VOPO Injection Bench Assembly FEA

LIGO MIT Lab

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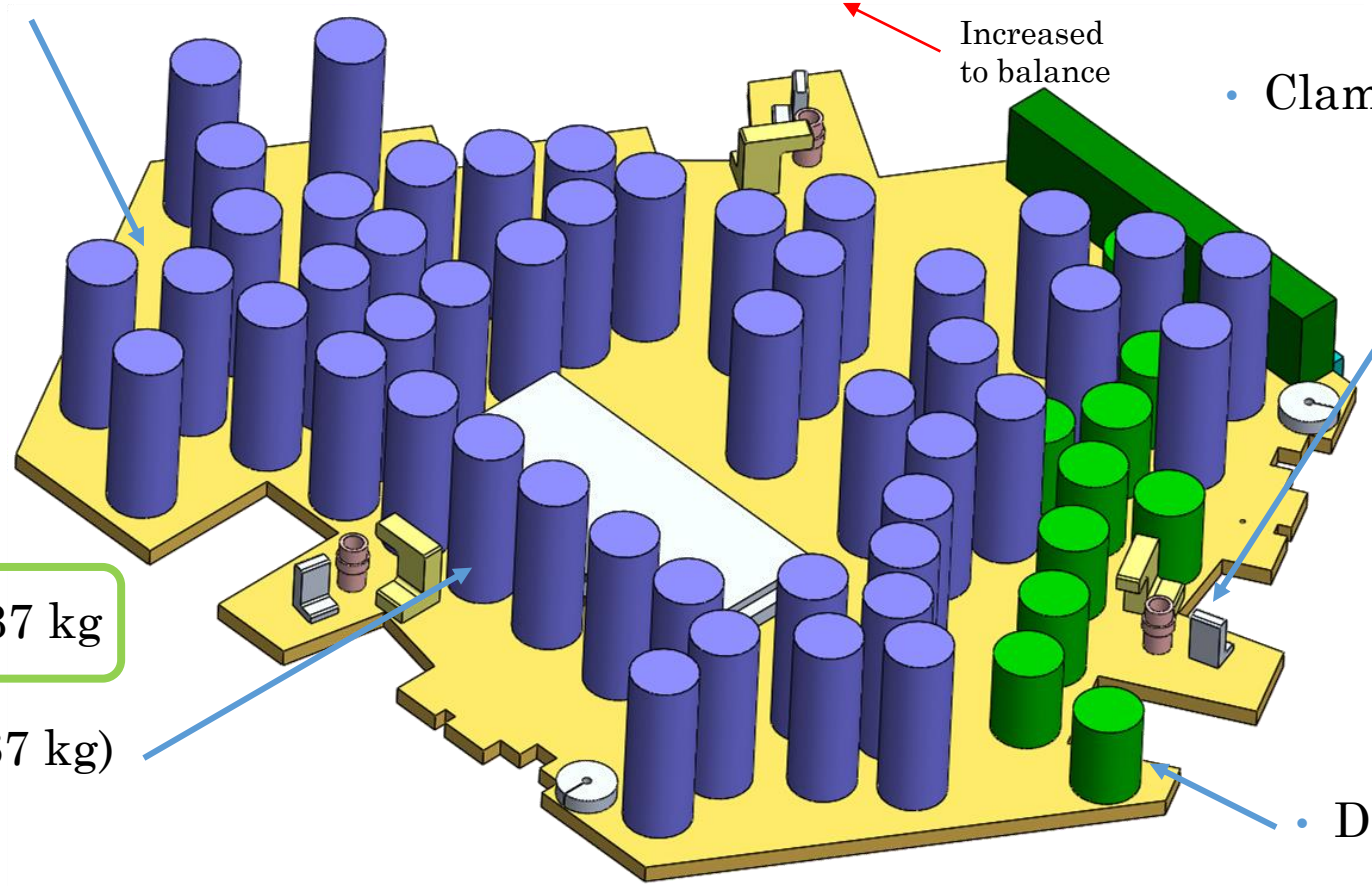
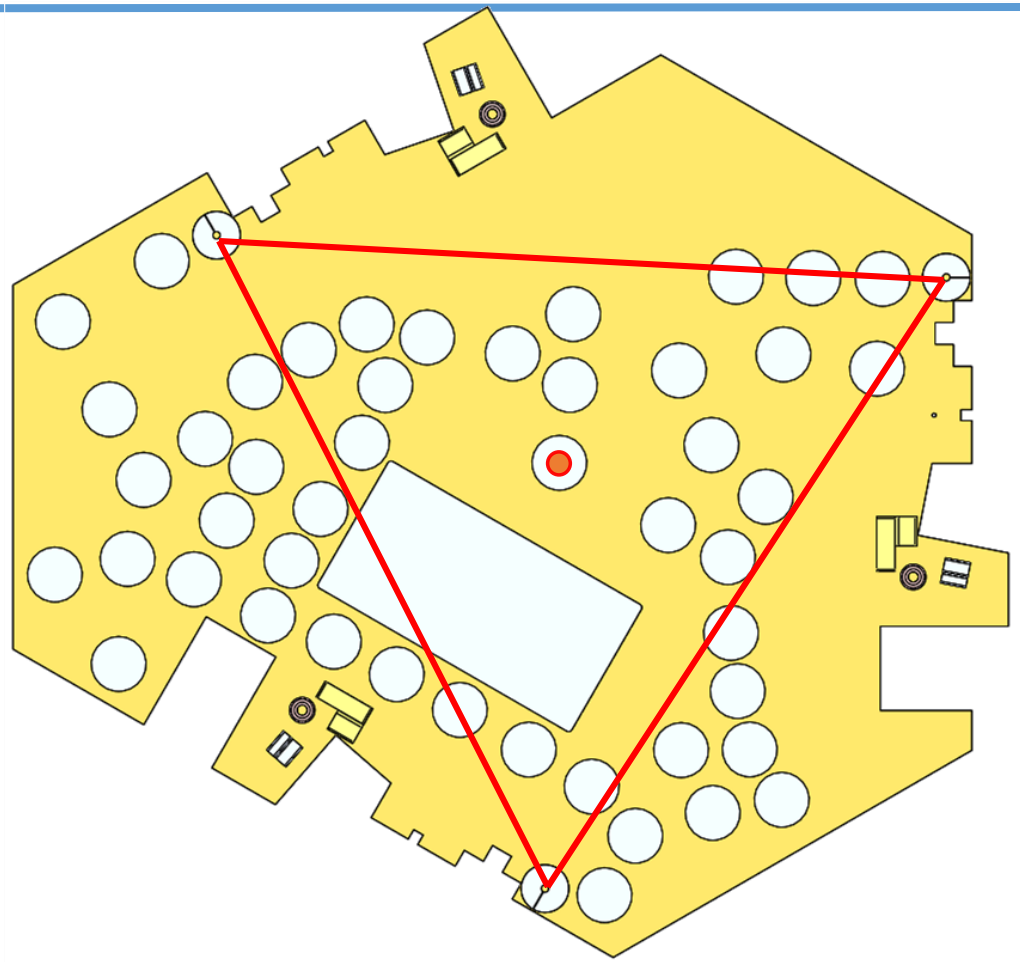
Injection Bench Assembly Components

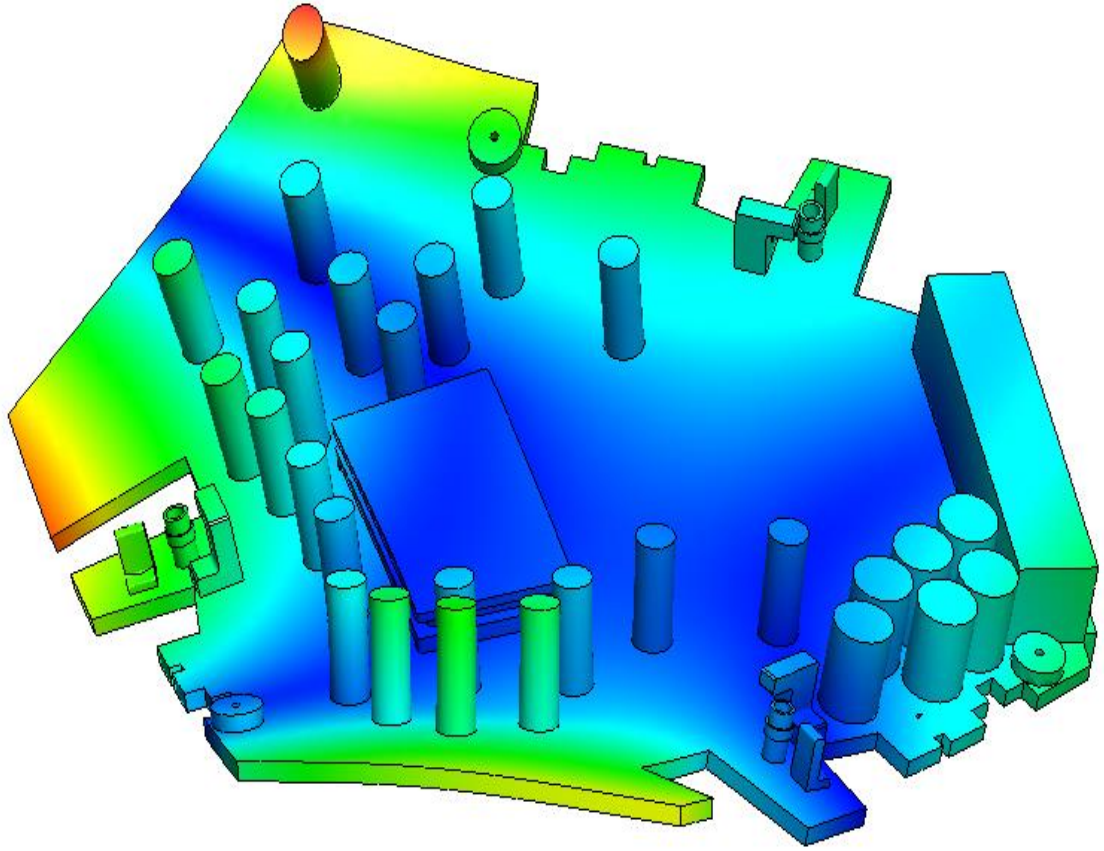
- D1500275 VOPO Injection Bench TO FEA (13.61kg)



- Clamps and Stops (0.25 kg)
- TOTAL: 37.37 kg
- Optics (15.67 kg)
- Dummy masses (7.84 kg)

Assembly Design Drivers

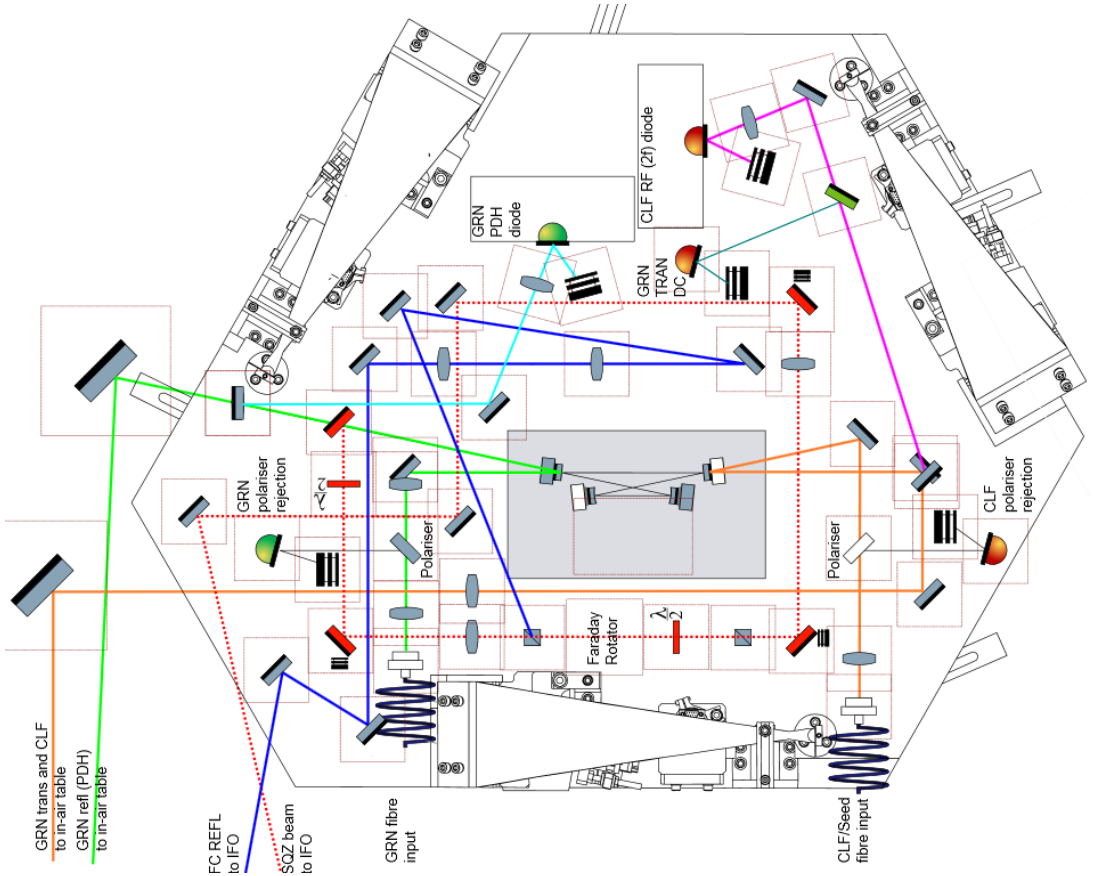




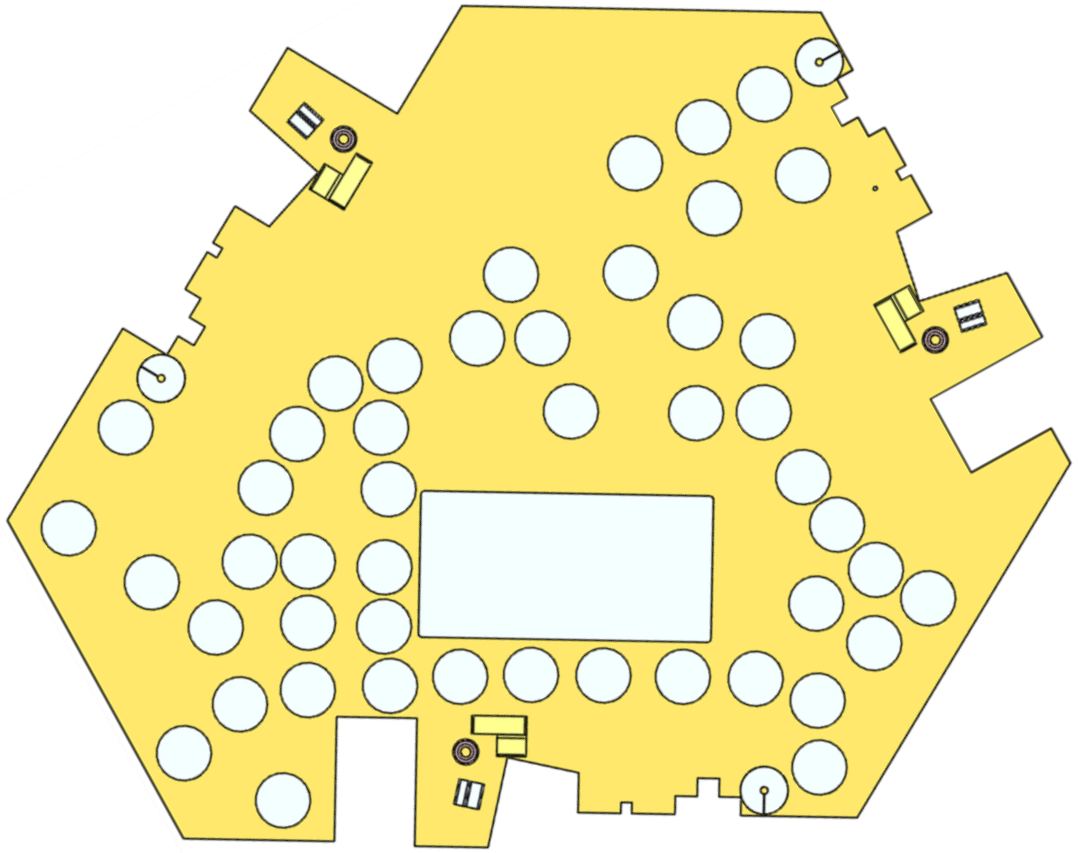
- Center of Mass in the Geometric Center
- First frequency as high as possible (min 150 Hz)

