Coupled Dynamics of Payload Structures on the Seismically Isolated Optics Table

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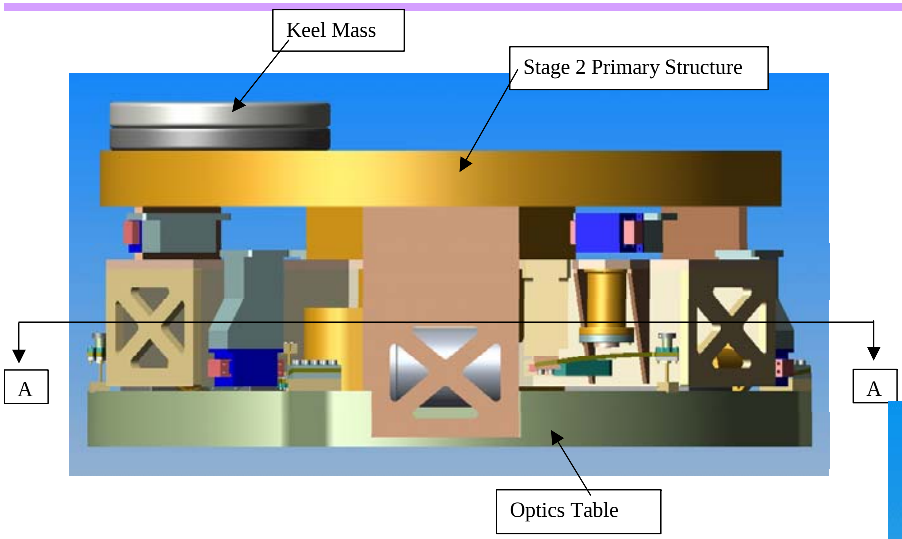
Seismic Isolation (SEI) System & Suspension System (SUS)

- Calculated perturbation to the SEI transfer functions due to the addition of the payload structures on the BSC optics table, e.g. quadruple SUS structure
  - Gain & phase variations must not destabilize the active SEI controls
  - Should not unduly increase in the control law complexity (decrease robustness)
  - Current planned upper unity gain frequency for the SEI system is about 60 Hz.
- The stiffness requirements of the seismic isolation inner stage structure are essentially that:
  - the phase lag is less than 90 degrees below 150 Hz for the transfer function from each actuator (force) to each non-collocated sensor (displacement), and
  - the phase lag is less than 90 degrees below 500 Hz for the transfer function from each actuator (force) to each collocated sensor (displacement)
- Wanted SUS quad structure 1st resonance > 150 Hz (for attachment to a perfectly stiff interface)
  - found impossible to meet, within the mass and envelope allocations
- Current SUS working baseline goal is as follows:
  - SUS design has provision to un-couple the lower structure from the upper structure & support the lower structure from the support tubes of the chamber
  - > 200 Hz 1st resonance for the upper quad SUS structure
  - > 100 Hz 1st resonance for lower quad SUS structure
  - > 100 Hz 1st resonance for combined upper and lower quad SUS structure

Sensor & Actuator Locations



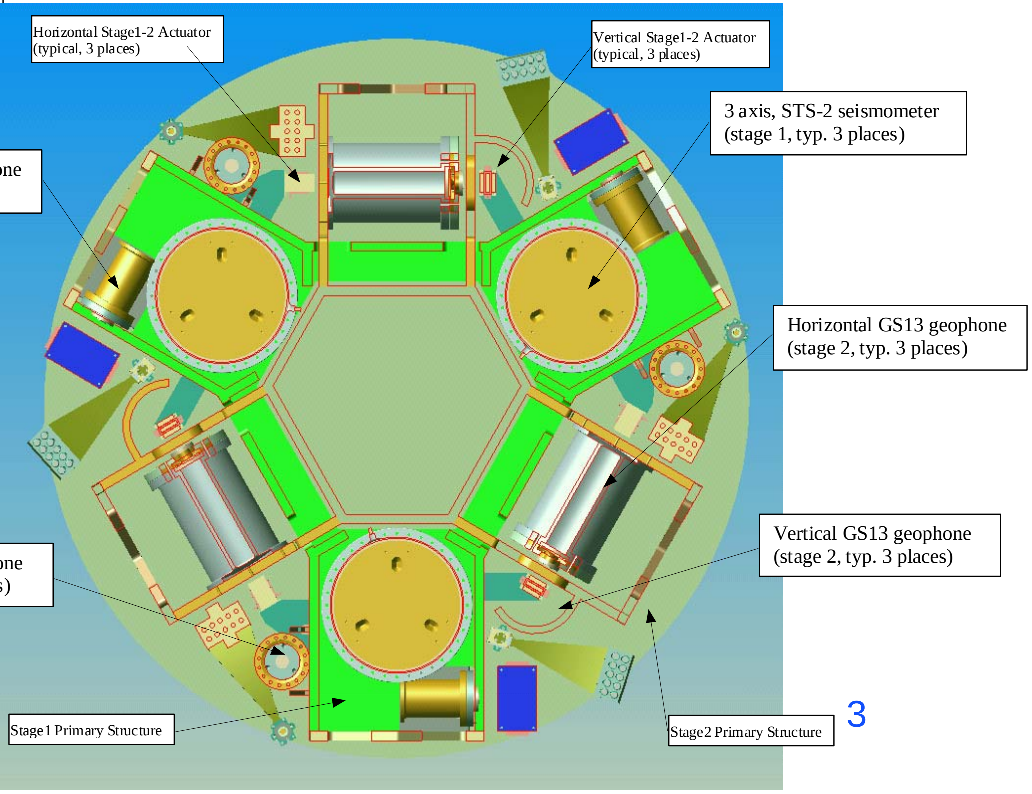
Keel Mass

Stage 2 Primary Structure

Optics Table

A

A



Horizontal Stage1-2 Actuator
(typical, 3 places)

Vertical Stage1-2 Actuator
(typical, 3 places)

3 axis, STS-2 seismometer
(stage 1, typ. 3 places)

Horizontal L4C geophone
(stage 1, typ. 3 places)

Horizontal GS13 geophone
(stage 2, typ. 3 places)

Vertical GS13 geophone
(stage 2, typ. 3 places)

