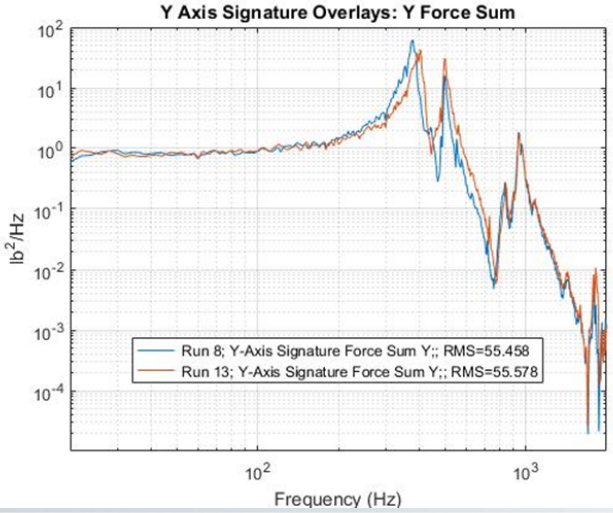
- Performed low level pre signature at the start of each axis
- Performed low level tests w/ response limiting (-18, -12, and -6 dB)
  - *All axes showed some mode shape shifts during -6 dB*
  - *Move forward with tests as it is much less than 2016 test and ceramic accelerometers are below capability predictions*
- Performed full level tests
  - *X & Y tests completed with no visual damage to thruster or discharge channel detected*
  - *Z test (Done in two segments due to shaker abort)*
    - White particulate emitted from inner/outer core for first time this test series
    - No damage to discharge channel detected after visual inspection
- Performed low level post test signature

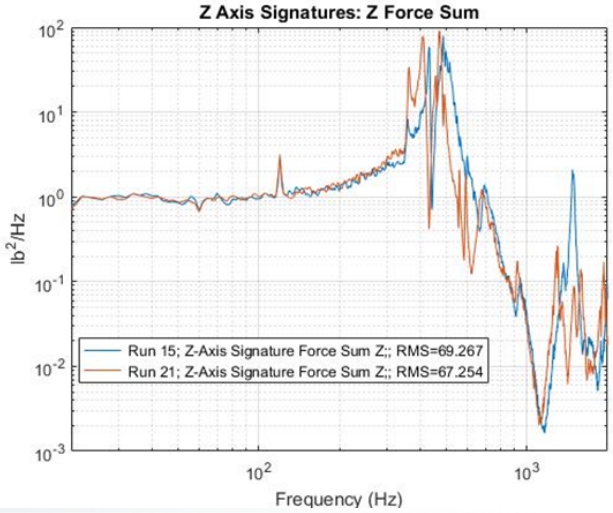
RV Test Results

Pre/Post Signatures

- Modal peaks and shape shift for all three axes
- X axis signatures (first axis tested) shows largest deviation from pre and post







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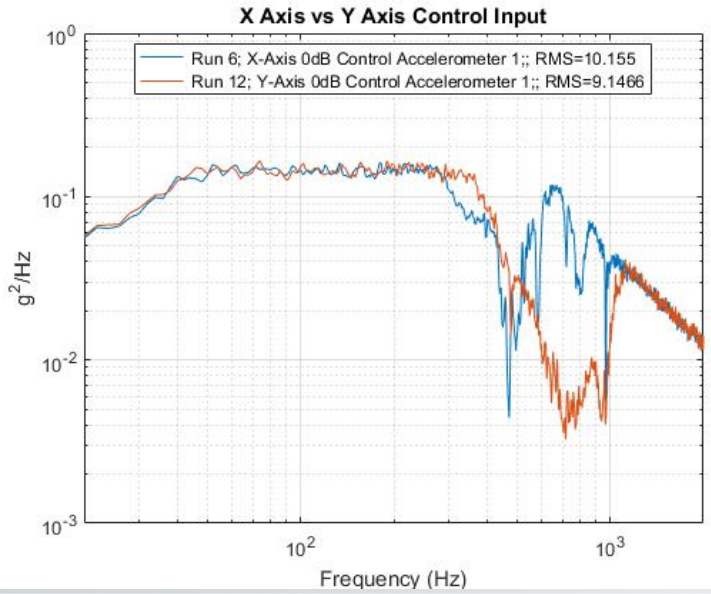
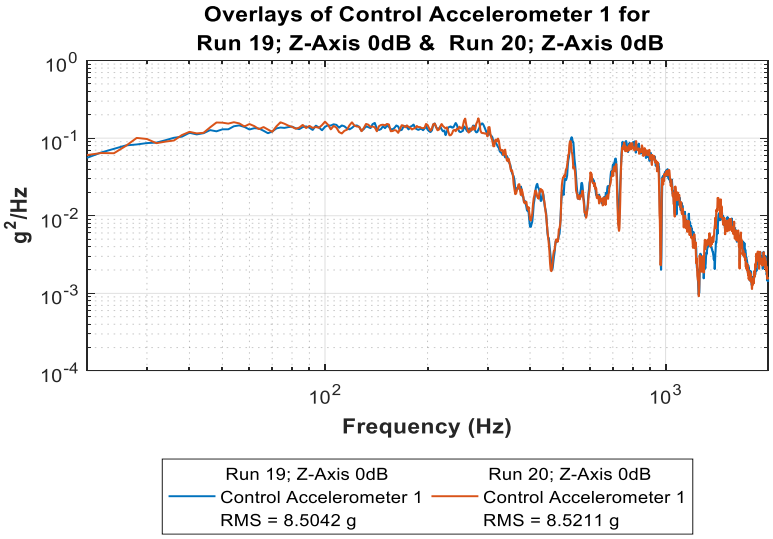
RV Test Results