Optics Layout

- Optics: 313 g each



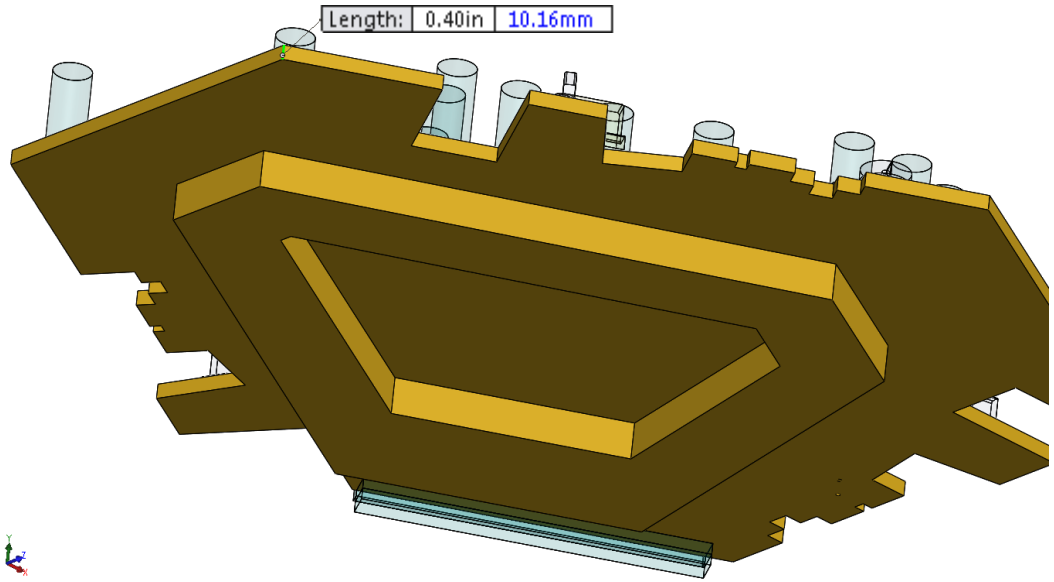
- Real Optics Layout

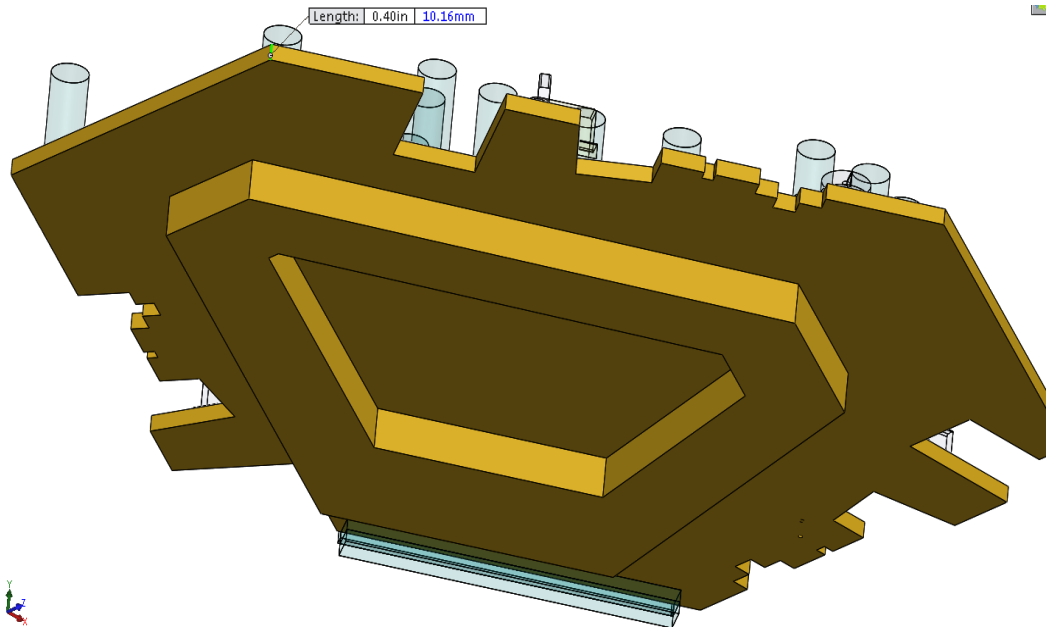


- Dummy Optics Layout

Bench Geometry

- No symmetry to partially compensate optics mass

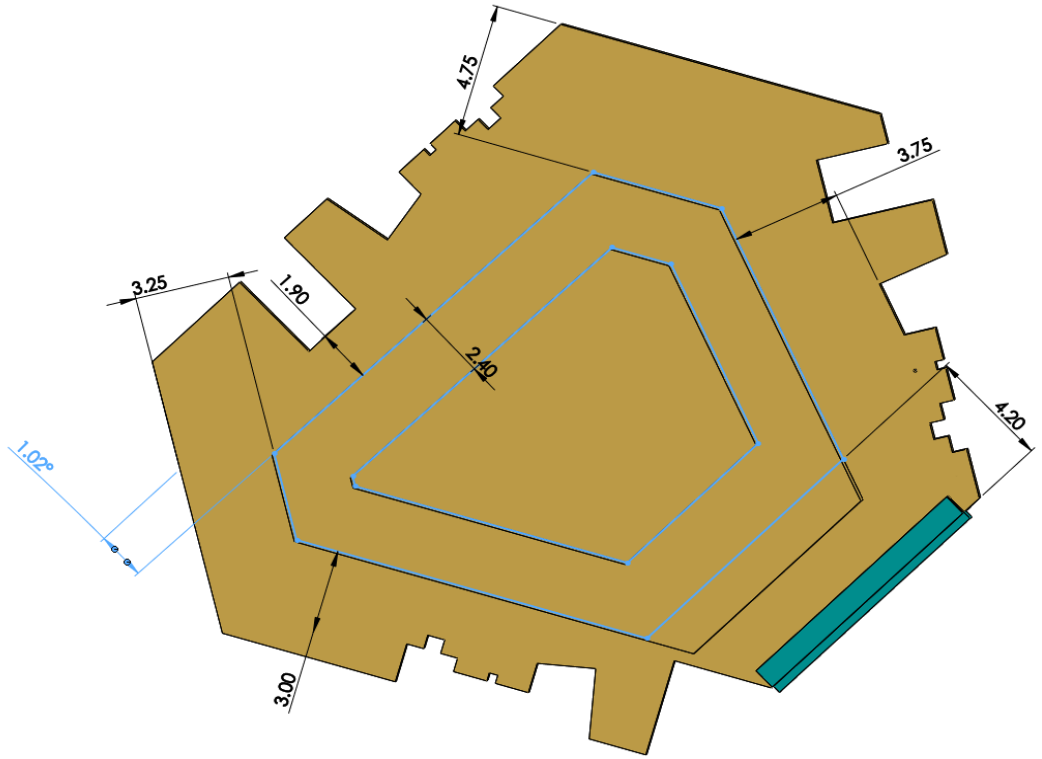




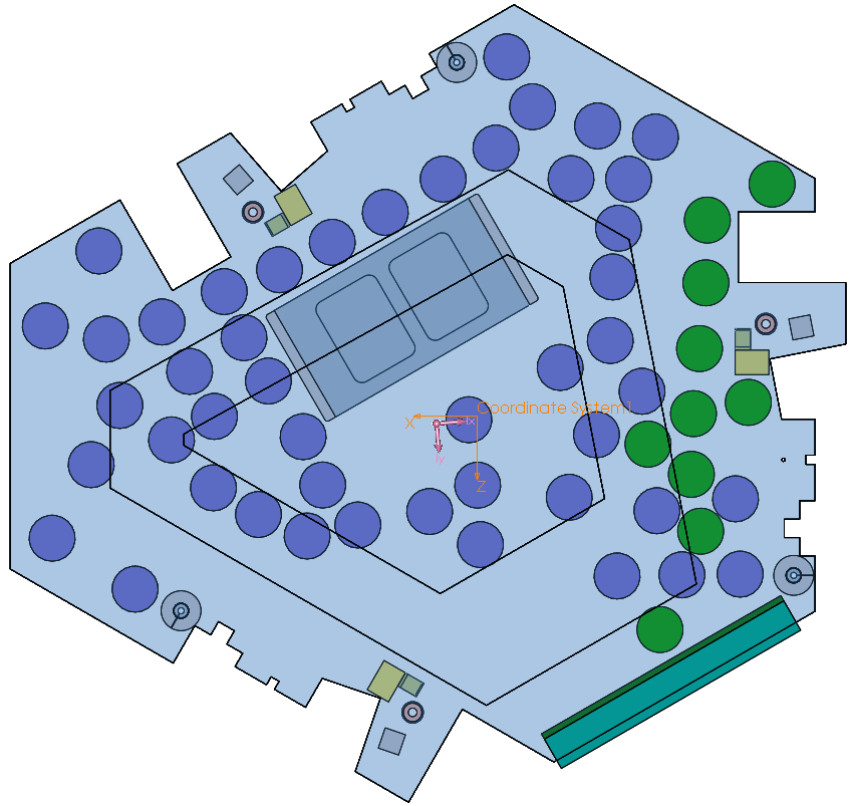
- Injection Bench Thickness

Bench Geometry

- No symmetry to partially compensate optics mass



- Injection Bench Bottom Geometry



- Injection Bench Center of Mass

Center of Mass

- Optics

Mass properties of selected components
Coordinate system: Coordinate System1

The center of mass and the moments of inertia are output in the coordinate system of
Mass = 15.67 kilograms

Volume = 354.13 cubic inches

Surface area = 1159.88 square inches

Center of mass: (inches)
X = 2.50
Y = 2.31
Z = -1.54

Principal axes of inertia and principal moments of inertia: (kilograms * square inches)
Taken at the center of mass.

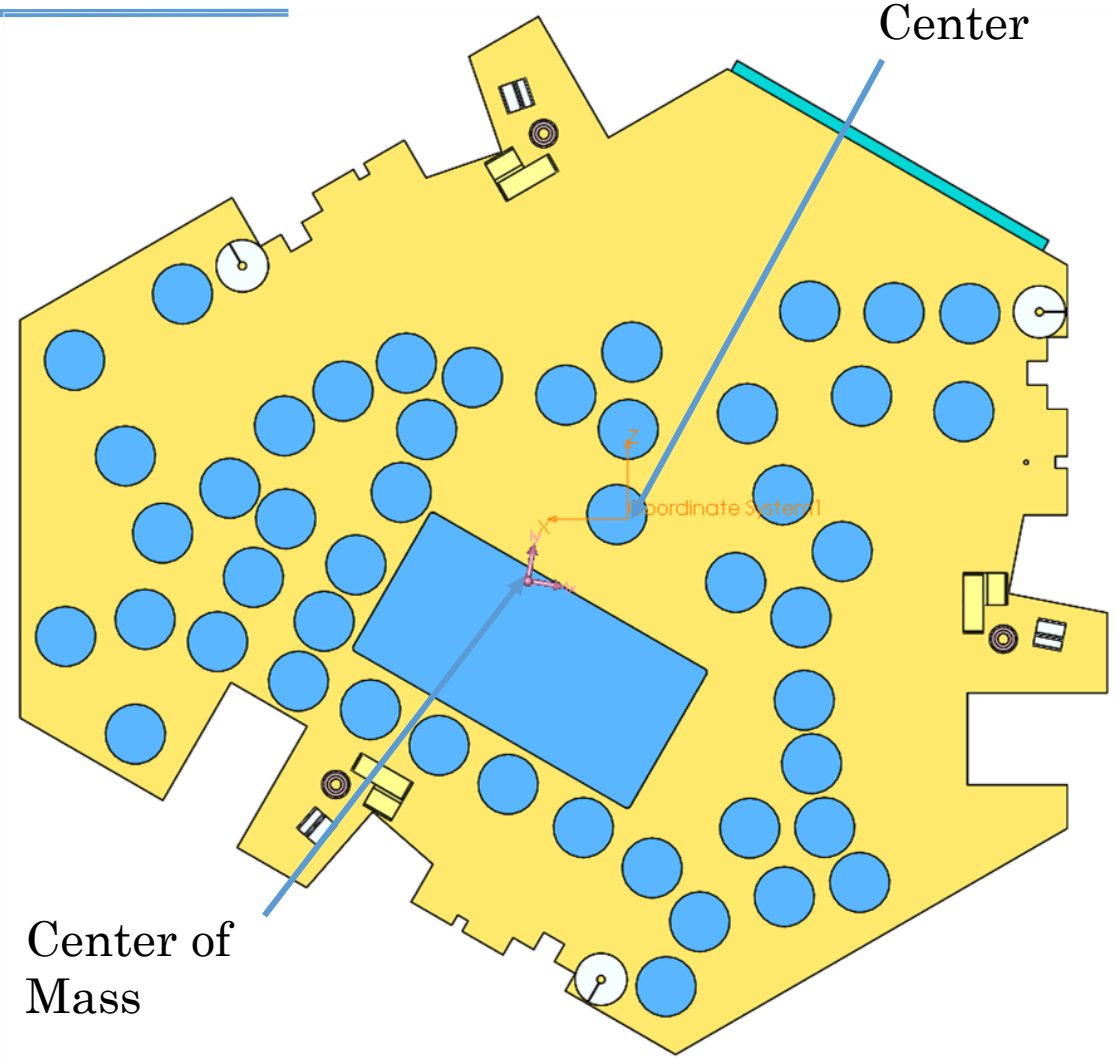
Ix = (-0.99, 0.00, -0.17)	Px = 349.61
Iy = (-0.17, 0.01, 0.99)	Py = 694.40
Iz = (0.00, 1.00, -0.01)	Pz = 1001.14

Moments of inertia: (kilograms * square inches)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 359.29	Lxy = 0.08	Lxz = 56.96
Lyx = 0.08	Lyy = 1001.11	Lyz = 2.71
Lzx = 56.96	Lzy = 2.71	Lzz = 684.75

Moments of inertia: (kilograms * square inches)
Taken at the output coordinate system.

Ixx = 480.28	Ixy = 90.68	Ixz = -3.36
Iyx = 90.68	Iyy = 1136.20	Iyz = -53.10
Izx = -3.36	Izy = -53.10	Izz = 866.50



Center of Mass

- Injection Bench + Clamps

Mass properties of selected components
Coordinate system: Coordinate System1

The center of mass and the moments of inertia are output in the coordinate system of
Mass = 13.86 kilograms

Volume = 313.23 cubic inches

Surface area = 1125.35 square inches

Center of mass: (inches)
X = 1.30
Y = -0.06
Z = 0.24

Principal axes of inertia and principal moments of inertia: (kilograms * square inches)
Taken at the center of mass.

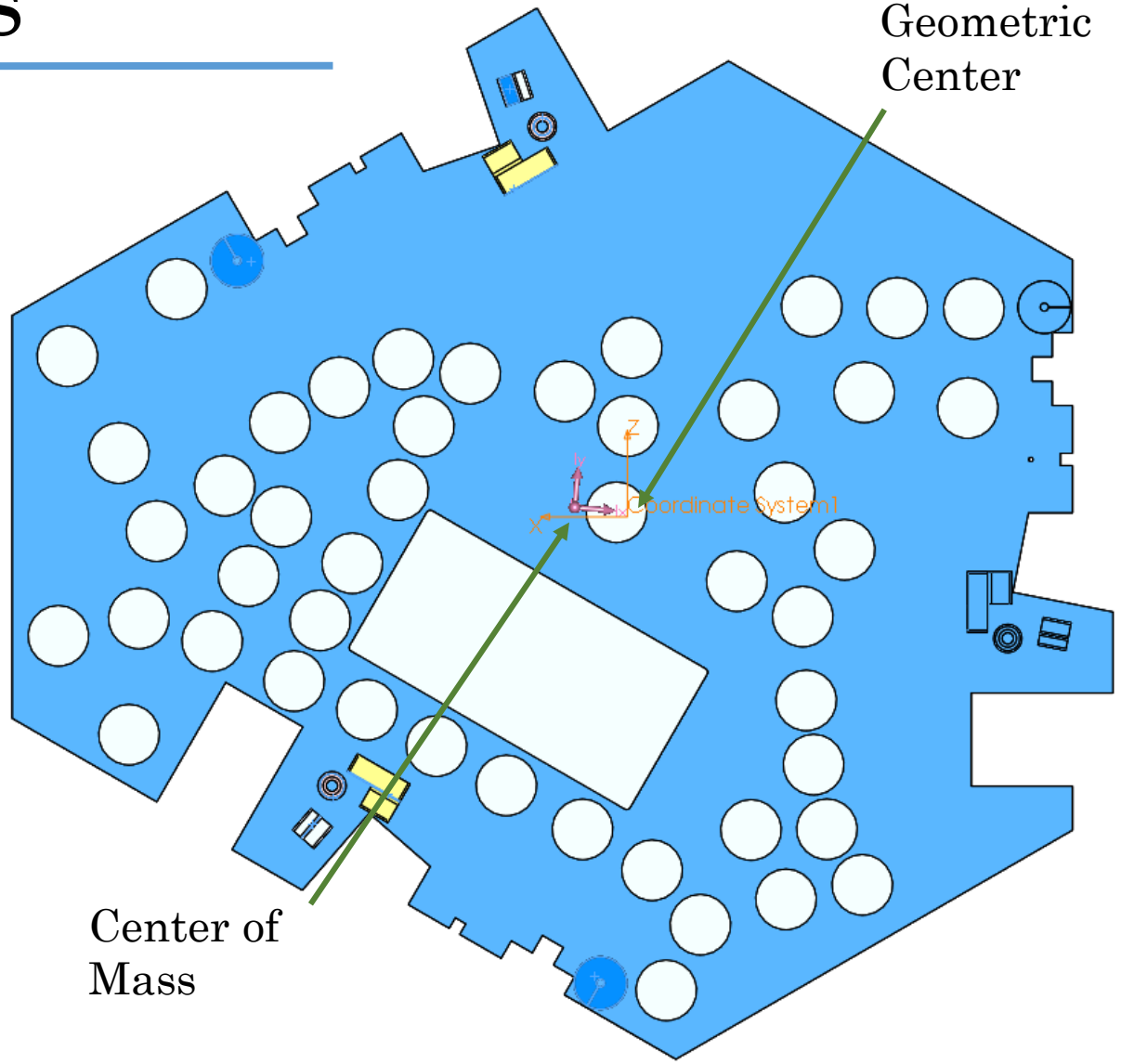
Ix = (-1.00, 0.00, -0.09)	Px = 395.36
Iy = (-0.09, -0.01, 1.00)	Py = 552.02
Iz = (0.00, 1.00, 0.01)	Pz = 942.50

Moments of inertia: (kilograms * square inches)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 396.51	Lxy = -0.42	Lxz = 13.34
Lyx = -0.42	Lyy = 942.47	Lyz = -3.24
Lzx = 13.34	Lzy = -3.24	Lzz = 550.90

Moments of inertia: (kilograms * square inches)
Taken at the output coordinate system.

Ixx = 397.34	Ixy = -1.51	Ixz = 17.61
Iyx = -1.51	Iyy = 966.63	Iyz = -3.44
Izx = 17.61	Izy = -3.44	Izz = 574.33



Center of Mass

- Without balancing masses

Mass properties of D1500292 aLIGO VOPO Injection Bench Assembly TO FEA
Configuration: Default
Coordinate system: Coordinate System1

Mass = 29.53 kilograms

Volume = 667.36 cubic inches

Surface area = 2285.23 square inches

Center of mass: (inches)
X = 1.94
Y = 1.20
Z = -0.71

Principal axes of inertia and principal moments of inertia: (kilograms * square inches)
Taken at the center of mass.