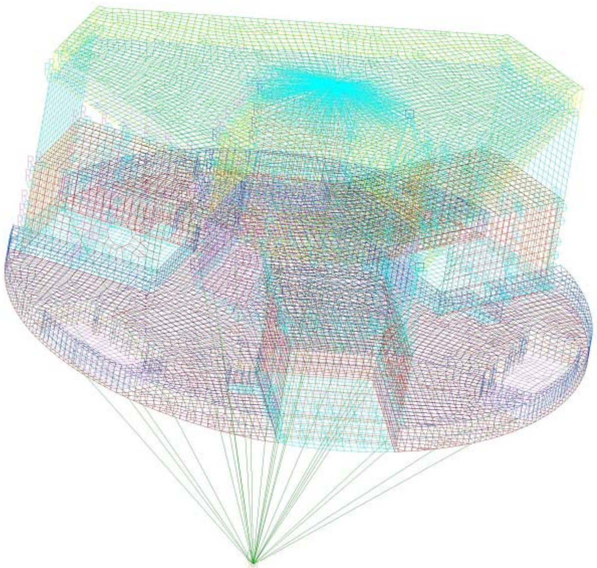
Vertical L4C geophone
(stage 1, typ 3 places)

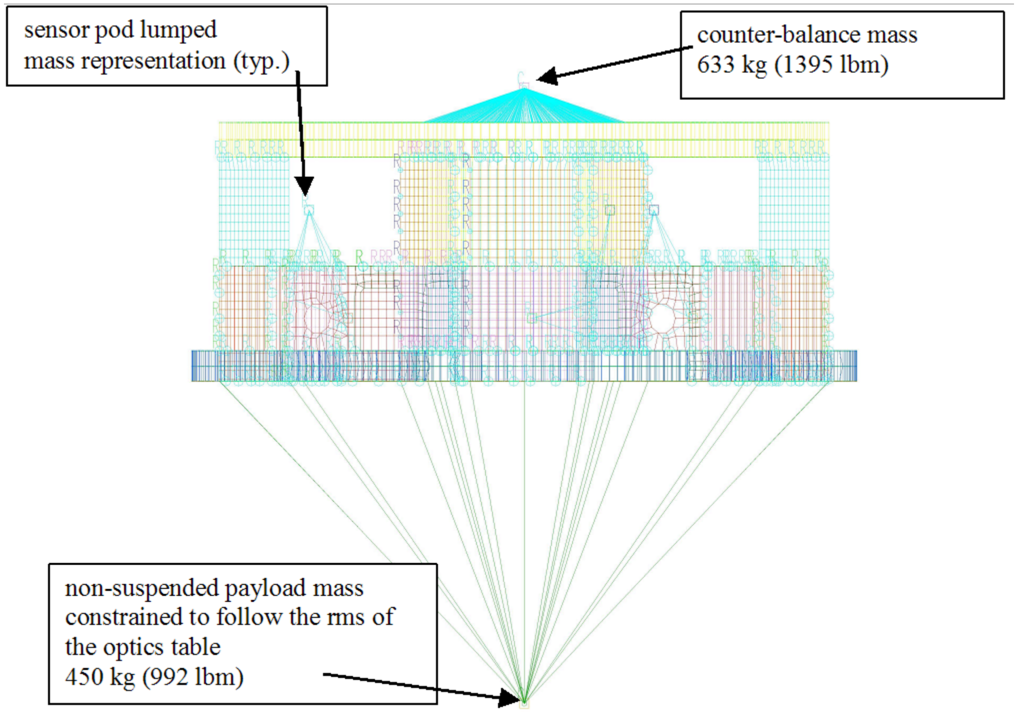
Stage1 Primary Structure

Stage2 Primary Structure

ASI FEA Model

- ☐ Considers payload total mass and center-of-mass position, but not flexibility of the payload (i.e. quad structure
- ☐ The total stage2 mass is 14.48 lbf-s2/inch (slinch) or 5591 lbm or 2536 kg
  - ➢ payload mass of 450 kg
  - ➢ "keel" ballast of 633 kg
  - ➢ stage2 structure mass of 1454 kg
- ☐ Used this Stage2 FEM for coupled dynamics analysis with Quadruple Pendulum (non-suspended) Mass/structure



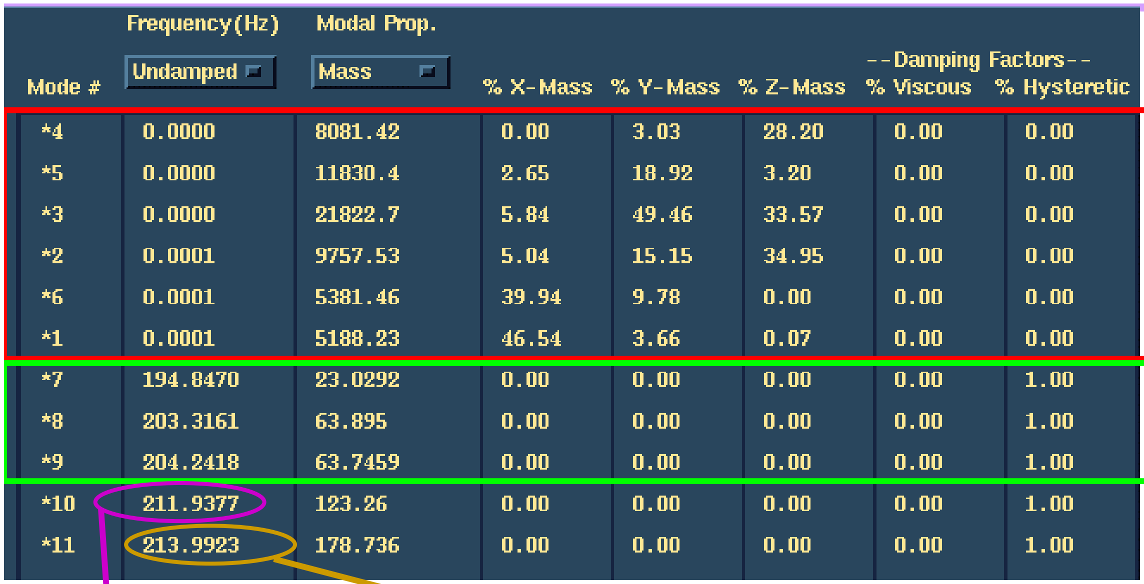


sensor pod lumped mass representation (typ.)

counter-balance mass 633 kg (1395 lbm)

non-suspended payload mass constrained to follow the rms of the optics table 450 kg (992 lbm)