Shaker Input & Discharge Channel Response

- Hardware damping in test was higher than analysis but max response of discharge channel accels within 10% for X & Z testing
- Y axis input was 10% lower than X axis
  - *Structural shifts caused change in notching*
  - *Y axis discharge channel response within 20% of prediction*

Maximum Ceramic Channel Acceleration in Axis - 5σ (g's)				
Axis	TDU Resp Limit Prediction	A12	A13	A14
X- Excitation	61	54	57	52
Y- Excitation	61	48.5	45.5	46.5
Z- Excitation	65	57.75	59.75	62.85





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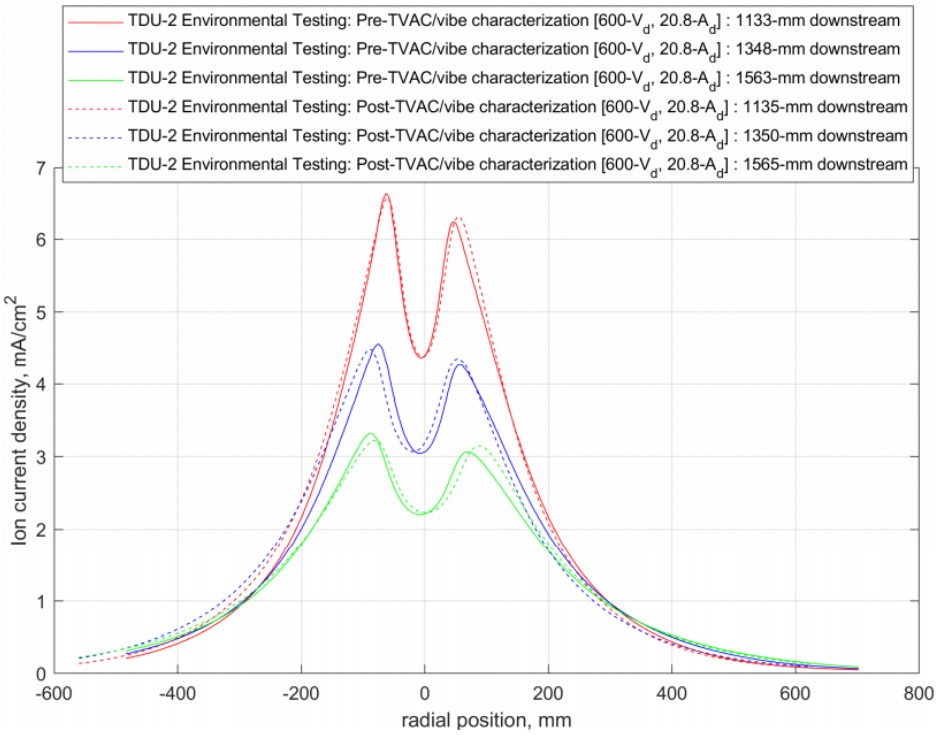
Environmental Testing

Post RV Tests

- Following RV testing the thruster underwent magnetic mapping and all post RV measurements were within tolerances of pre test measurements
- The thruster then underwent functional testing in TVAC
- Following successful TVAC the magnetic mapping was once again completed with no deviations measured



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Summary

- The goal for this test series was to expose the ceramic discharge channel to predicted qualification levels based on a future design featuring an isolation system
- The following approach was taken:
  - *TDU-2 FEM modified to derive isolated responses*
  - *TDU-2 underwent RV testing w/ response limits*
  - *Environmental testing was completed following RV testing*
- The test effort was successful
  - *Discharge channel accelerometers were within 10% of predicted qual levels*
  - *Structural changes occurred but overall performance of thruster was not impacted*
- No future work by JPL dynamics team is currently planned but it would be interesting to compare results from this effort to future test

Questions?