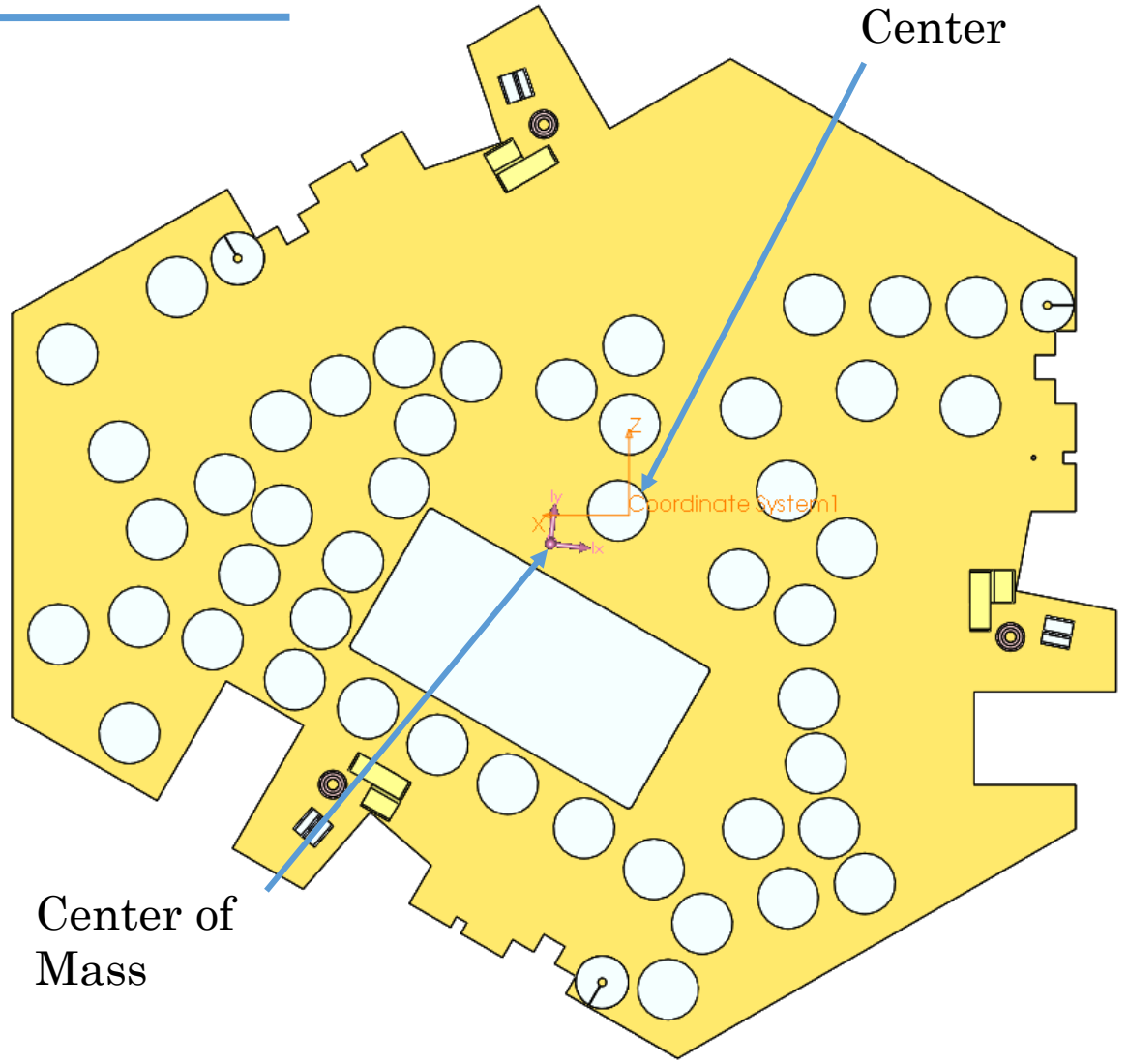
Ix = (-0.99, -0.01, -0.11)	Px = 813.91
Iy = (-0.11, -0.05, 0.99)	Py = 1292.33
Iz = (-0.02, 1.00, 0.05)	Pz = 1979.32

Moments of inertia: (kilograms * square inches)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 820.45	Lxy = 20.62	Lxz = 54.60
Lyx = 20.62	Lyy = 1977.42	Lyz = -31.54
Lzx = 54.60	Lzy = -31.54	Lzz = 1287.69

Moments of inertia: (kilograms * square inches)
Taken at the output coordinate system.

Ixx = 877.62	Ixy = 89.17	Ixz = 14.25
Iyx = 89.17	Iyy = 2102.83	Iyz = -56.53
Izx = 14.25	Izy = -56.53	Izz = 1440.84



Center of Mass

- With balancing masses

Mass properties of D1500292 aLIGO VOPO Injection Bench Assembly TO FEA
Configuration: Default
Coordinate system: Coordinate System1

Mass = 37.37 kilograms

Volume = 727.18 cubic inches

Surface area = 2533.66 square inches

Center of mass: (inches)
X = 0.08
Y = 1.21
Z = 0.09

Principal axes of inertia and principal moments of inertia: (kilograms * square inches)
Taken at the center of mass.

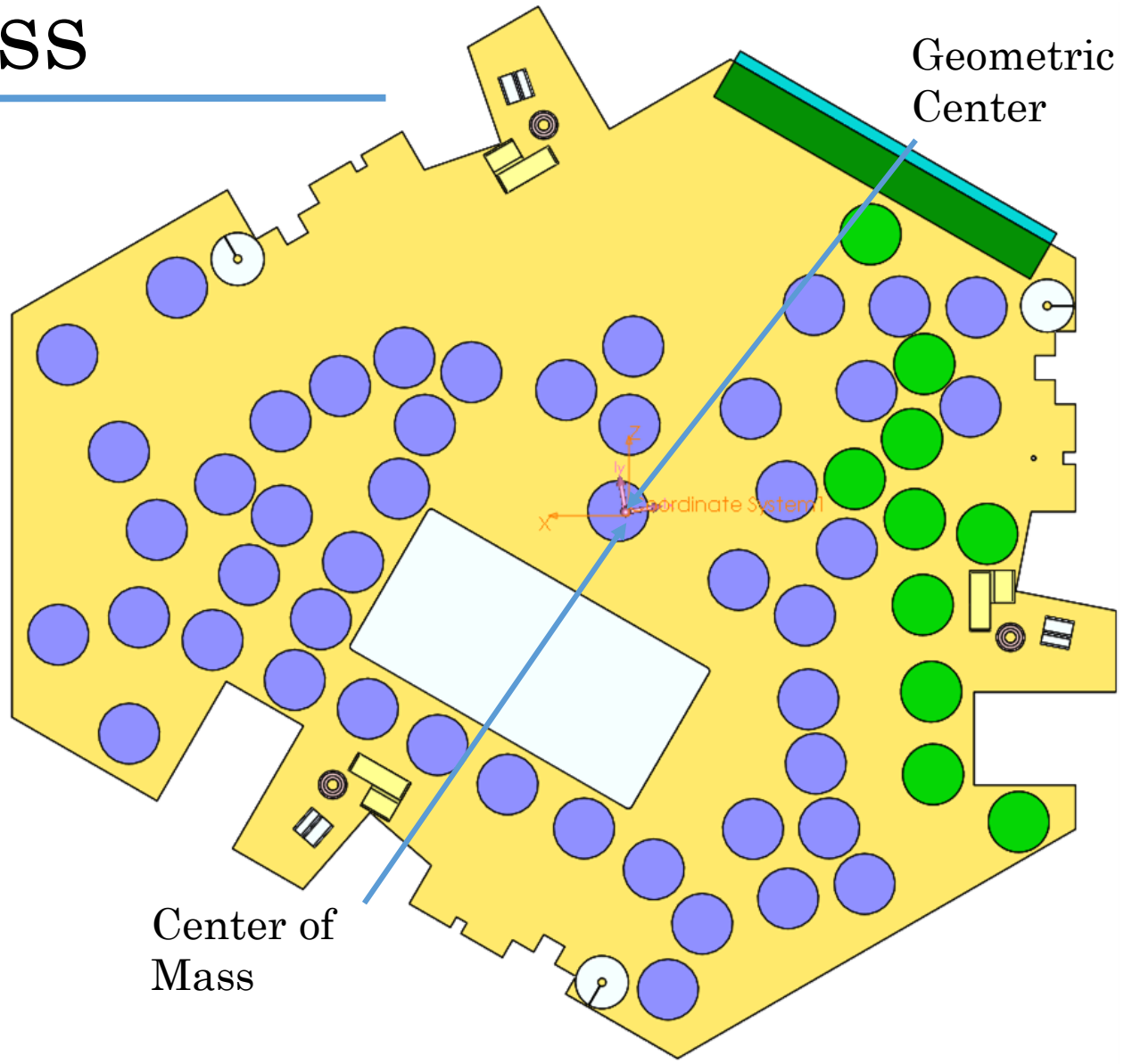
Ix = (-0.99, -0.01, 0.17)	Px = 1150.51
Iy = (0.17, -0.03, 0.99)	Py = 1818.71
Iz = (-0.01, 1.00, 0.04)	Pz = 2833.14

Moments of inertia: (kilograms * square inches)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 1169.36	Lxy = 18.00	Lxz = -109.72
Lyx = 18.00	Lyy = 2831.62	Lyz = -38.10
Lzx = -109.72	Lzy = -38.10	Lzz = 1801.38

Moments of inertia: (kilograms * square inches)
Taken at the output coordinate system.

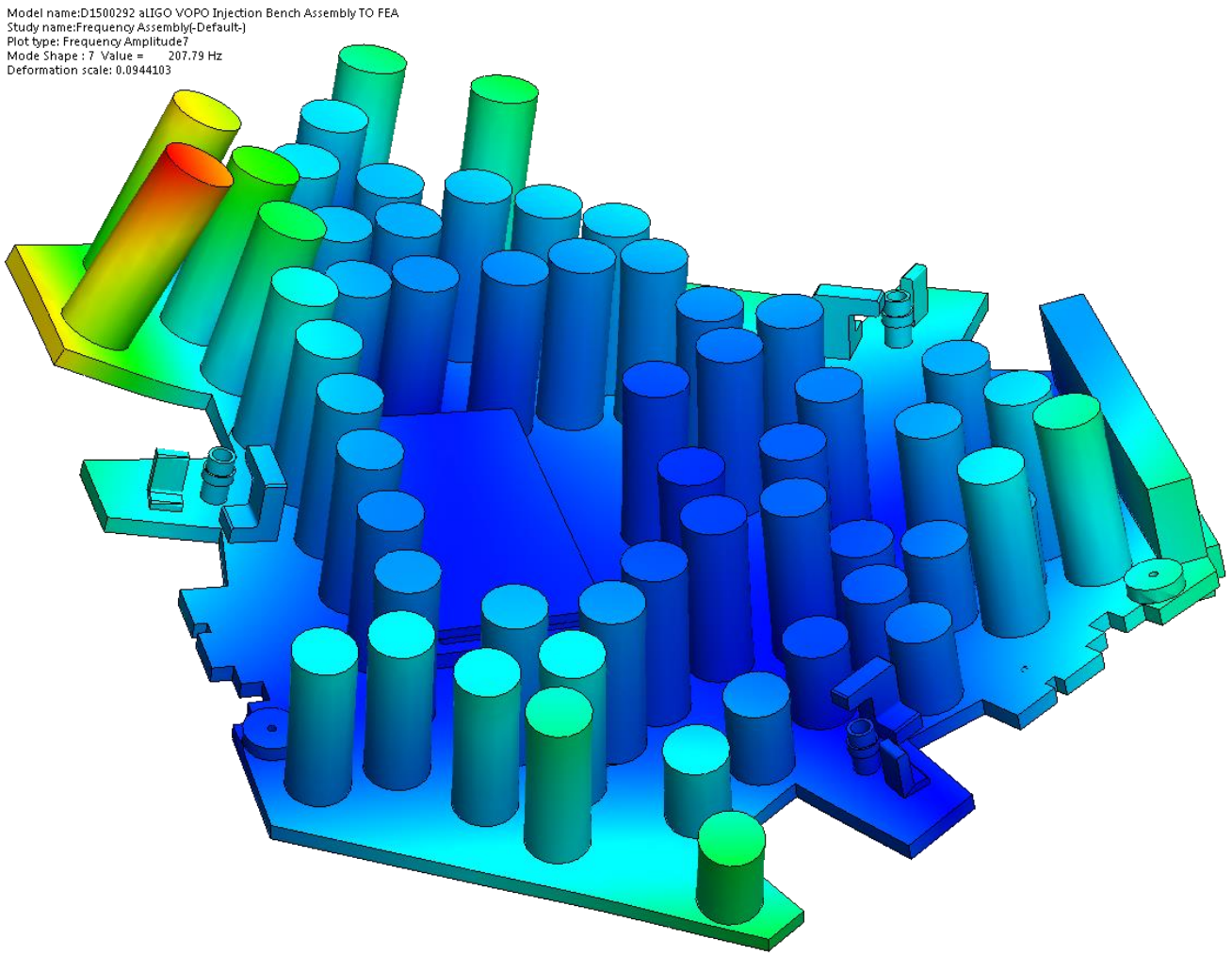
Ixx = 1224.02	Ixy = 21.63	Ixz = -109.46
Iyx = 21.63	Iyy = 2832.14	Iyz = -34.21
Izx = -109.46	Izy = -34.21	Izz = 1856.00



FEA

- Using SW Simulation with bonded contacts

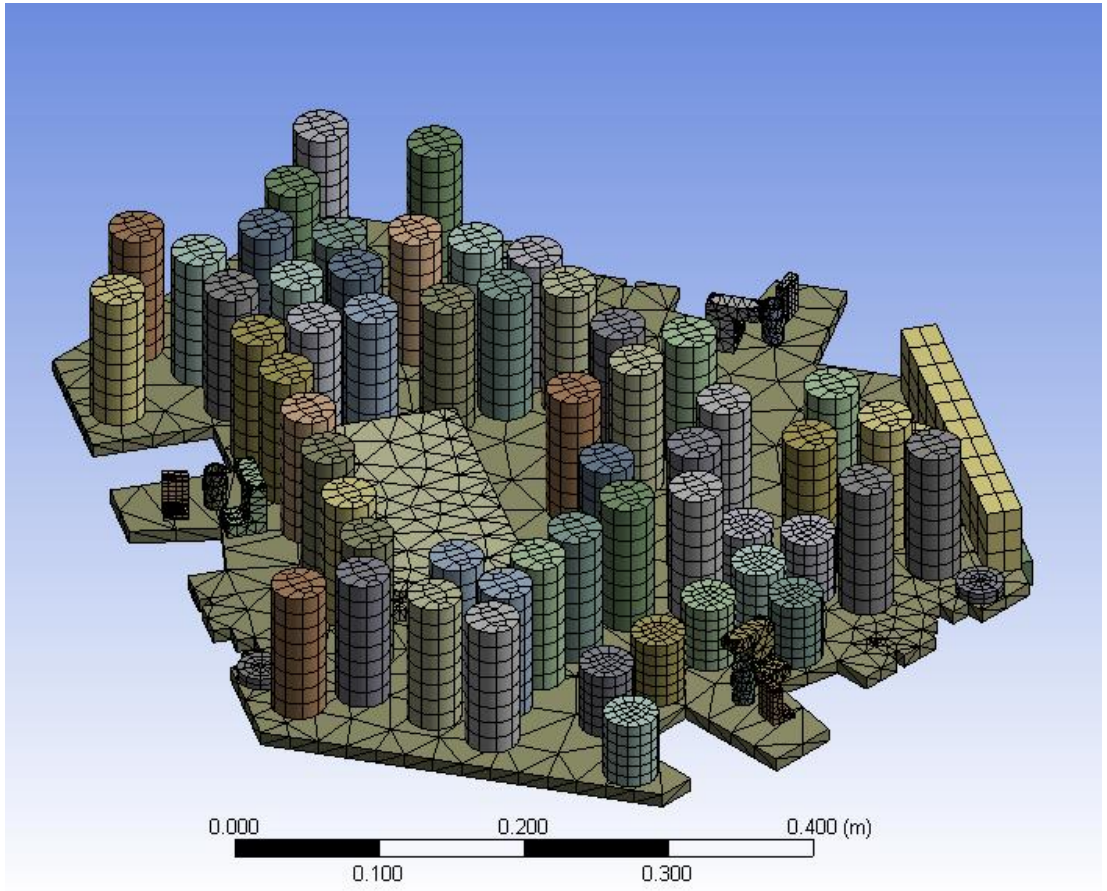
FEA Results



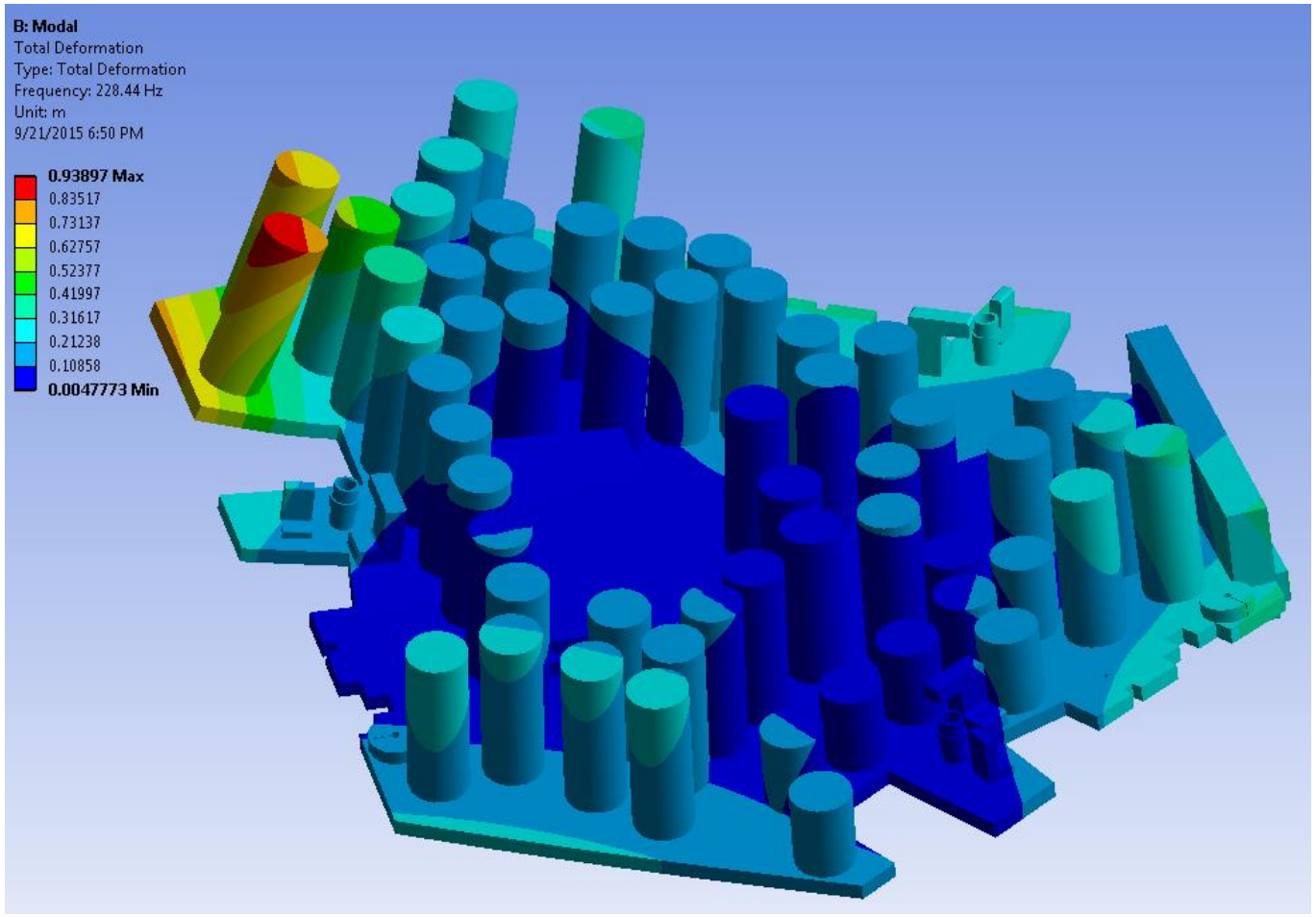
Plot type: Frequency Amplitude7
Mode Shape : 7 Value = 207.79 Hz
Deformation scale: 0.0944103