Stage 2 Modes
with Rigid Body Payload

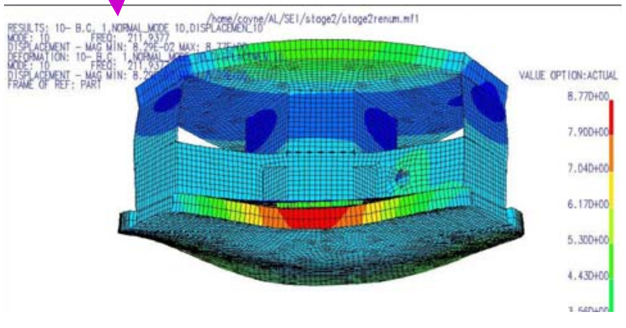


Mode #	Frequency(Hz) Undamped	Modal Prop. Mass	% X-Mass	% Y-Mass	% Z-Mass	--Damping Factors-- % Viscous	% Hysteretic
*4	0.0000	8081.42	0.00	3.03	28.20	0.00	0.00
*5	0.0000	11830.4	2.65	18.92	3.20	0.00	0.00
*3	0.0000	21822.7	5.84	49.46	33.57	0.00	0.00
*2	0.0001	9757.53	5.04	15.15	34.95	0.00	0.00
*6	0.0001	5381.46	39.94	9.78	0.00	0.00	0.00
*1	0.0001	5188.23	46.54	3.66	0.07	0.00	0.00
*7	194.8470	23.0292	0.00	0.00	0.00	0.00	1.00
*8	203.3161	63.895	0.00	0.00	0.00	0.00	1.00
*9	204.2418	63.7459	0.00	0.00	0.00	0.00	1.00
*10	211.9377	123.26	0.00	0.00	0.00	0.00	1.00
*11	213.9923	178.736	0.00	0.00	0.00	0.00	1.00

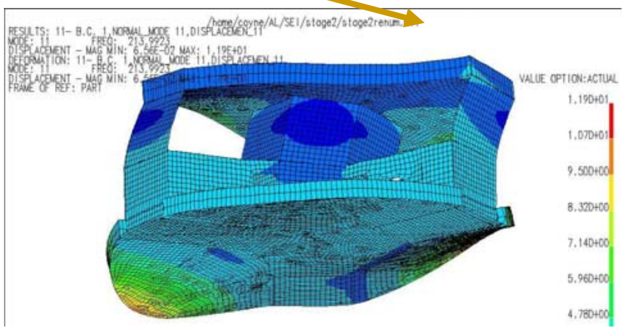
Rigid Body Modes
(flexures not modeled)

Seismometer/mount modes

Large Scale Elastic Modes



```
/home/coyne/AL/SEI/stage2/stage2renum.mf1
RESULTS: 10- B.C. 1,NORMAL_MODE 10,DISPLACEMEN_10
MODE: 10          FREQ:  211.9377
DISPLACEMENT - MAG MIN: 8.29E-02 MAX: 8.77E+00
DEFORMATION: 10- B.C. 1,NORMAL_MO
MODE: 10          FREQ:  211.937
DISPLACEMENT - MAG MIN: 8.2
FRAME OF REF: PART
```



```
/home/coyne/AL/SEI/stage2/stage2renum.
RESULTS: 11- B.C. 1,NORMAL_MODE 11,DISPLACEMEN_11
MODE: 11          FREQ:  213.9923
DISPLACEMENT - MAG MIN: 6.56E-02 MAX: 1.19E+01
DEFORMATION: 11- B.C. 1,NORMAL_MODE 11,DISPLACEMEN_11
MODE: 11          FREQ:  213.9923
DISPLACEMENT - MAG MIN: 6.
FRAME OF REF: PART
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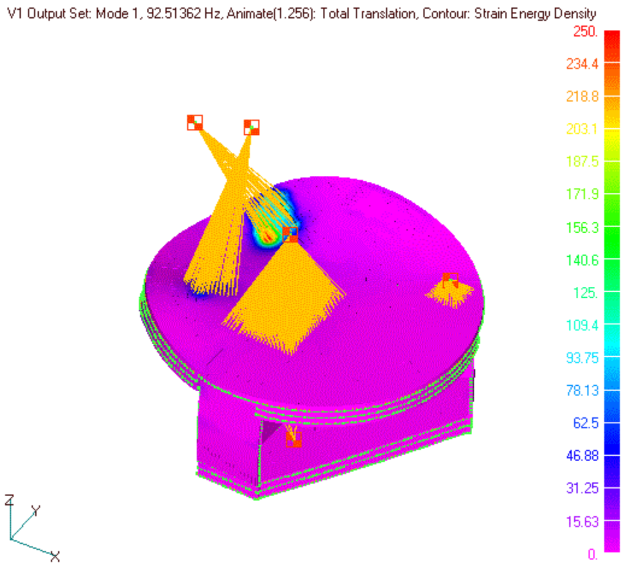
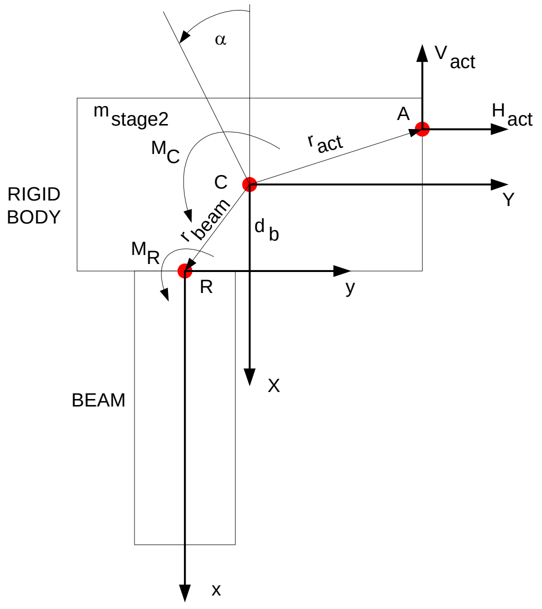
Revised & Final ASI FEA Results

- In the final FEA model prepared by ASI:
  - discrete point masses represent payload elements at their expected center of mass and constrained to follow the rms of the optics table nodes within the payload’s footprint
  - Smaller payload elements with less definition, such as the pickoff mirror structures were typicaly represented as a single composite mass, constrained to follow the optics table
  - First "global" elastic mode occurs at 174 Hz
  - A lowest "payload lateral" mode of 153 Hz is predicted
- ASI modeling indicated that lighter mass payload elements like the pickoff mirror structures (non-suspended mass = 51 kg) with small footprints (0.3 m x 0.2 m) and low centers of mass (1 m from the optics table) could have "low" frequency coupled modes (93 Hz), especially if the footprint was on an unsupported span near the table edge (see Figure)



Simple Beam and Rigid Mass Model

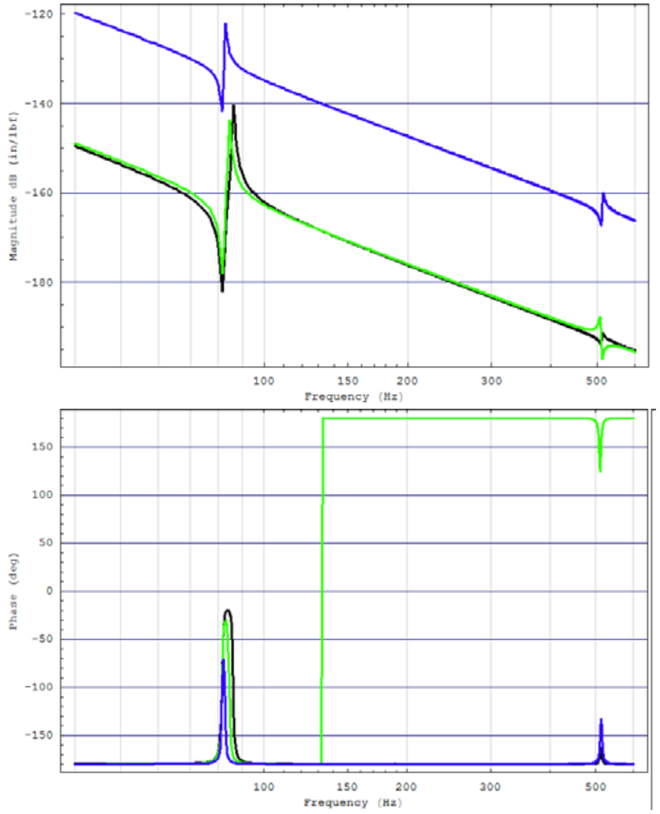
- Cantilevered uniform beam is a reasonable first order approximation to the quad suspension structure
- Simple beam connected to a rigid stage2 mass (Figure) is a reasonable approximation to the low frequency coupled dynamics of a suspension structure and the stage2 structure