FEA

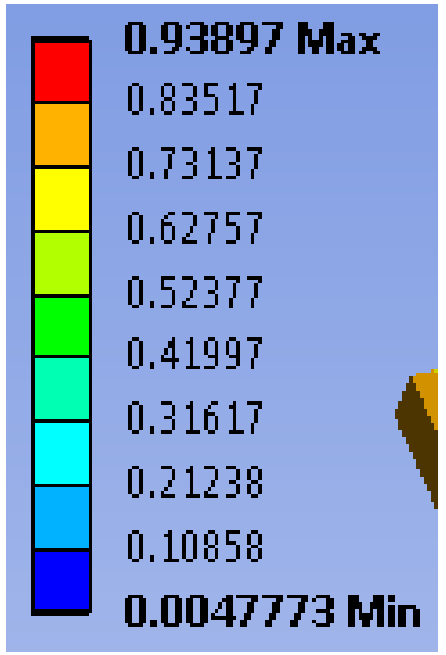
- Using ANSYS with bonded contacts



FEA Results

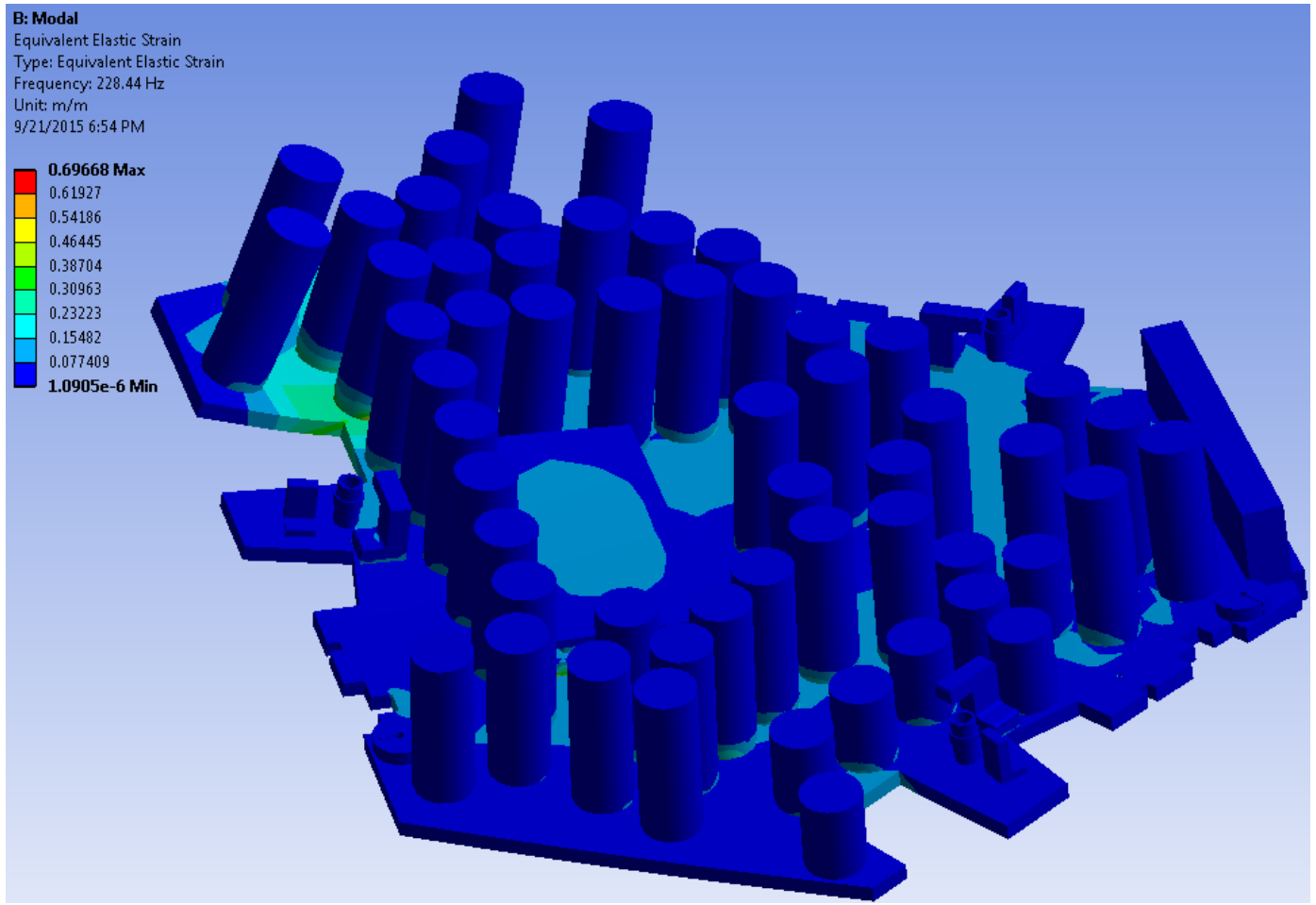


- Deformation

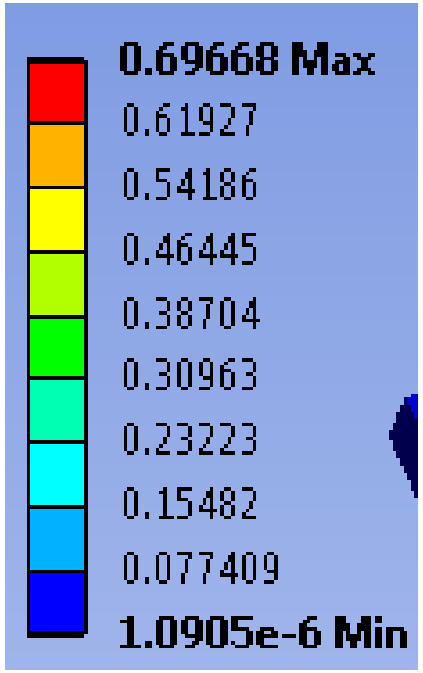


Frequency: 228.44 Hz

FEA Results

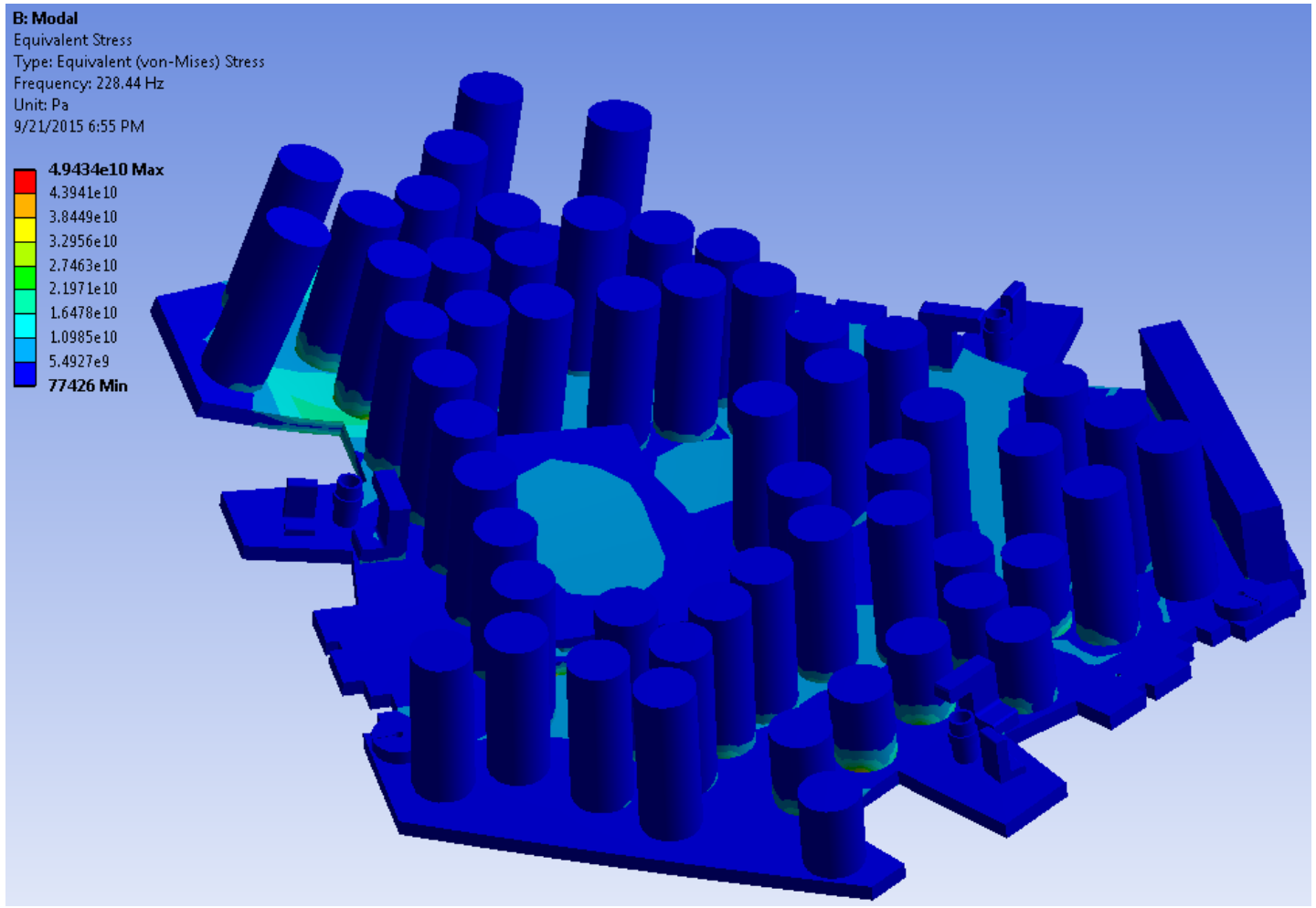


- Strain

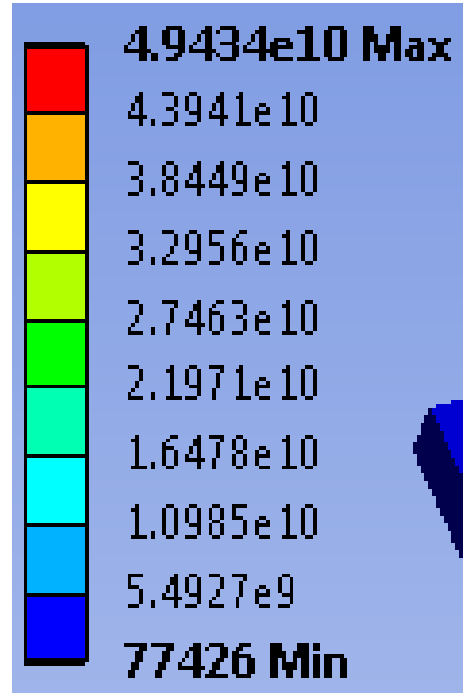


Frequency: 228.44 Hz

FEA Results



- Stress



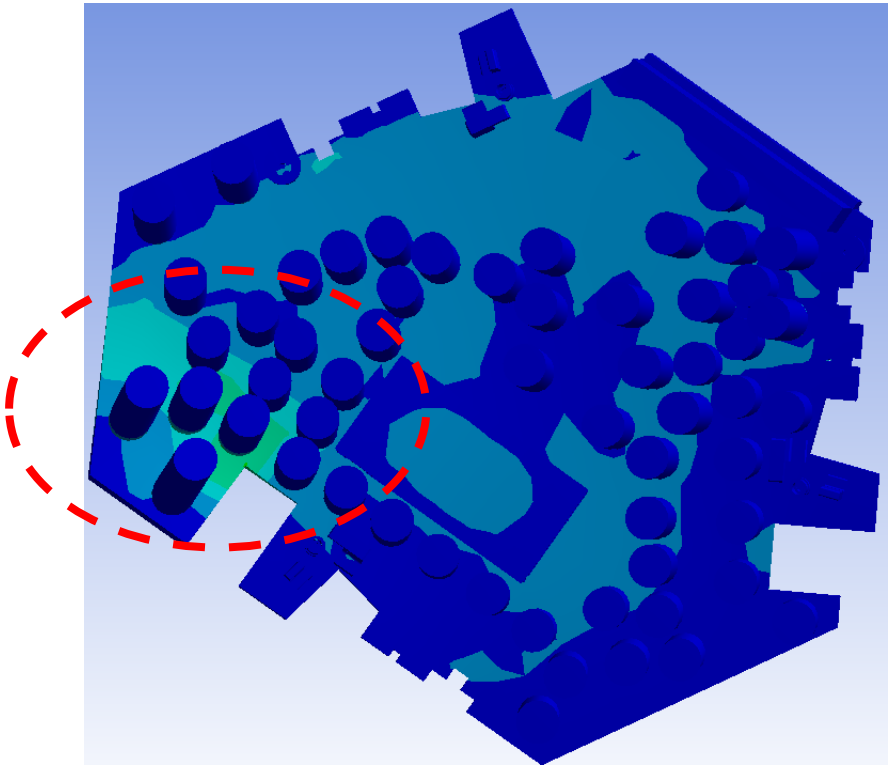
Frequency: 228.44 Hz

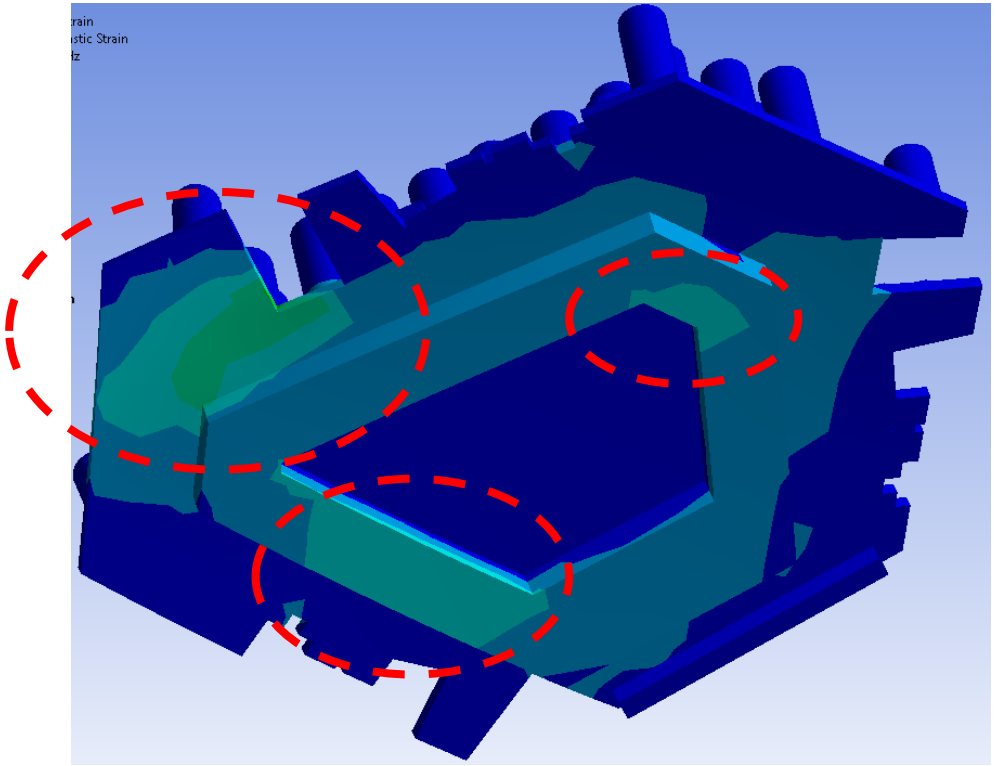
Global Results

- First Resonance Frequency:

FEA			
	SW	ANSYS	Difference %
Stress (MPa)	207.79	228.44	9.040

- Areas to be reinforced (Strain plot)



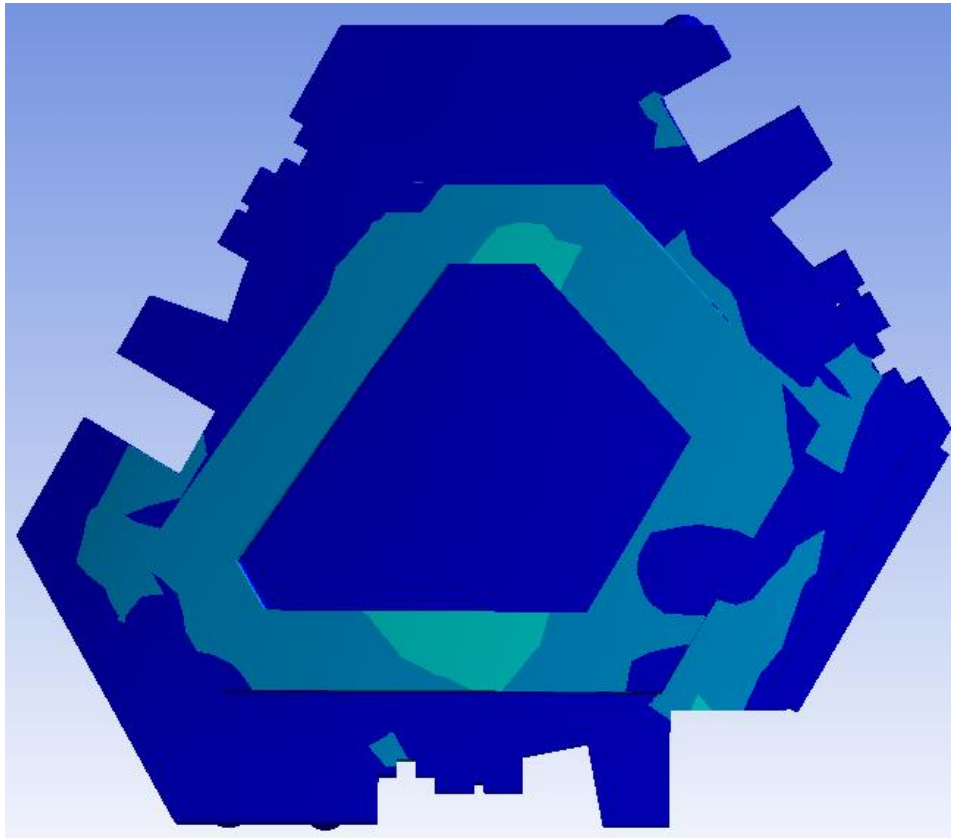


Work to be done

- Refine the Dummy Mass models
- Work on the Dummy Mass attachment
- Refine the whole model with the real optics layout
- Reinforce the areas with more Strain