  - the first elastic mode of the suspension structure is likely about 100 Hz
  - the first stage2 "global" structure elastic mode is ~174 Hz (including payload mass loading)
  - the suspension structure footprint is large relative to the optics table (and so should not couple to local table/structure compliance).



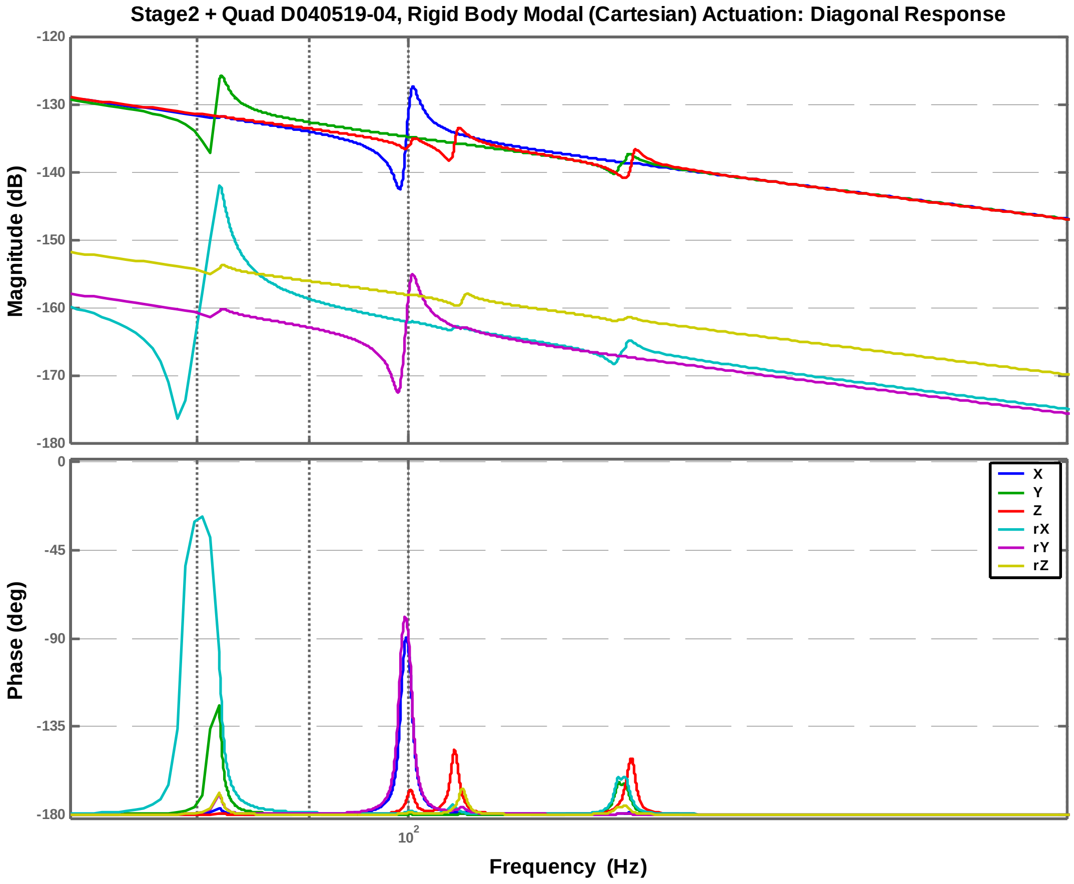
Beam/Mass and FEM Comparison

- ❑ Semi-quantitative agreement between simple model and detailed FEM

Beam + Rigid Body Model

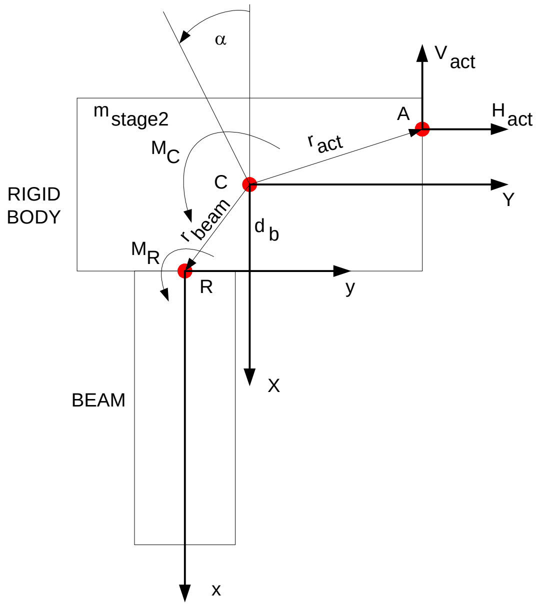


Finite Element Model



Effect of Cantilevered Beam

- ❑ Models predicts that 1st & 2nd bending modes each add a zero-pole pair (in that order) when the root of the beam is near the stage center of mass (i.e. when r_{beam} ~ 0 and 'R' is coincident near 'C' in Figure).
  - ➢ reduces phase lag
  - ➢ transfer functions are typical of the effect of a flexible appendage when the control is collocated

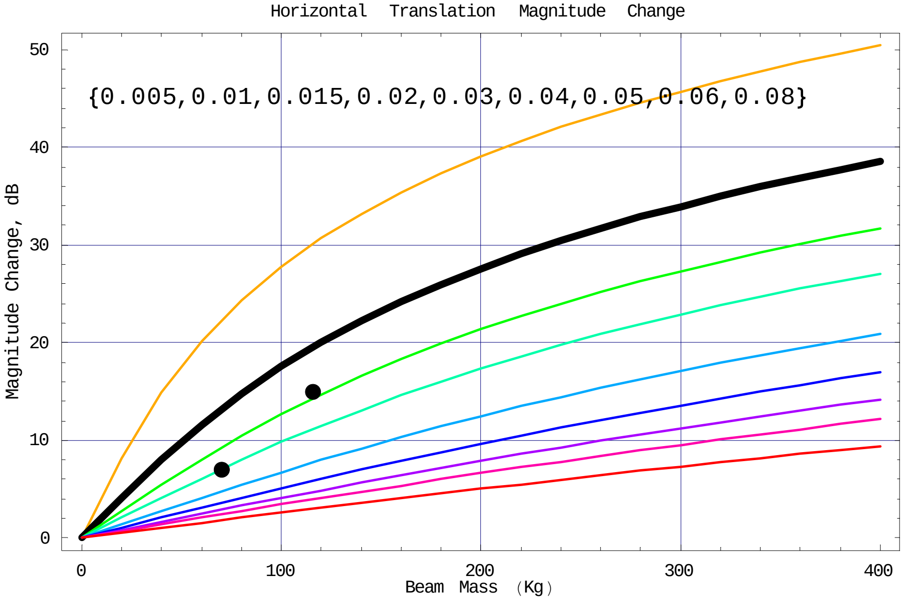


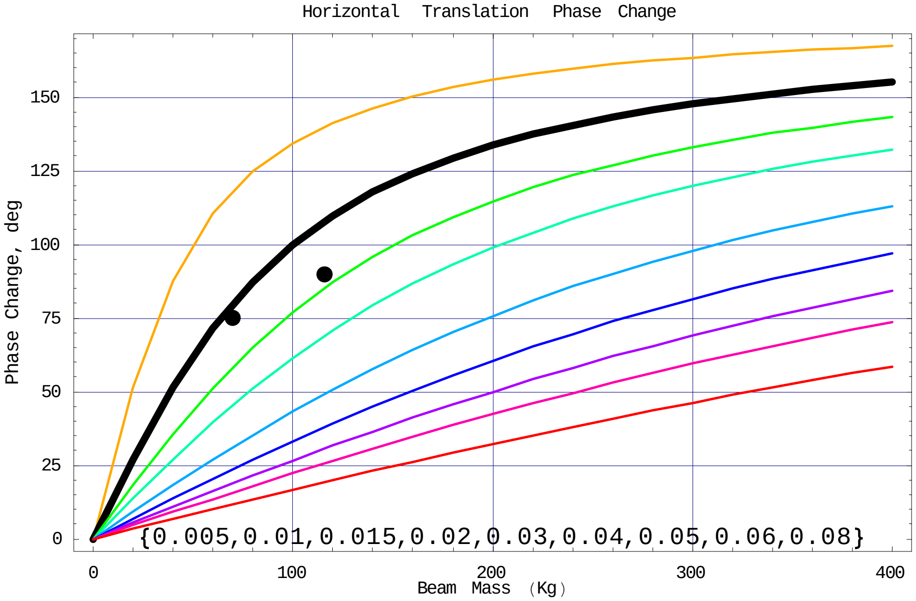
❑ When the beam root and center of mass are distant from each other (~5 times greater than the nominal distance of 0.2 m) then the order of the pair reverses to pole-zero for the 2nd beam mode with rotation actuation (around a horizontal axis through 'C') and phase lag is increased.

❑ Magnitude & phase perturbations are independent of frequency and, for fixed rigid mass properties, depend only on the beam mass and modal damping factor

Horizontal Translation:
Gain & Phase Changes versus Beam Mass
(with varying damping factor)

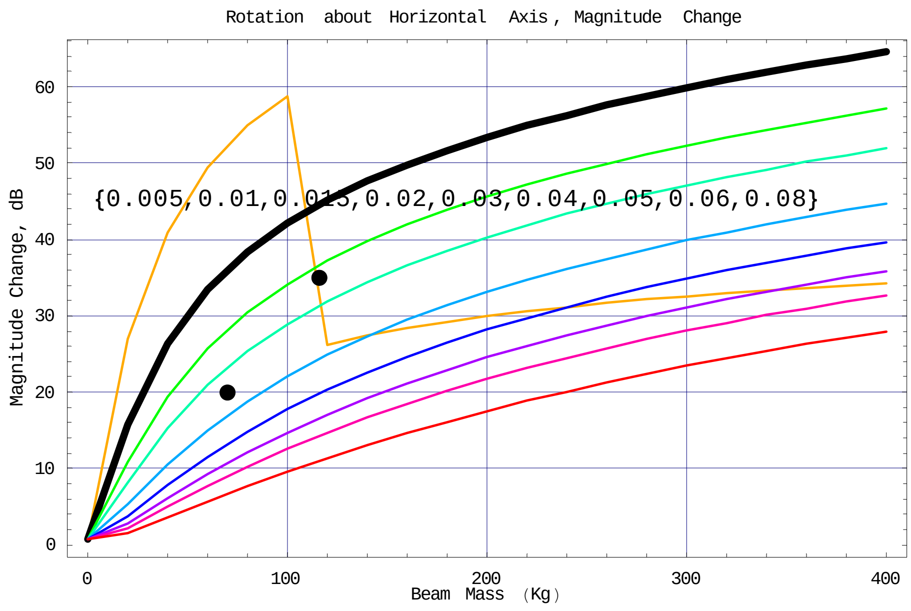
- ❑ Points are FEA results for 2 suspension structure designs with a damping factor of 0.01
- ❑ Curves are for damping factor varying from .5% to 8%. The bold black curve is for 1% damping.

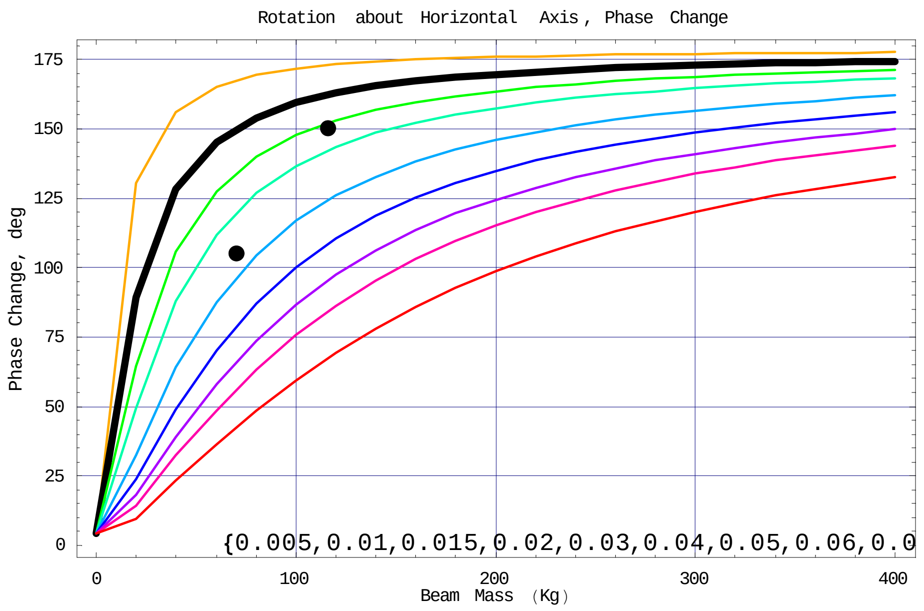




Rotation about a Horizontal Axis: Gain & Phase Changes versus Beam Mass (with varying damping factor)

- Points are FEA results for 2 suspension structure designs with a damping factor of 0.01
- Curves are for damping factor varying from .5% to 8%. The bold black curve is for 1% damping.
  - The 0.5% damping curve is incorrect (numerical problem with FindMinimum)

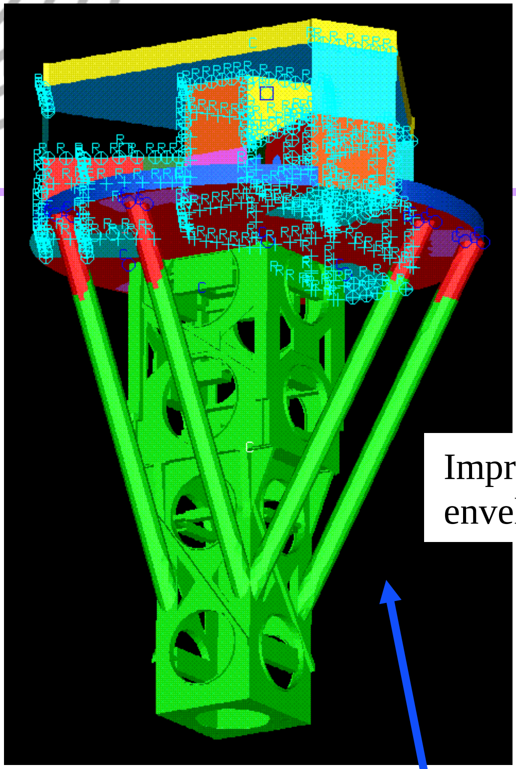




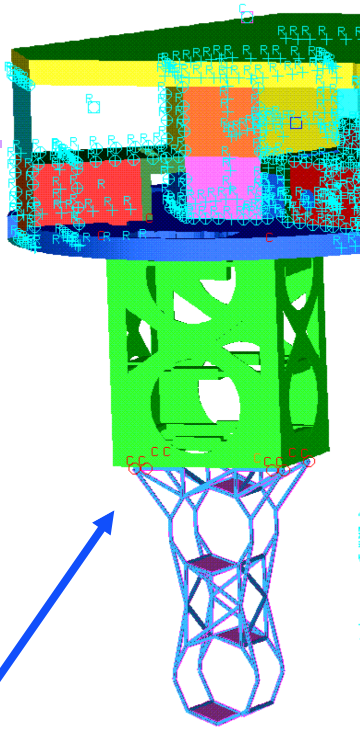
Practicalities

- Upper unity gain frequency of SEI stage 2 controls is ~ 60Hz, so would like payload 1st frequency > ~150 Hz
  - Without ‘exotic’ (non-UHV?) materials, this is impractical for a 2 m x [0.5 m x 0.7 m] footprint cantilevered structure within the structure mass budget of 70 kg and non-suspended, non-structural mass of 70 kg
  - Truss frames (e.g. quadx33) that violate the “shrink wrap” footprint can achieve > 150 Hz (likely at higher mass than current budget)
- Alternatively make structure light &/or heavily damped and let 1st frequency be low
  - For small perturbations (say <~6 dB & <~30 deg), then the payload must have mass <~30 kg for 1% damping, or < ~100 kg for 4% damping
  - Since the non-structural mass is estimated to be ~70 kg (T030137-05), light weighting can only be achieved by supporting the lower section of the quad structure from the crossbeams
  - 4% damping might be possible with UHV-compatible, tuned mass damper – adding broadband damping to structure in UHV-compatible manner seems difficult

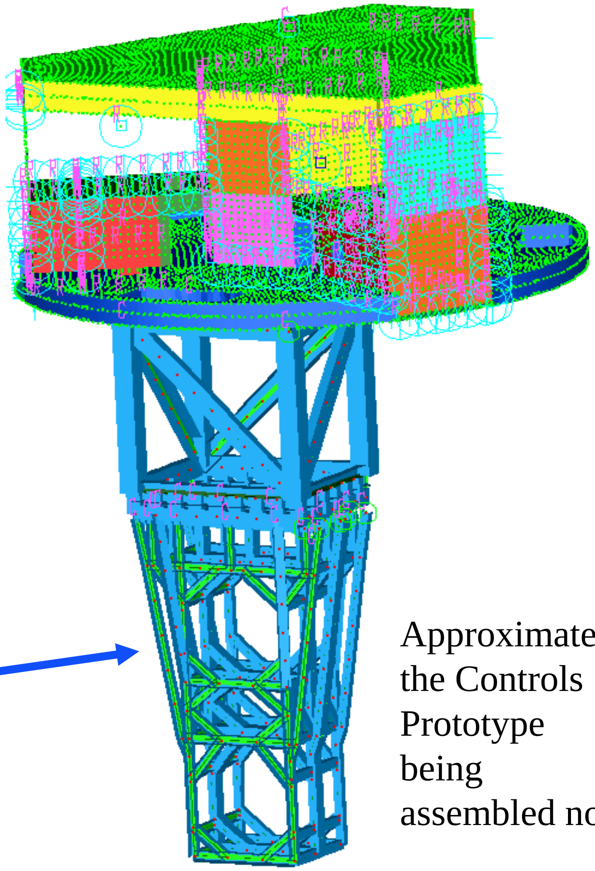
Quad Structures Explored



Impractical – violates envelope



Impractical (with current design paradigm) – lower structure doesn't support assembly fixtures/procedures



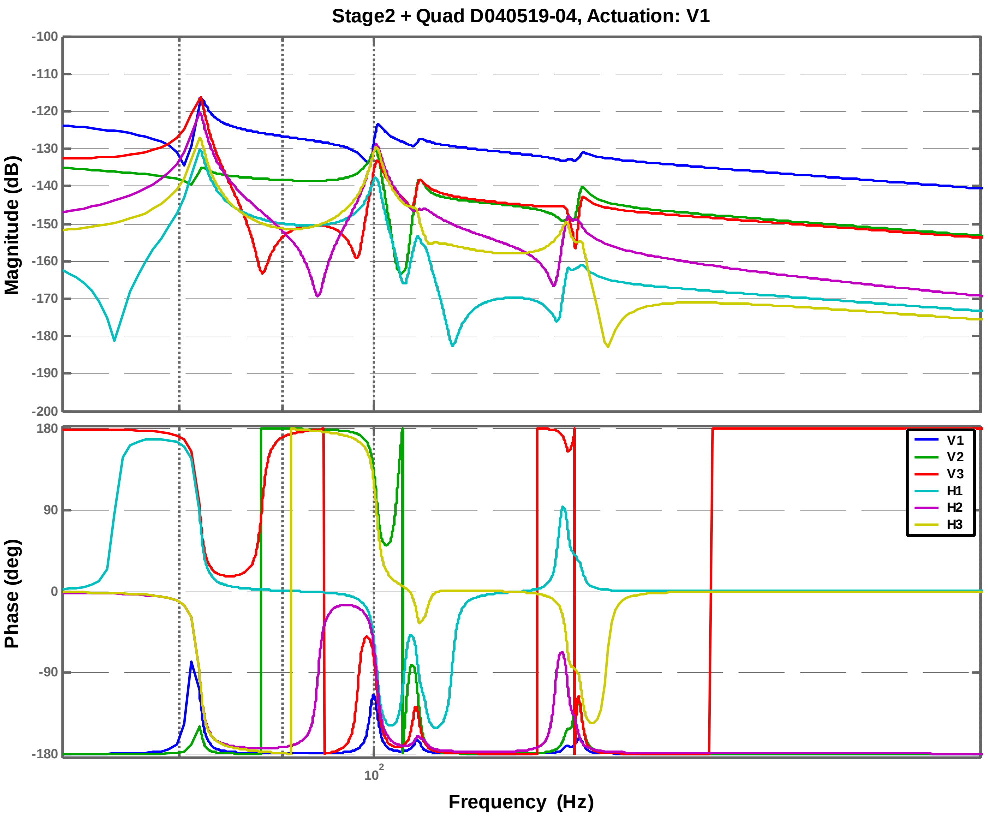
Approximates the Controls Prototype being assembled now

Name	Description	Mass (kg)	Freq. (Hz)
quadx33	structure with outriggers, heavy, high frequency	214	147, 153, 163, 168, …
quadx51	light, low frequency	84 total	77, 91, 150, 157, 189, …
quady2	lighter still, lower half light weight and flexible	70 total (9 lower)	27, 86, 91, 93, 123, …
D040519-04	medium mass, design used for quad SUS controls prototype	115 total 38 lower	86, 101, 102, 108, …

Single Actuator to Sensor Transfer Functions