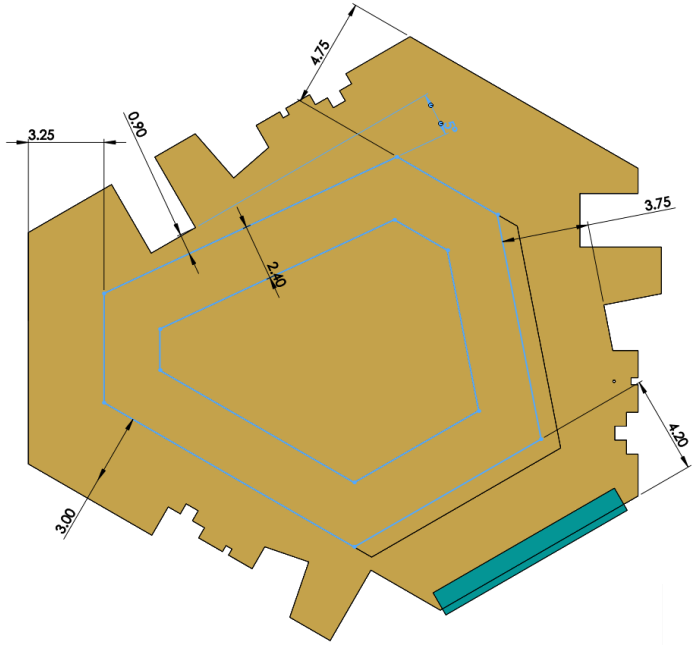
Last Version

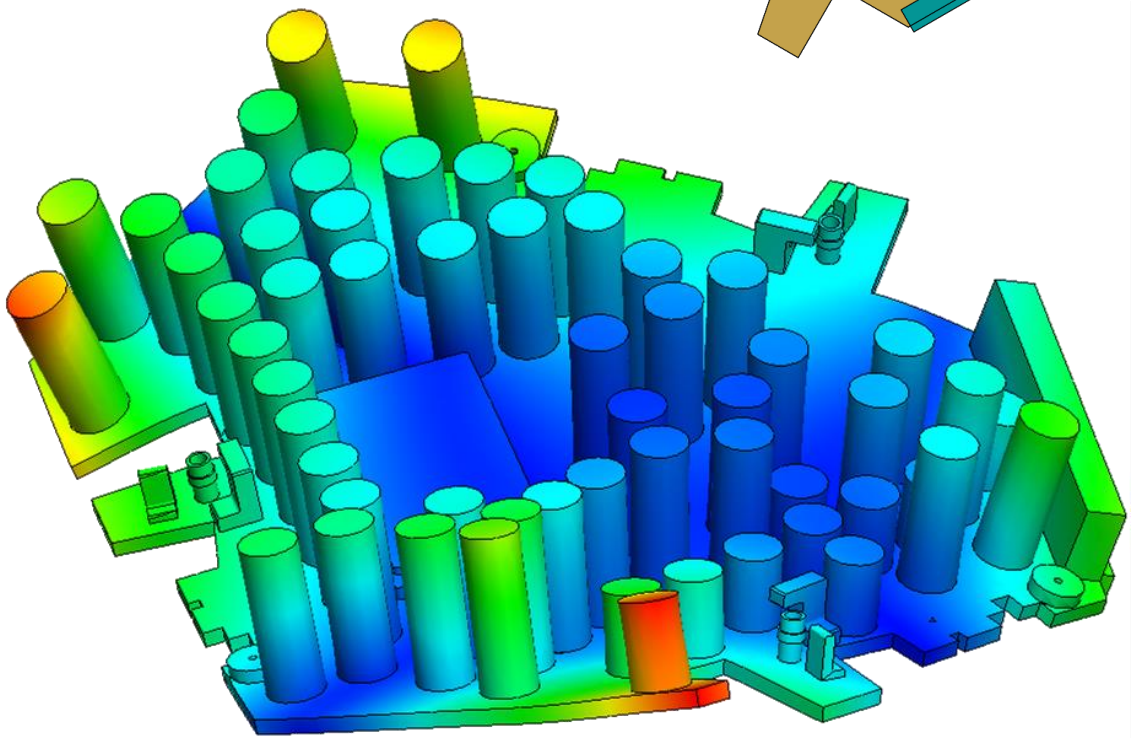
- Modal Analysis



- ANSYS: 239.31 Hz

- Weight: 13.78kg





- SW: 217.87.31 Hz

Last Version

- Mechanical Properties

Mass properties of D1500292 aLIGO VOPO Injection Bench Assembly TO FEA
Configuration: Default
Coordinate system: Coordinate System2

Mass = 37.542 kilograms

Volume = 0.012 cubic meters

Surface area = 1.636 square meters

Center of mass: (meters)
X = 0.000
Y = -0.002
Z = 0.020

Principal axes of inertia and principal moments of inertia: (kilograms * square meters)
Taken at the center of mass.

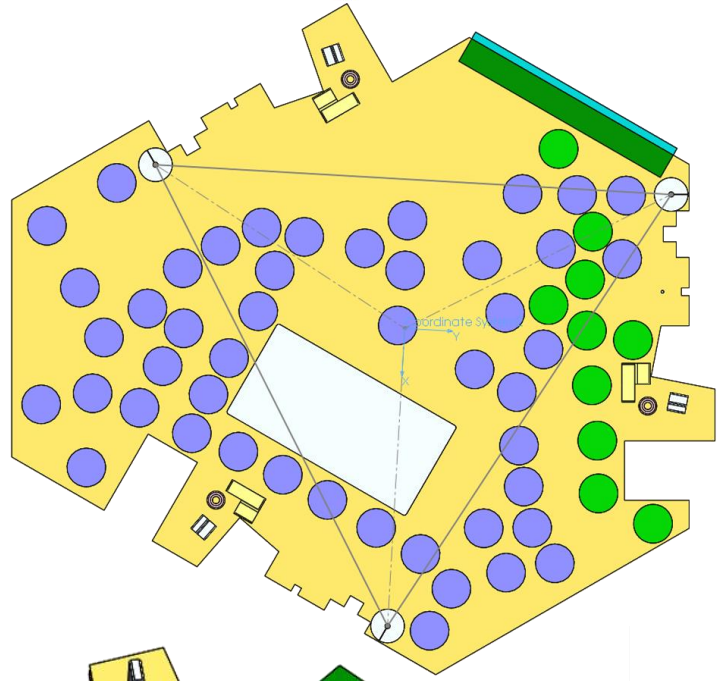
Ix = (-0.219, 0.976, -0.013)	Px = 0.741
Iy = (-0.975, -0.220, -0.029)	Py = 1.190
Iz = (-0.031, 0.007, 0.999)	Pz = 1.842

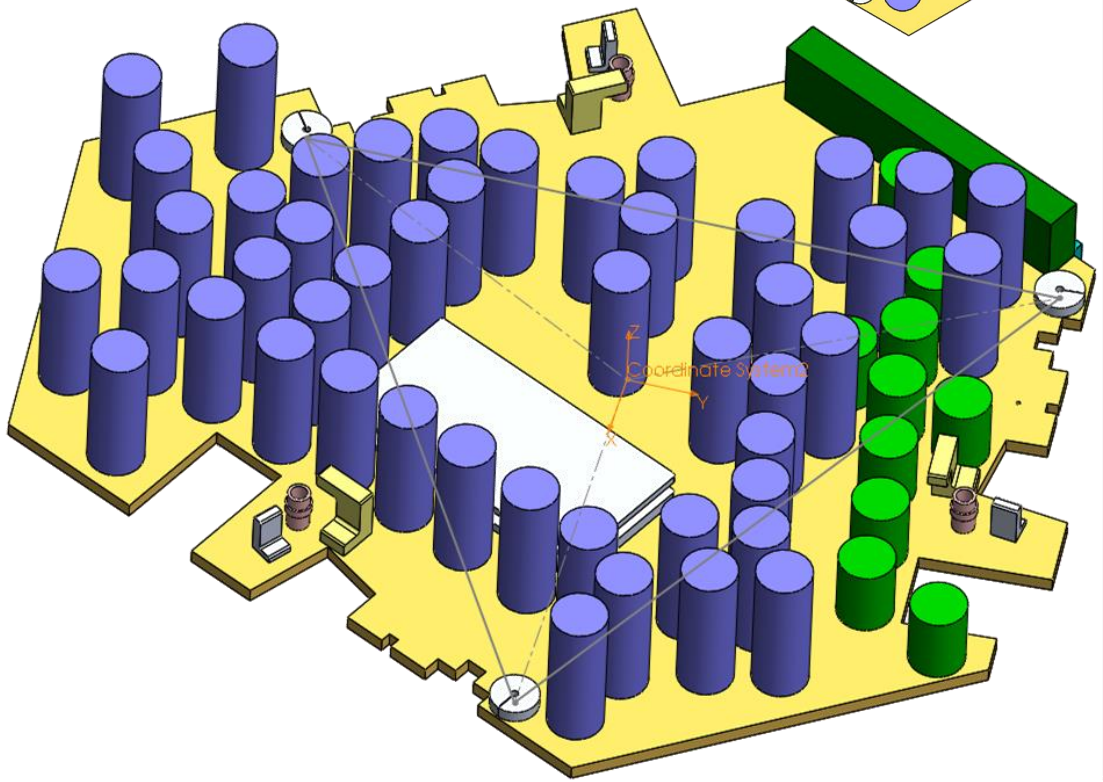
Moments of inertia: (kilograms * square meters)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 1.169	Lxy = -0.096	Lxz = 0.021
Lyx = -0.096	Lyy = 0.763	Lyz = -0.010
Lzx = 0.021	Lzy = -0.010	Lzz = 1.841

Moments of inertia: (kilograms * square meters)
Taken at the output coordinate system.

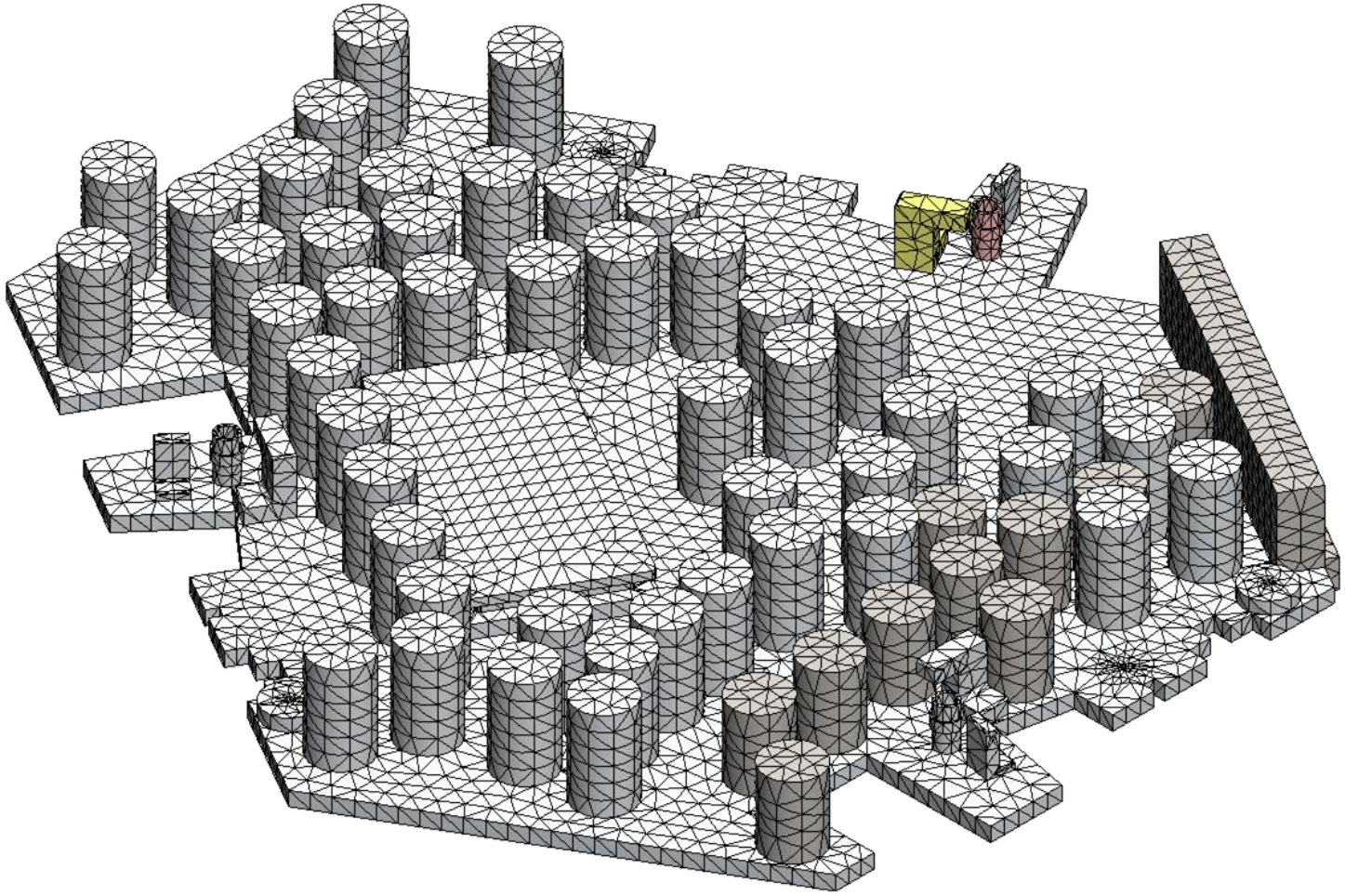
Ixx = 1.185	Ixy = -0.096	Ixz = 0.022
Iyx = -0.096	Iyy = 0.778	Iyz = -0.012
Izx = 0.022	Izy = -0.012	Izz = 1.842

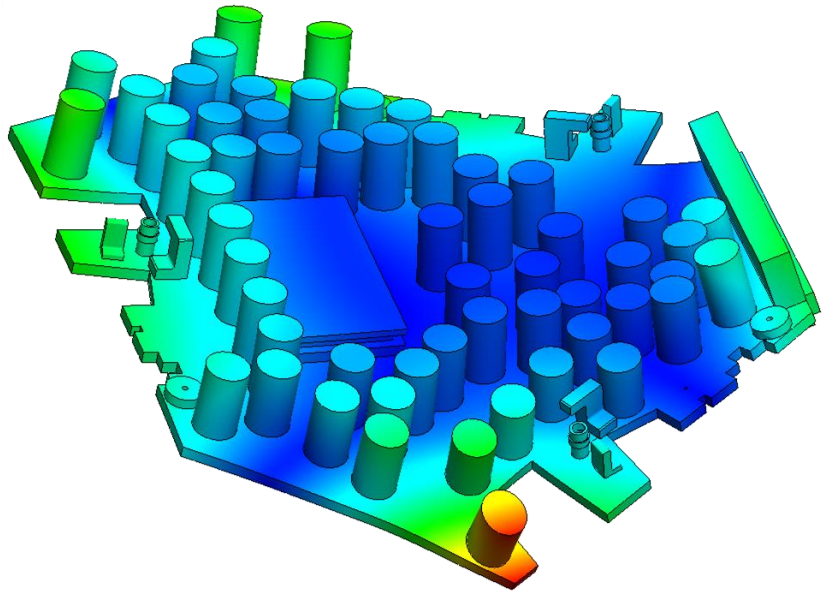




Last Version

- Difference Continuous vs. Contact



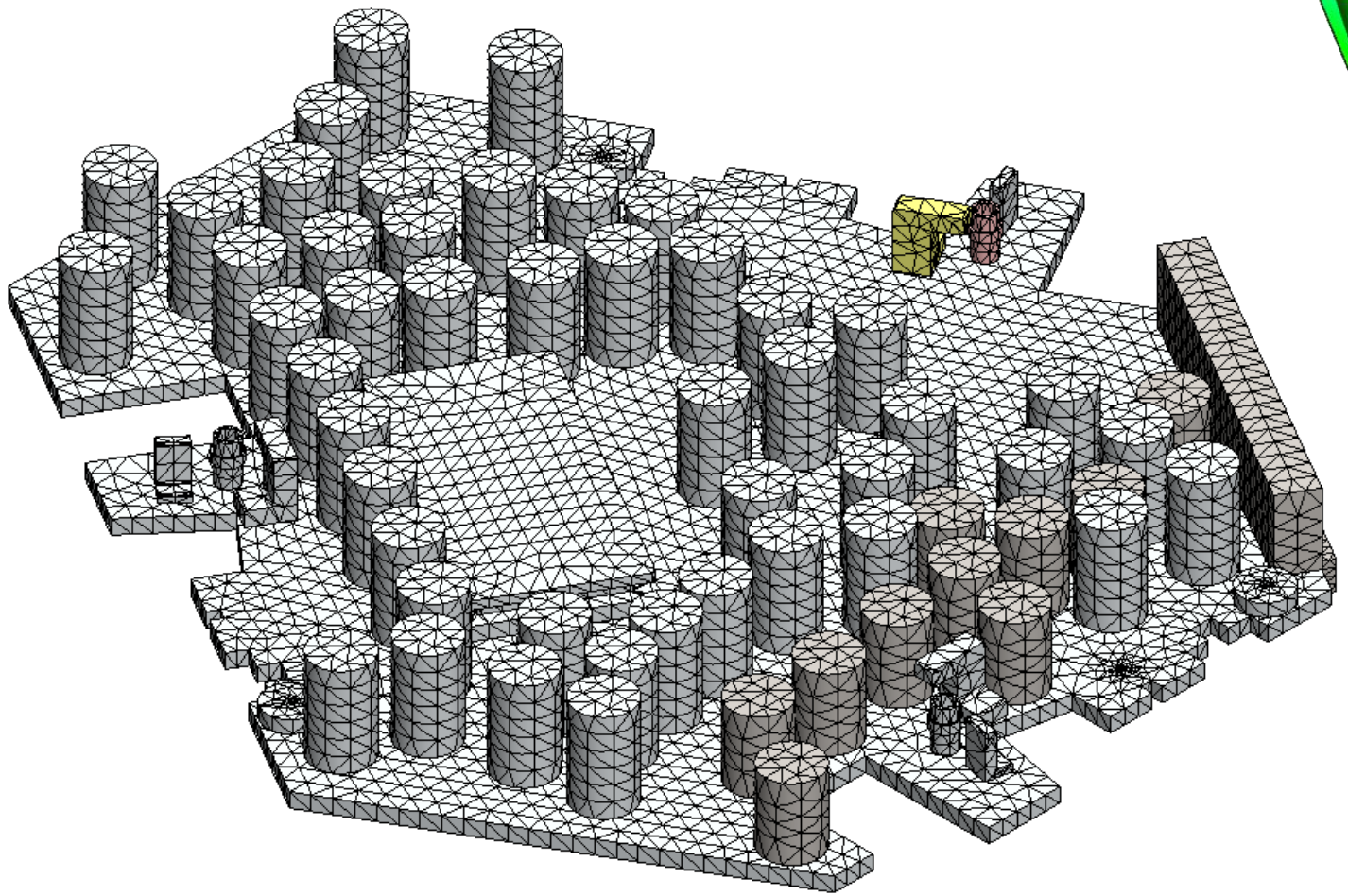


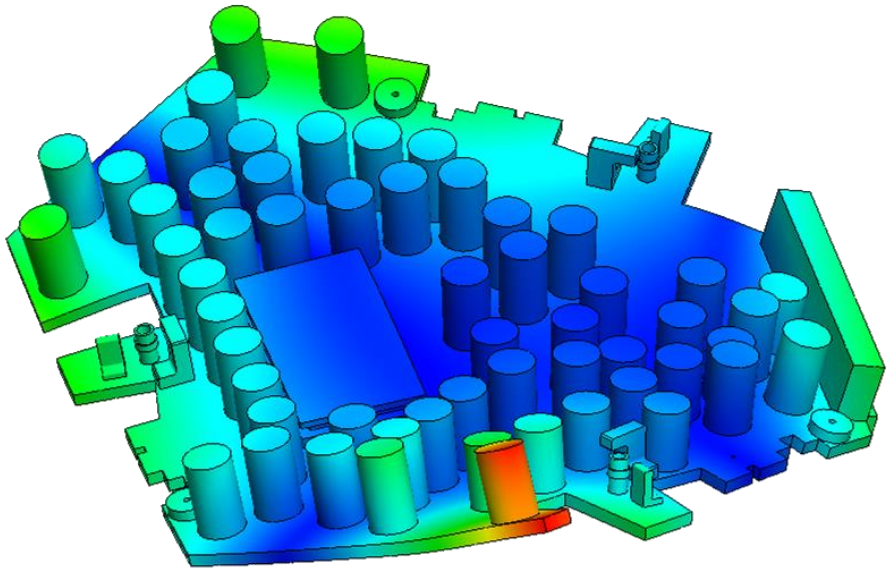
- COMPATIBLE

f = 224.96 Hz

Last Version

- Difference Compatible vs. Incompatible Mash





- INCOMPATIBLE

f = 224.66 Hz

Last Version

- YAW Frequency Calculation

$$I\ddot{\theta} = -3\,R\,KR\theta$$

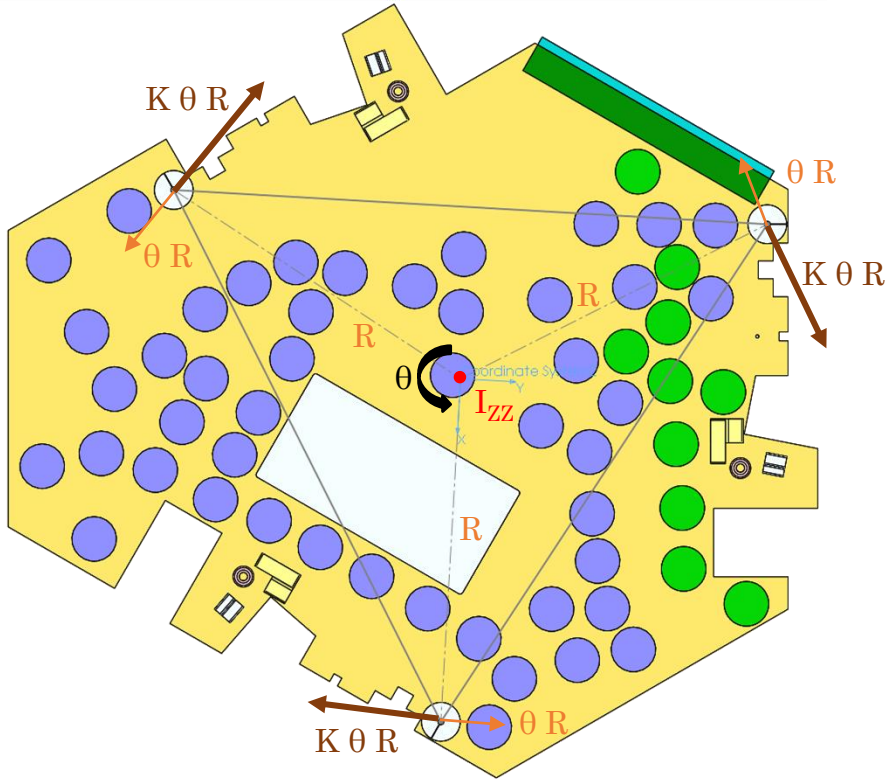
$$\ddot{\theta} + \frac{3KR^2}{I}\theta = 0$$