- Significant phase excursions at Quad Structure resonance for the transfer function from a single actuator to a non-collocated sensor, e.g. V1 actuation to V3 displacement response

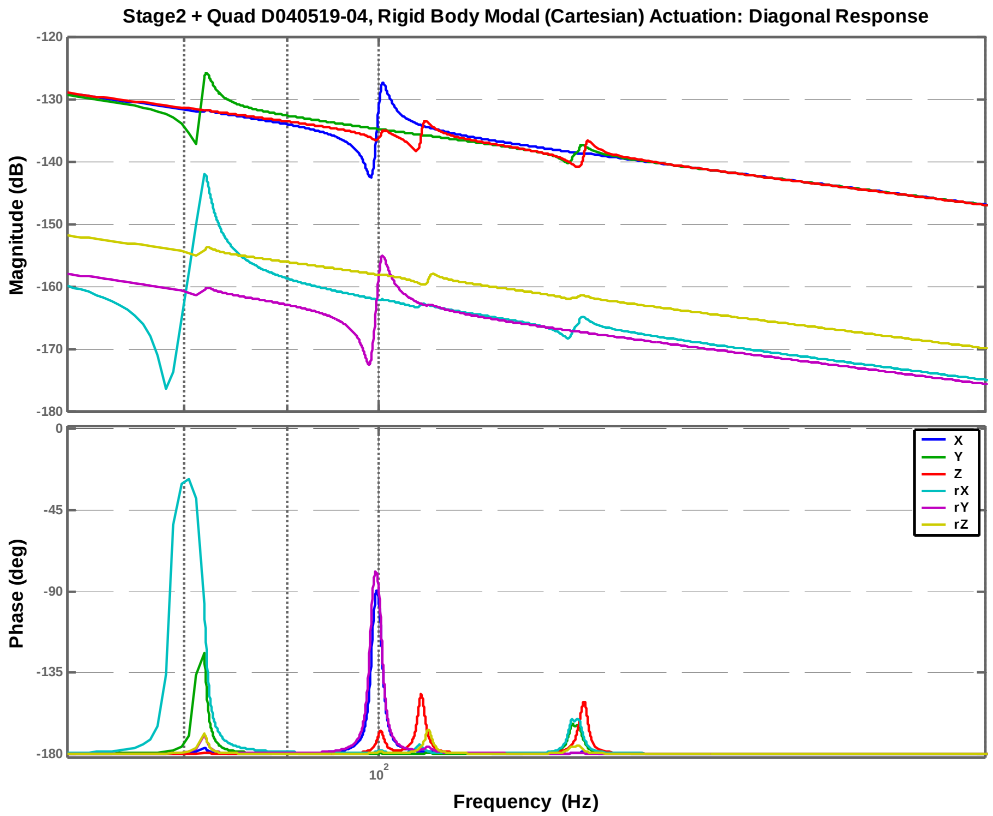
- All of the single actuation to collocated (adjacent) sensors have zero-pole pairs and positive phase excursions associated with the payload modes



Modal Transfer Functions

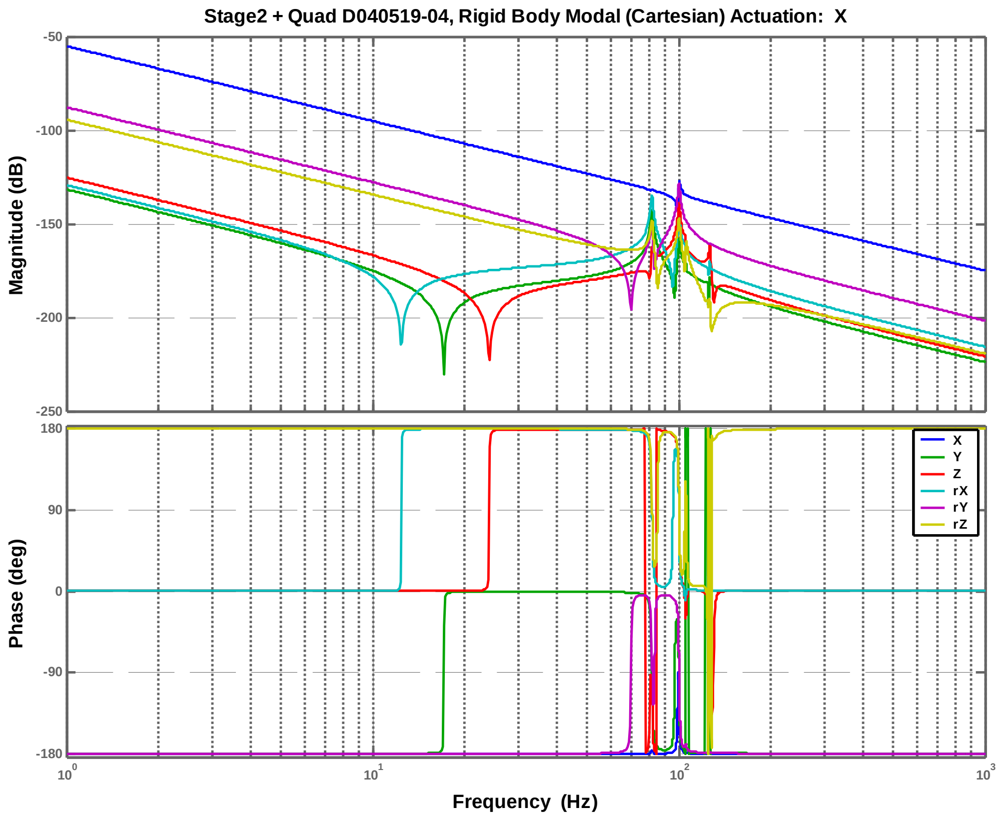
- Combined the actuator to sensor transfer functions (6 actuators x 6 sensor locations x 6 dof = 216 transfer functions) into cartesian modal transfer functions
- Rotational modes have been multiplied by the distance from the center of mass to the sensor locations, so that they can be compared to the translational modes

- All modal transfer functions have zero-pole pairings with positive phase perturbation, or no effect (modal actuation force has no component in the modal generalized force direction)


Stage2 + Quad D040519-04, Rigid Body Modal (Cartesian) Actuation: Diagonal Response

Cross-coupling

- ❑ Significant cross coupling at the payload resonances
- ❑ For example, the X-mode transfer function has significant coupling to rotation about the y-axis



Conclusions

- Given the high Q of the suspension structure mode, the control could be destabilized if the control law does not explicitly compensate for the presence of the quad suspension induced feature in the transfer function
  - If the SEI Stage-2 isolation control had a 1/f control law, then the positive phase excursions caused by dynamic coupling to the quad structure would not be destabilizing
  - However the need for aggressive broad-band suppression of structural plant modes (at >~150 Hz) causes a lot of phase loss at the ~80-100 Hz quad suspension mode
- Means to accommodate the coupled payload effect:
  - compensate the gain peak due to the SUS coupling
    - In principle could cancel the zero-pole pair introduced by the payload, and this might be stable (robust)
    - Could use a broad notch (more robust?) and suffer a slightly lower upper unity gain frequency, and some slight feedback performance,
  - switch to local feedback control (instead of modal control),
  - transition from modal feedback at low frequency to local feedback control at higher frequencies,
  - add damping to the SUS structure (UHV-compatible tuned mass damper?), or
  - reduce the SUS structure first mode frequency (and thus the mass and coupling magnitude) to be well below the upper unity gain frequency of the SEI control
    - However this requires a considerable departure from the current SUS structural design
- Bottom Line: Quad Strucutre 1st frequency target of 100 Hz appears reasonable and can accommodated in the SEI Control

Further Work

- More careful consideration of the effect of the modal cross-coupling resulting from the payload dynamics on the SEI control system design
- Use the more current ASI FEM for coupled analysis with the payloads
  - Better still; develop a more appropriate model for use in these dynamics studies. The current model has far too many degrees of freedom (more appropriate for a stress analysis)
- Use a higher fidelity model for the SUS quad structure, D040519-04
  - The relatively simple FEM used herein has a first frequency of 82 Hz vs 100 Hz with more detailed FEM
  - The simple FEM used here also has some local modes which likely do not exist in the real structure
- Develop a full stage 0, 1, 2 and suspension system (pendulums and structure) model and use it to export a state space model for control system work in Matlab
- Study the effect of a small footprint payload with a more significant lower end mass (such as the current concept for a pickoff mirror). While there is likely to be significant elastic coupling in this scenario, the result should not compromise the collocation of the SEI sensing and actuation
- Test for coupled dynamics with a representative SUS structure on the SEI ETF system at Stanford
  - Copy of the Quad Controls Prototype structure to be delivered to Stanford ~September