$$\omega^2 = \frac{3KR^2}{I}$$

$$f = \frac{1}{2\pi}\sqrt{\frac{3KR^2}{I}}$$

$$K = Kxx = 1004.3\ N/m$$

$$f_{YAW} = 1.878\ Hz$$



$I_{ZZ} = 1.842\ kg\ m^2$

R = 0.293 m

Last Version

- PITCH Frequency Calculation

$$I\ddot{\gamma} = -2\ d\ Kd\gamma$$

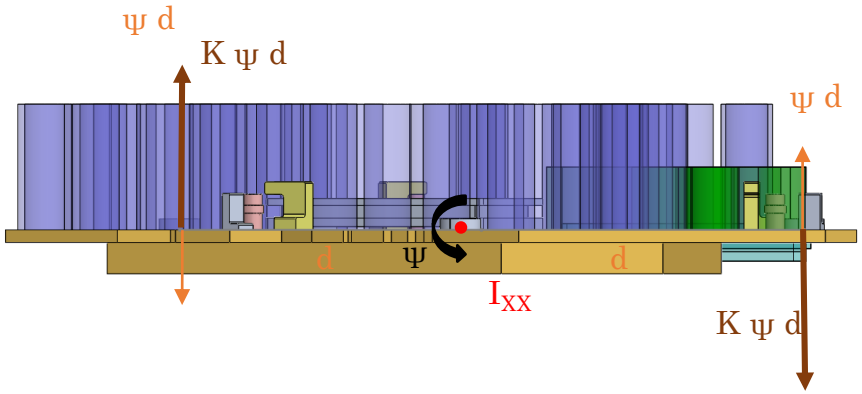
$$\ddot{\gamma} + \frac{2Kd^2}{I}\gamma = 0$$

$$\omega^2 = \frac{2Kd^2}{I}$$

$$f = \frac{1}{2\pi}\sqrt{\frac{2K\frac{3}{4}R^2}{I}}$$

$$K = Kzz = 1443.0\ N/m$$

$$f_{PITCH} = 1.9862Hz$$



$I_{XX} = 1.185\ kg\ m^2$

$d = R\cos(30°)$

$d = 0.254\ m$

Last Version

- ROLL Frequency Calculation

$$I\ddot{\varphi} = -2\, d_2\, K d_2 \varphi - d_1 K d_1\, \varphi$$

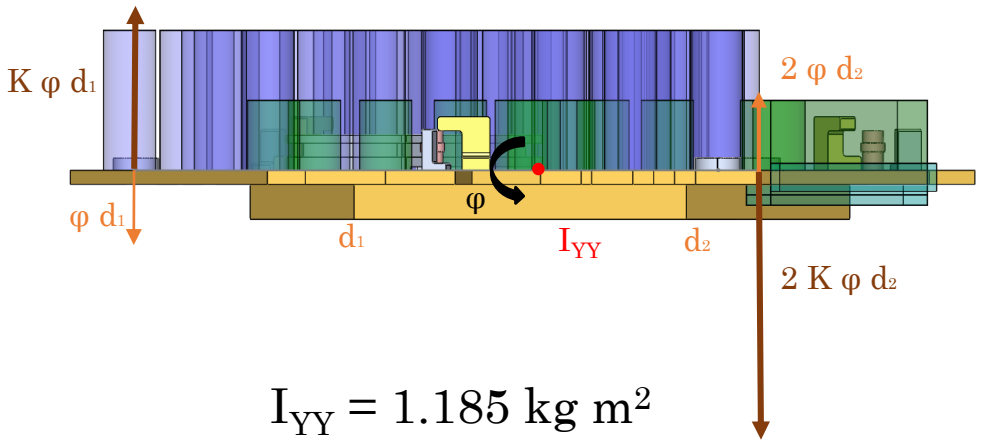
$$\ddot{\varphi} + \frac{K(2{d_2}^2 + {d_1}^2)}{I}\varphi = 0$$

$$\omega^2 = \frac{K(2{d_2}^2 + {d_1}^2)}{I}$$

$$f = \frac{1}{2\pi}\sqrt{\frac{K\frac{3}{2}R^2}{I}}$$

$$K = Kzz = 1443.0\ N/m$$

$$f_{ROLL} = 2.4513\ Hz$$



$I_{YY} = 1.185\ \text{kg m}^2$

$d_1 = \text{R}$

$d_2 = \text{R}\, sin(30°)$

Last Version

- Proper calculation

Mass properties of D1500292 aLIGO VOPO Injection Bench Assembly TO FEA
Configuration: Default
Coordinate system: Coordinate System2

Mass = 37.562 kilograms

Volume = 0.010 cubic meters

Surface area = 1.422 square meters

Center of mass: (meters)
X = 0.000
Y = -0.002
Z = 0.013

Principal axes of inertia and principal moments of inertia: (kilograms * square meters)
Taken at the center of mass.

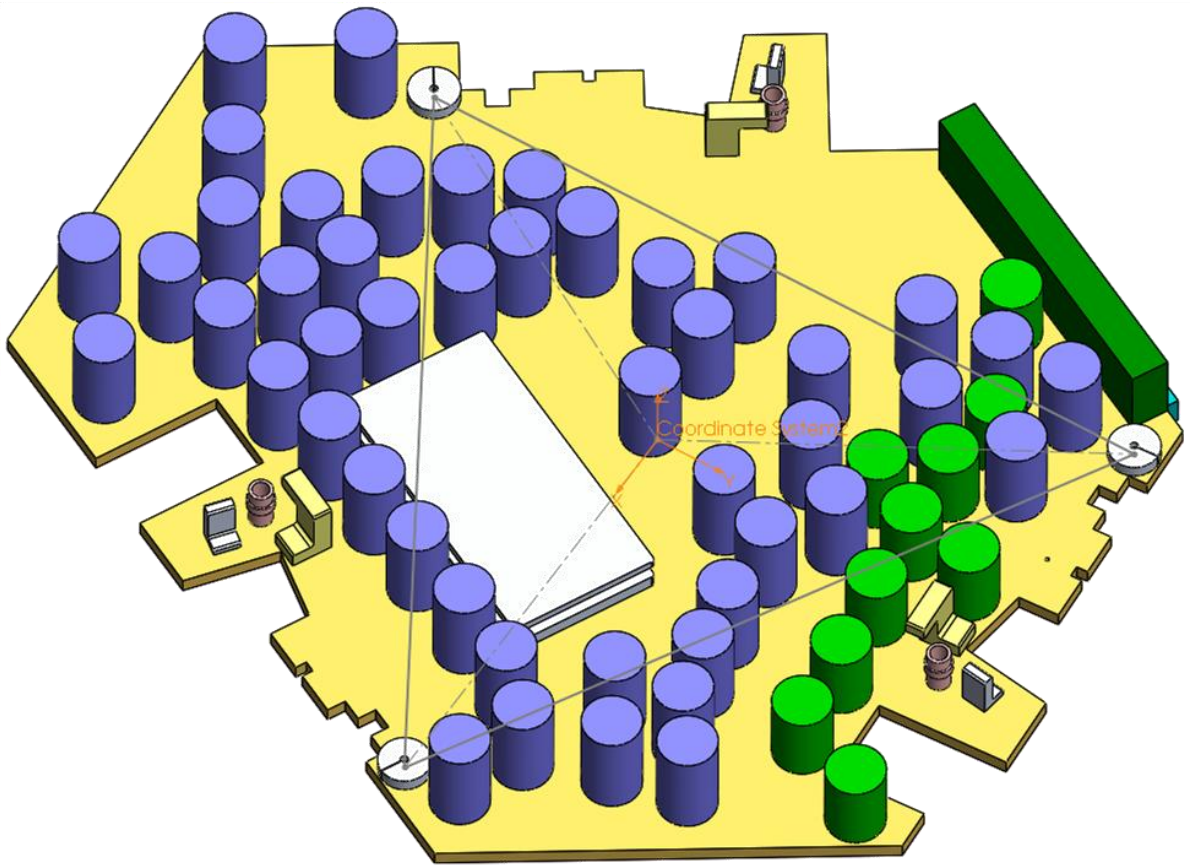
Ix = (-0.228, 0.974, 0.004)	Px = 0.724
Iy = (-0.974, -0.228, -0.017)	Py = 1.165
Iz = (-0.016, -0.007, 1.000)	Pz = 1.842

Moments of inertia: (kilograms * square meters)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 1.142	Lxy = -0.098	Lxz = 0.010
Lyx = -0.098	Lyy = 0.747	Lyz = 0.007
Lzx = 0.010	Lzy = 0.007	Lzz = 1.842

Moments of inertia: (kilograms * square meters)
Taken at the output coordinate system.

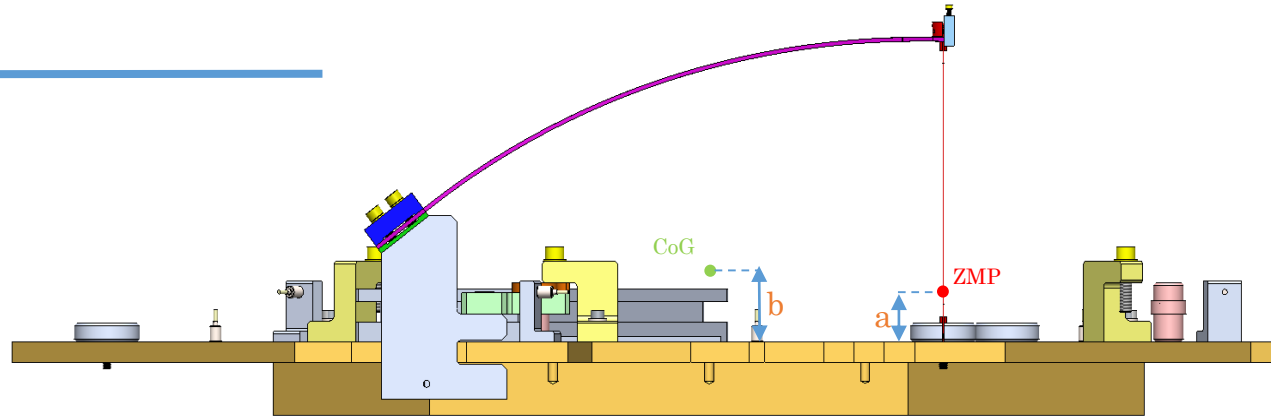
Ixx = 1.149	Ixy = -0.098	Ixz = 0.011
Iyx = -0.098	Iyy = 0.753	Iyz = 0.006
Izx = 0.011	Izy = 0.006	Izz = 1.842



Last Version

- Proper calculation

$$\mathbf{M} = \begin{bmatrix} m_u & 0 & 0 & 0 & 0 & 0 \\ 0 & m_u & 0 & 0 & 0 & 0 \\ 0 & 0 & m_u & 0 & 0 & 0 \\ 0 & 0 & 0 & J_{xx} & 0 & 0 \\ 0 & 0 & 0 & 0 & J_{yy} & 0 \\ 0 & 0 & 0 & 0 & 0 & J_{zz} \end{bmatrix} \qquad \mathbf{U} = \begin{Bmatrix} x \\ y \\ z \\ rx \\ ry \\ rz \end{Bmatrix}$$



a = 10.1596 + 3.4117 = 13.5713 mm

b = 7.035 mm

h_f = b – a = -6.5363 mm

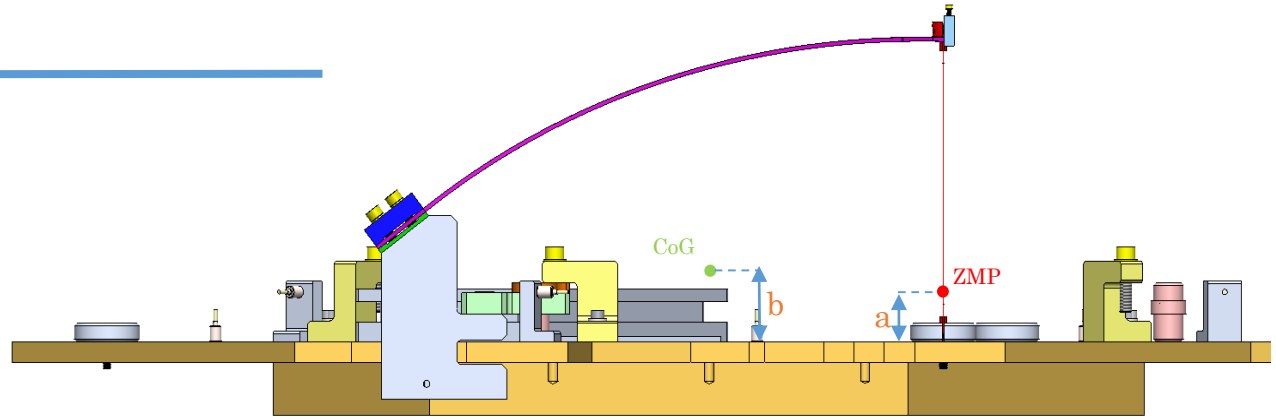
$$\mathbf{K} = \begin{bmatrix} 3k_{xx} & 0 & 0 & 0 & 3k_{xx}h & 0 \\ 0 & 3k_{yy} & 0 & 3k_{yy}h & 0 & 0 \\ 0 & 0 & 3k_{zz} & 0 & 0 & 0 \\ 0 & 3k_{yy}h & 0 & \frac{3}{2}k_{zz}r_s^2 + 3k_{yy}h^2 - m_u gh - m_s gh_s & 0 & 0 \\ 3k_{xx}h & 0 & 0 & 0 & \frac{3}{2}k_{zz}r_s^2 + 3k_{xx}h^2 - m_u gh - m_s gh_s & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{3}{\sqrt{2}}\sqrt{k_{xx}^2 + k_{yy}^2}r_s^2 + 3\frac{GJ_f}{l_f} \end{bmatrix}$$

$$M\ddot{U} + KU = 0$$

Last Version

- Proper calculation: AssemblyFrequencies.m

$$\mathbf{M} = \begin{bmatrix} m_u & 0 & 0 & 0 & 0 & 0 \\ 0 & m_u & 0 & 0 & 0 & 0 \\ 0 & 0 & m_u & 0 & 0 & 0 \\ 0 & 0 & 0 & J_{xx} & 0 & 0 \\ 0 & 0 & 0 & 0 & J_{yy} & 0 \\ 0 & 0 & 0 & 0 & 0 & J_{zz} \end{bmatrix} \qquad \mathbf{U} = \begin{Bmatrix} x \\ y \\ z \\ rx \\ ry \\ rz \end{Bmatrix}$$



a = 12.05 + 3.14 = 15.19 mm

b = 7.035 mm

h_f = b – a = -2.19 mm

$$\mathbf{K} = \begin{bmatrix} 3k_{xx} & 0 & 0 & 0 & 3k_{xx}h & 0 \\ 0 & 3k_{yy} & 0 & 3k_{yy}h & 0 & 0 \\ 0 & 0 & 3k_{zz} & 0 & 0 & 0 \\ 0 & 3k_{yy}h & 0 & \frac{3}{2}k_{zz}r_s^2 + 3k_{yy}h^2 - m_u gh - m_s gh_s & 0 & 0 \\ 3k_{xx}h & 0 & 0 & 0 & \frac{3}{2}k_{zz}r_s^2 + 3k_{xx}h^2 - m_u gh - m_s gh_s & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{3}{\sqrt{2}}\sqrt{k_{xx}^2 + k_{yy}^2}r_s^2 + 3\frac{GJ_f}{l_f} \end{bmatrix}$$

$$M\ddot{U} + KU = 0$$

Last Version

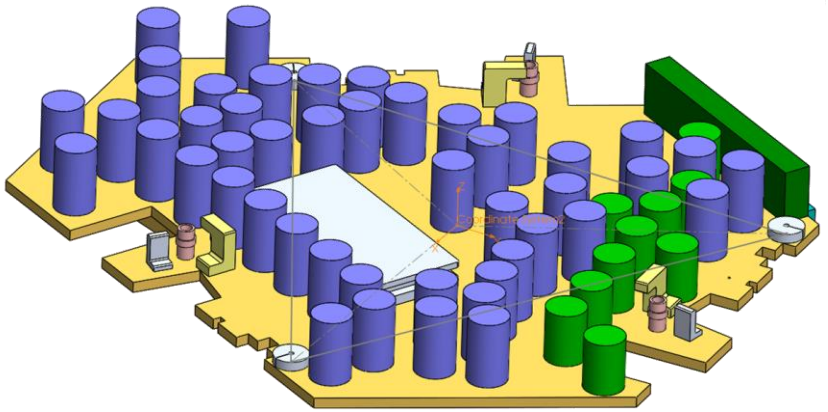
- Proper calculation

$$M\ddot{U} + KU = 0$$

$$\ddot{U} + [M^{-1}K]U = 0$$

$$\omega^2 = eigenvalue(M^{-1}K)$$

$$f = \frac{2}{2\pi}\sqrt{eigenvalue(M^{-1}K)}$$

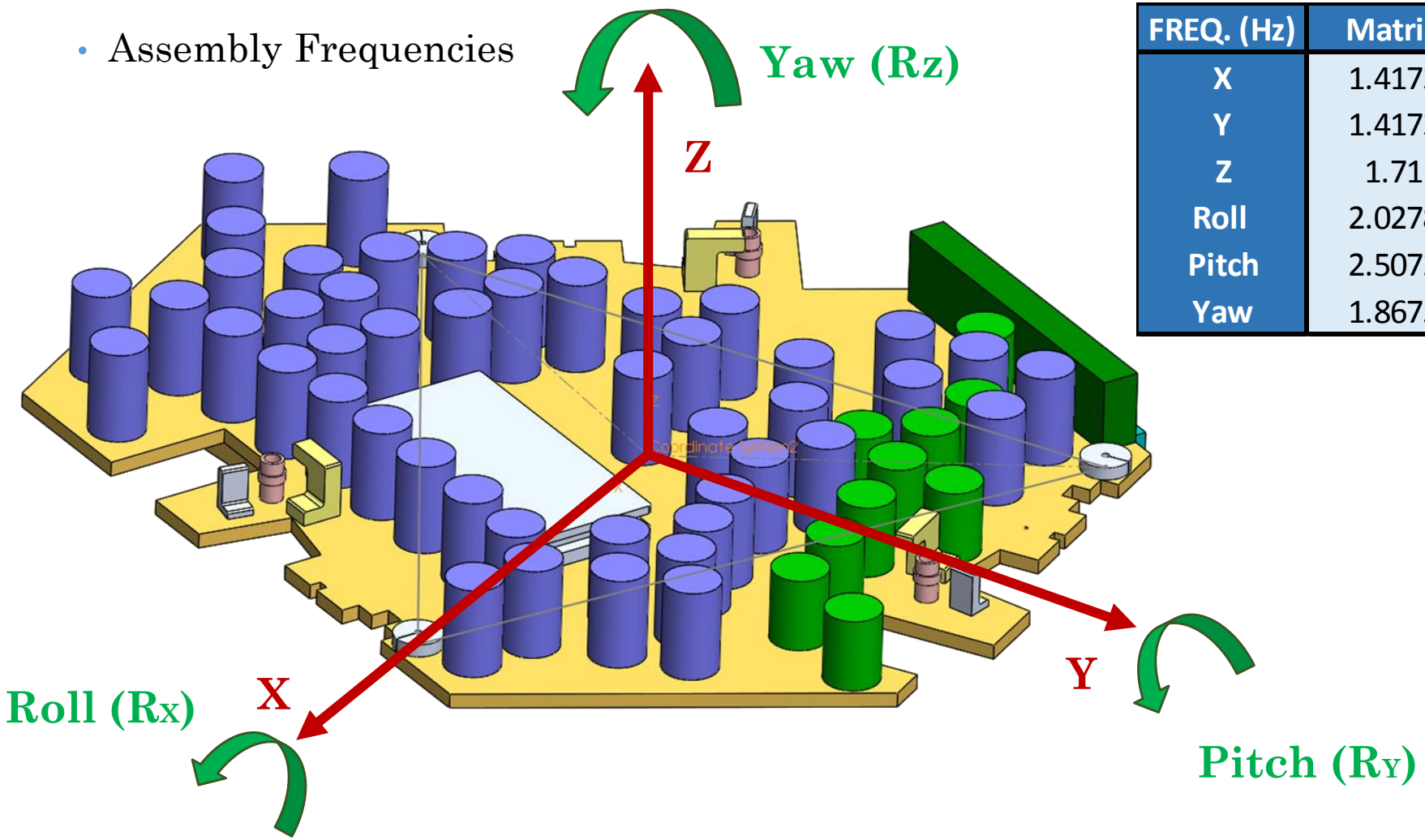


```
Natural_frequencies =

    1.4173         0         0         0         0         0
         0    2.5072         0         0         0         0
         0         0    1.4173         0         0         0
         0         0         0    2.0278         0         0
         0         0         0         0    1.7100         0
         0         0         0         0         0    1.8675


Mode_shapes =

   -0.9987    0.0010         0         0         0         0
         0         0   -0.9977    0.0021         0         0
         0         0         0         0    1.0000         0
         0         0   -0.0685   -1.0000         0         0
   -0.0516   -1.0000         0         0         0         0
         0         0         0         0         0    1.0000


Response_variables =

X
Y
Z
RX
RY
RZ
```

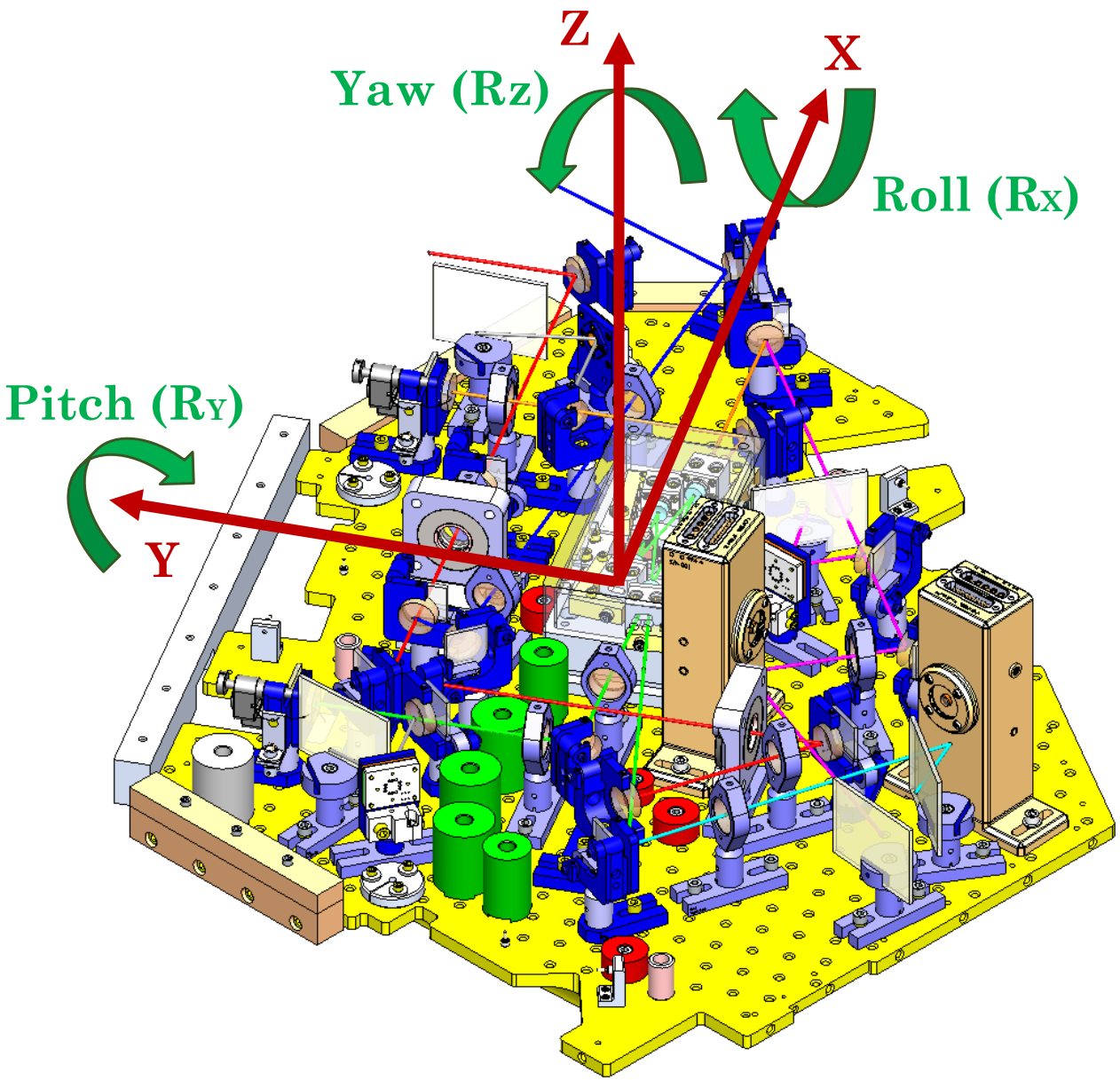
AssemblyFrequencies.m

Last Version

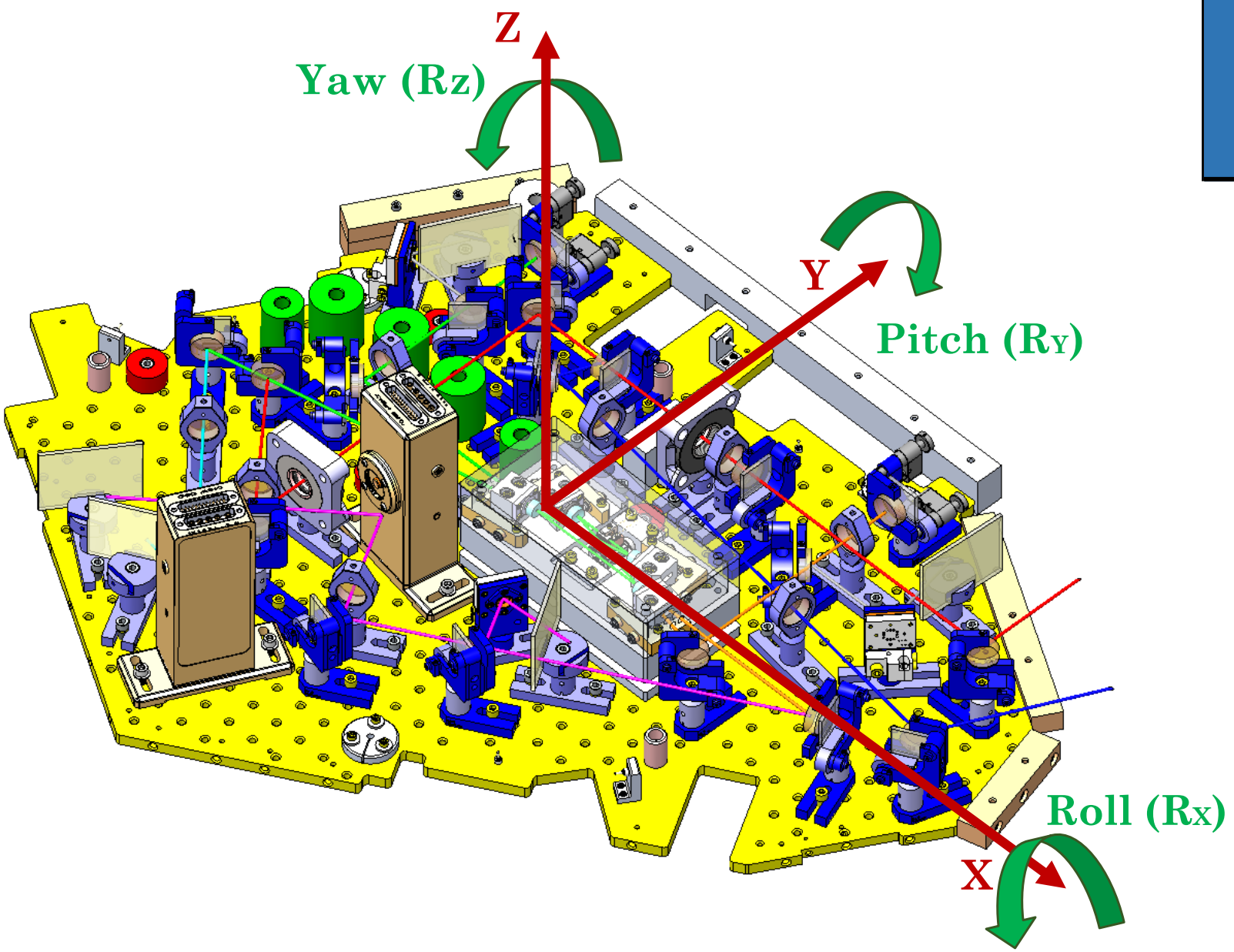
- Assembly Frequencies



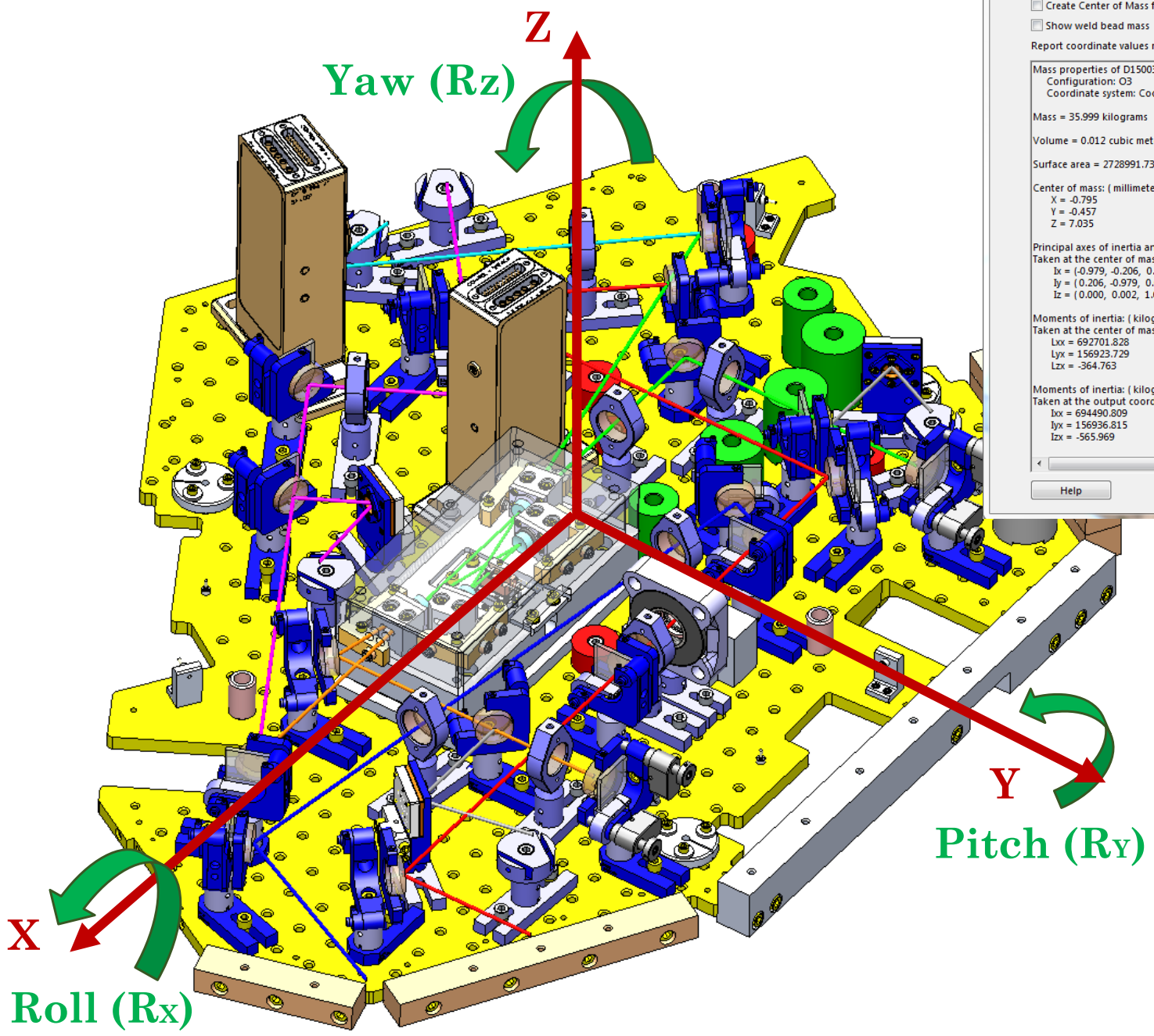
FREQ. (Hz)	Matrix	Formulated	Difference %
X	1.4173	1.4172	0.0
Y	1.4173	1.4172	0.0
Z	1.71	1.71	0.0
Roll	2.0278	1.9862	2.1
Pitch	2.5072	2.4513	2.2
Yaw	1.8675	1.878	-0.6



X	1.4173	1.4172	0.0
Y	1.4173	1.4172	0.0
Z	1.71	1.71	0.0
Roll	2.0278	1.9862	2.1
Pitch	2.5072	2.4513	2.2
Yaw	1.8675	1.878	-0.6



X	1.4173	1.4172	0.0
Y	1.4173	1.4172	0.0
Z	1.71	1.71	0.0
Roll	2.0278	1.9862	2.1
Pitch	2.5072	2.4513	2.2
Yaw	1.8675	1.878	-0.6



Create Center of Mass feature
Show weld bead mass
Report coordinate values relative to: Coordinate System2

Mass properties of D1500302 aLIGO VOPO Suspended Optical Layout
Configuration: O3
Coordinate system: Coordinate System2

Mass = 35.999 kilograms

Volume = 0.012 cubic meters

Surface area = 2728991.732 square millimeters

Center of mass: (millimeters)
X = -0.795
Y = -0.457
Z = 7.035

Principal axes of inertia and principal moments of inertia: (kilograms * square millimeters)
Taken at the center of mass.
Ix = (-0.979, -0.206, 0.000) Px = 659649.816
Iy = (0.206, -0.979, 0.002) Py = 1437745.424
Iz = (0.000, 0.002, 1.000) Pz = 2032325.761

Moments of inertia: (kilograms * square millimeters)
Taken at the center of mass and aligned with the output coordinate system.
Lxx = 692701.828 Lxy = 156923.729 Lxz = -364.763
Lyx = 156923.729 Lyy = 1404696.893 Lyz = -1478.164
Lzx = -364.763 Lzy = -1478.164 Lzz = 2032322.280

Moments of inertia: (kilograms * square millimeters)
Taken at the output coordinate system.
Ixx = 694490.809 Ixy = 156936.815 Ixz = -565.969
Iyx = 156936.815 Iyy = 1406501.064 Iyz = -1594.020
Izx = -565.969 Izy = -1594.020 Izz = 2032352.540

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ended Optical Layout.SLDASM

Options...

Recalculate

nponents

Create Center of Mass feature
Show weld bead mass
Report coordinate values relative to: Coordinate System2

Mass properties of D1500302 aLIGO VOPO Suspended Optical Layout
Configuration: O3
Coordinate system: Coordinate System2

Mass = 35.999 kilograms

Volume = 0.012 cubic meters

Surface area = 2.729 square meters

Center of mass: (meters)
X = -0.001
Y = 0.000
Z = 0.007

Principal axes of inertia and principal moments of inertia: (kilograms * square meters)
Taken at the center of mass.
Ix = (-0.979, -0.206, 0.000) Px = 0.660
Iy = (0.206, -0.979, 0.002) Py = 1.438
Iz = (0.000, 0.002, 1.000) Pz = 2.032

Moments of inertia: (kilograms * square meters)
Taken at the center of mass and aligned with the output coordinate system.
Lxx = 0.693 Lxy = 0.157 Lxz = 0.000
Lyx = 0.157 Lyy = 1.405 Lyz = -0.001
Lzx = 0.000 Lzy = -0.001 Lzz = 2.032

Moments of inertia: (kilograms * square meters)
Taken at the output coordinate system.
Ixx = 0.694 Ixy = 0.157 Ixz = -0.001
Iyx = 0.157 Iyy = 1.407 Iyz = -0.002
Izx = -0.001 Izy = -0.002 Izz = 2.032

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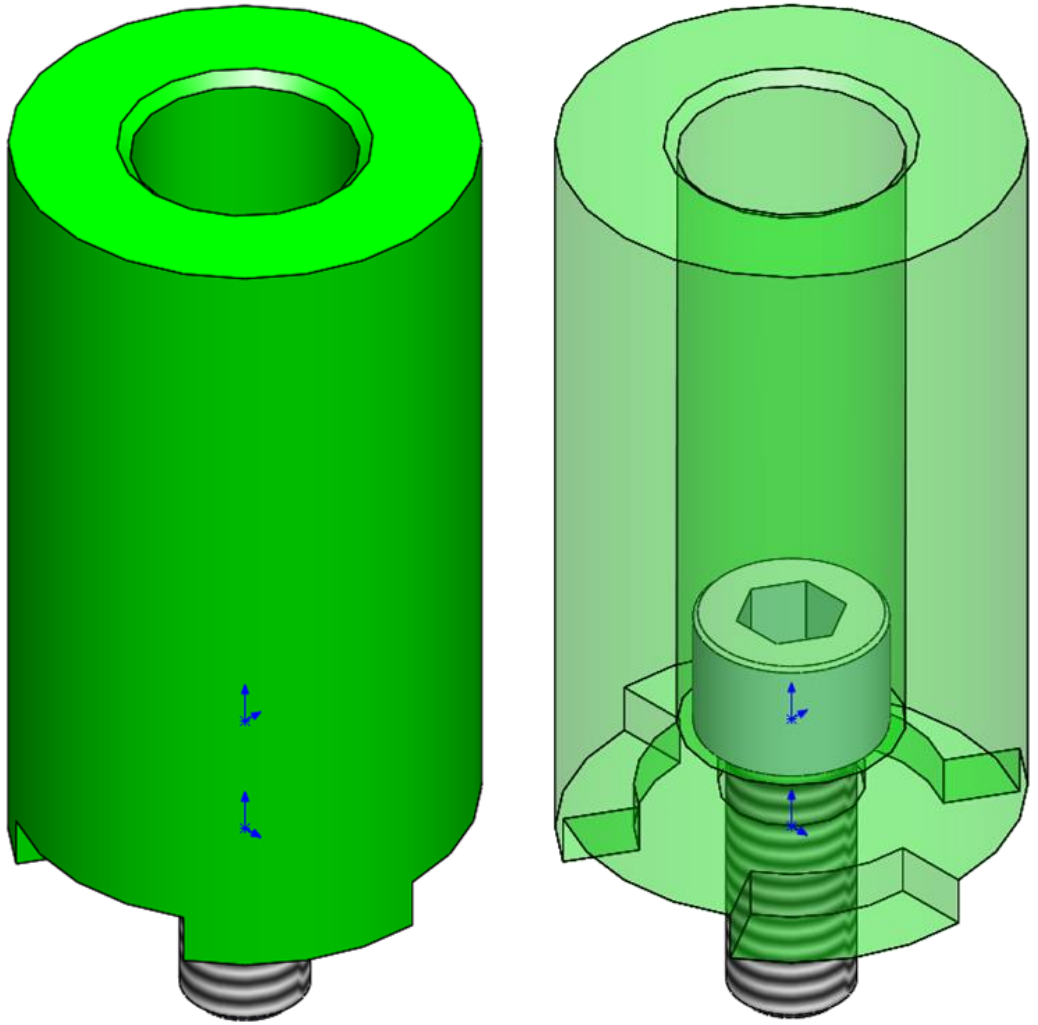
Balancing Masses

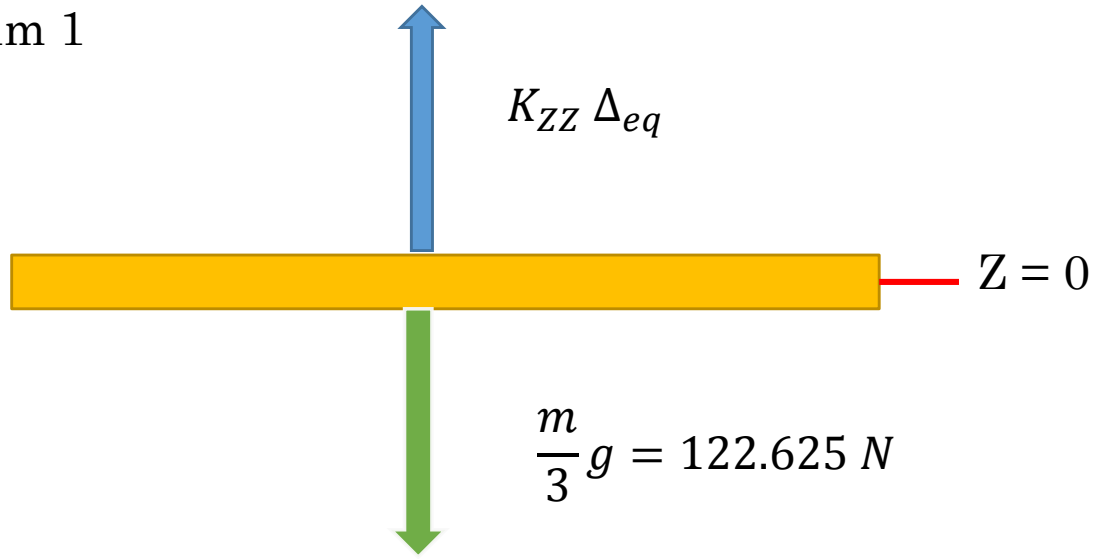
- Masses in a high range of values
  - 25g
  - 53g
  - 76g
  - 100g (x2)
  - 146g
  - 200g
  - 245g
  - 252g
  - 302g
  - 402g
  - 413g
  - 507g
  - 610g
- Maximum height = 2 in (-0.5in beam plane)
- Holo-Kromme SHCS ¼”-20 x 0.625: 6g



Balancing Masses

- Minimum Mass Range Calculation
  - "Perfect" alignment without extra mass addition/removal

Equilibrium 1 blade



$$K_{zz}\,\Delta_{eq} = \frac{m}{3}g$$

$$\Delta_{eq} = \frac{\frac{m}{3}g}{K_{zz}}$$

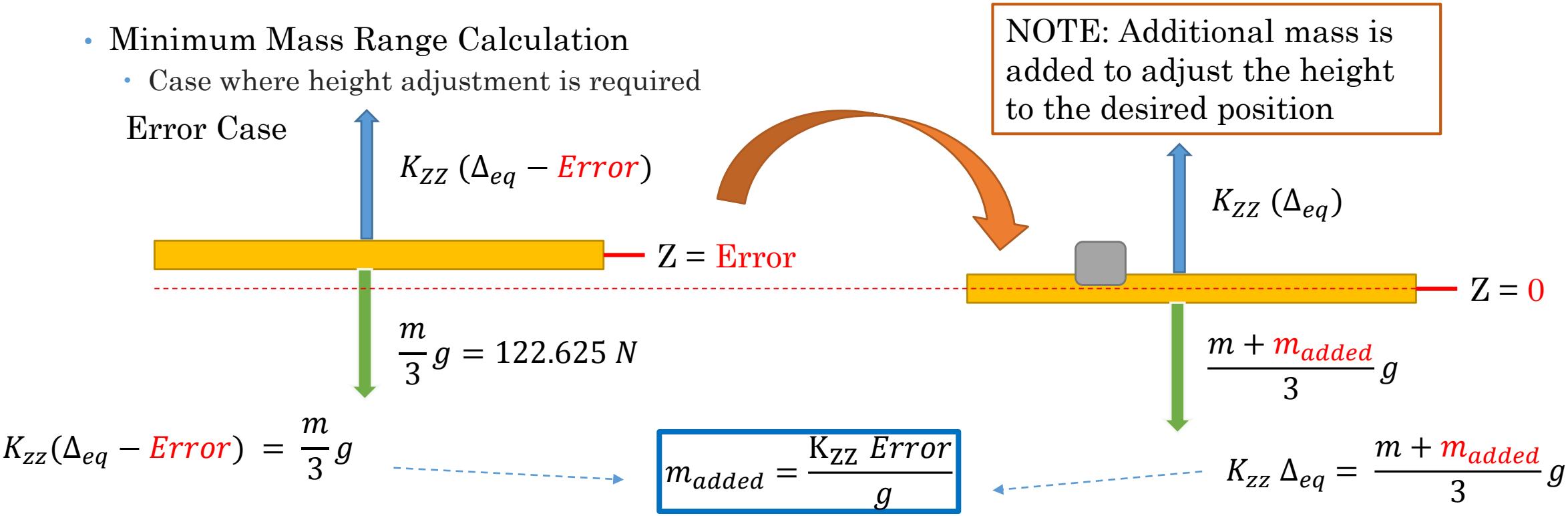
$$K_{zz} = 1443\,\frac{N}{m}$$

$$m = 37.5\ kg$$

$$\Delta_{eq} = 84.98\ \text{mm}$$

Balancing Masses

- Minimum Mass Range Calculation
  - Case where height adjustment is required



Error (mm)	0.01	0.05	0.1	0.15	0.2	0.25	0.5	0.75	1	1.5	2	3
Mass to be added (g)	1.47	7.35	14.71	22.06	29.42	36.19	73.55	110.32	147.09	220.64	294.19	441.28

NOTE: The final balancing will be made using screws and washers as they are about the desired weight

Balancing Masses

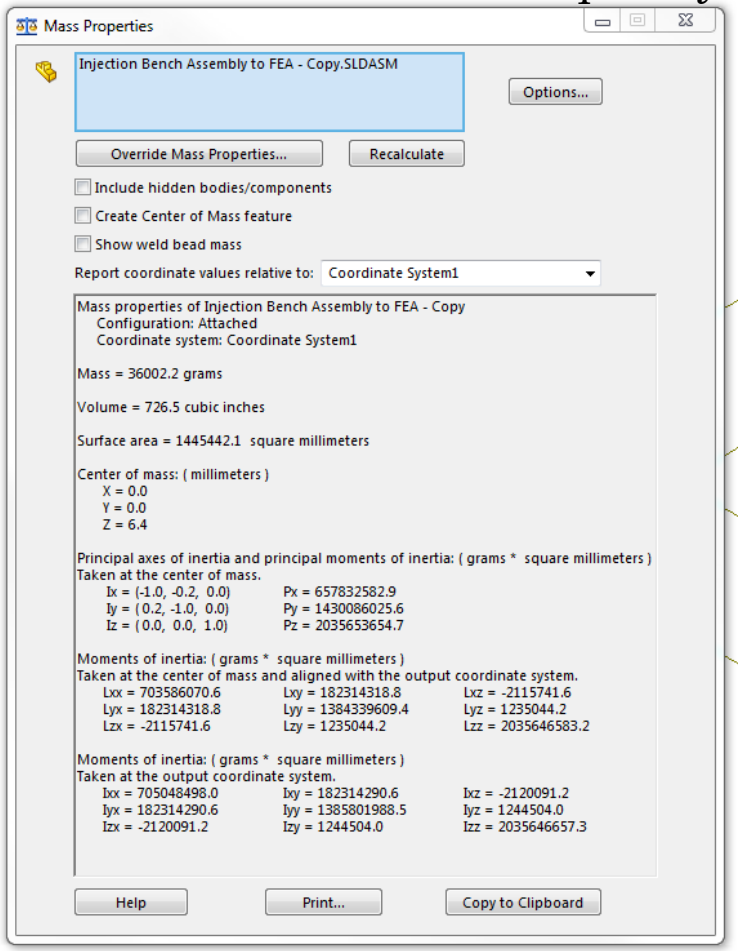
VOPO Injection Bench Assembly FEA II

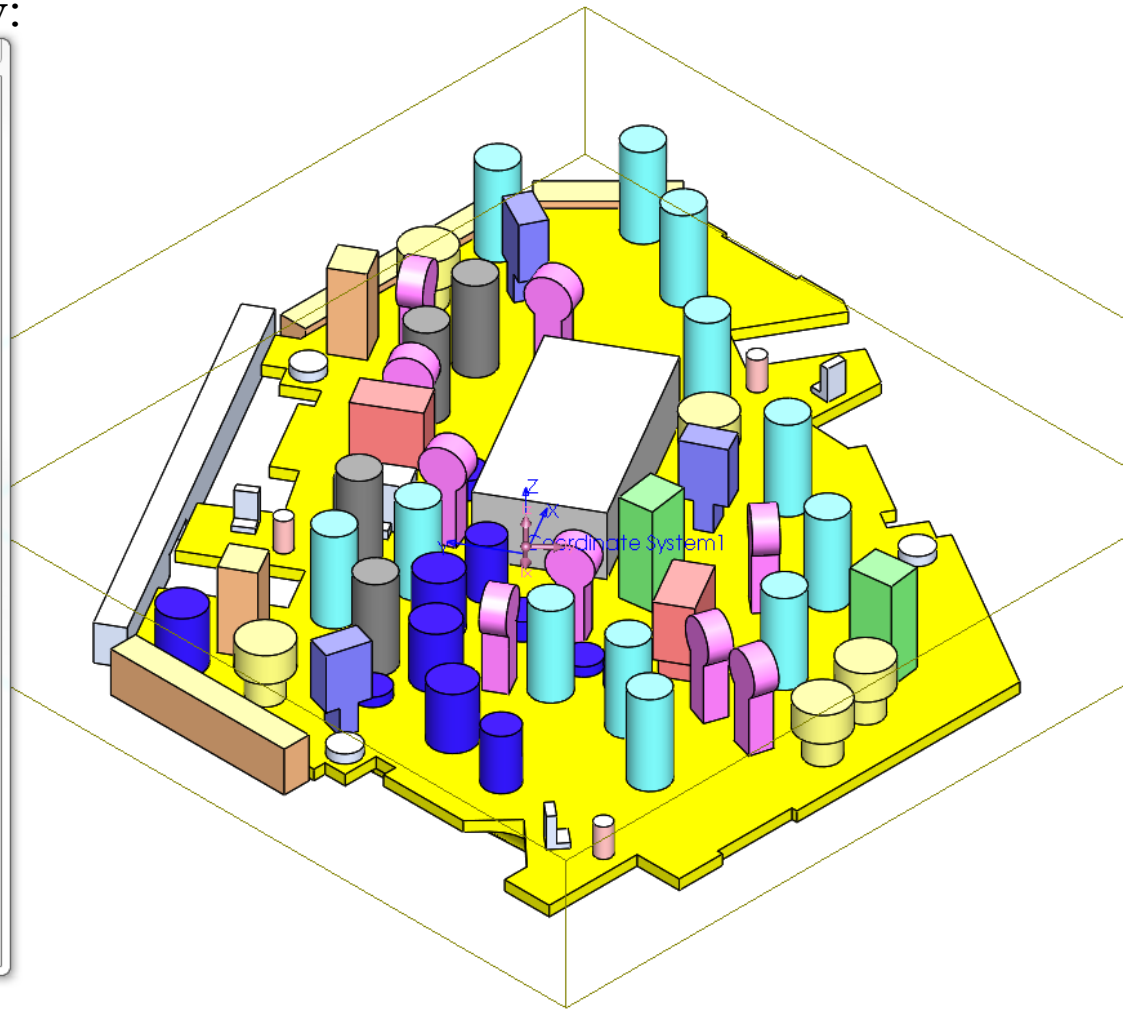
LIGO MIT Lab

Matichard, Fabrice
Fernandez Galiana, Alvaro

Global Results

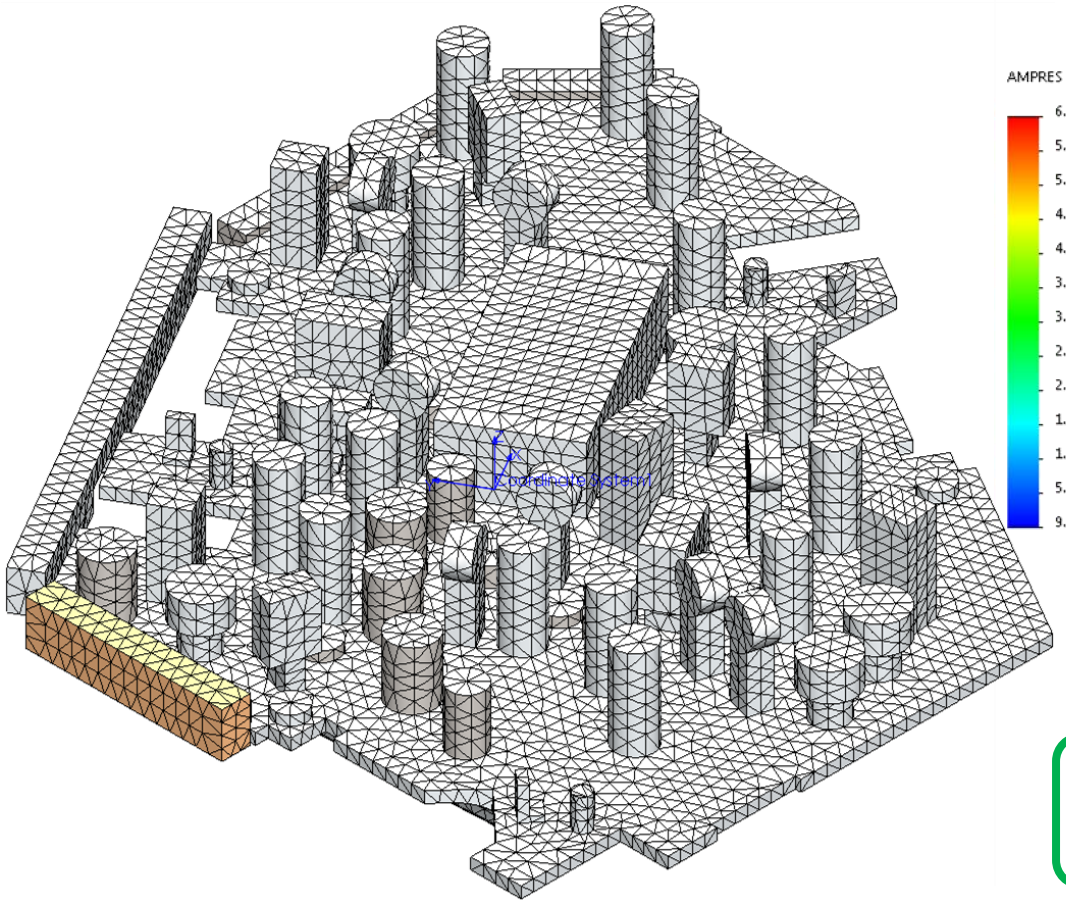
- First Resonance Frequency:

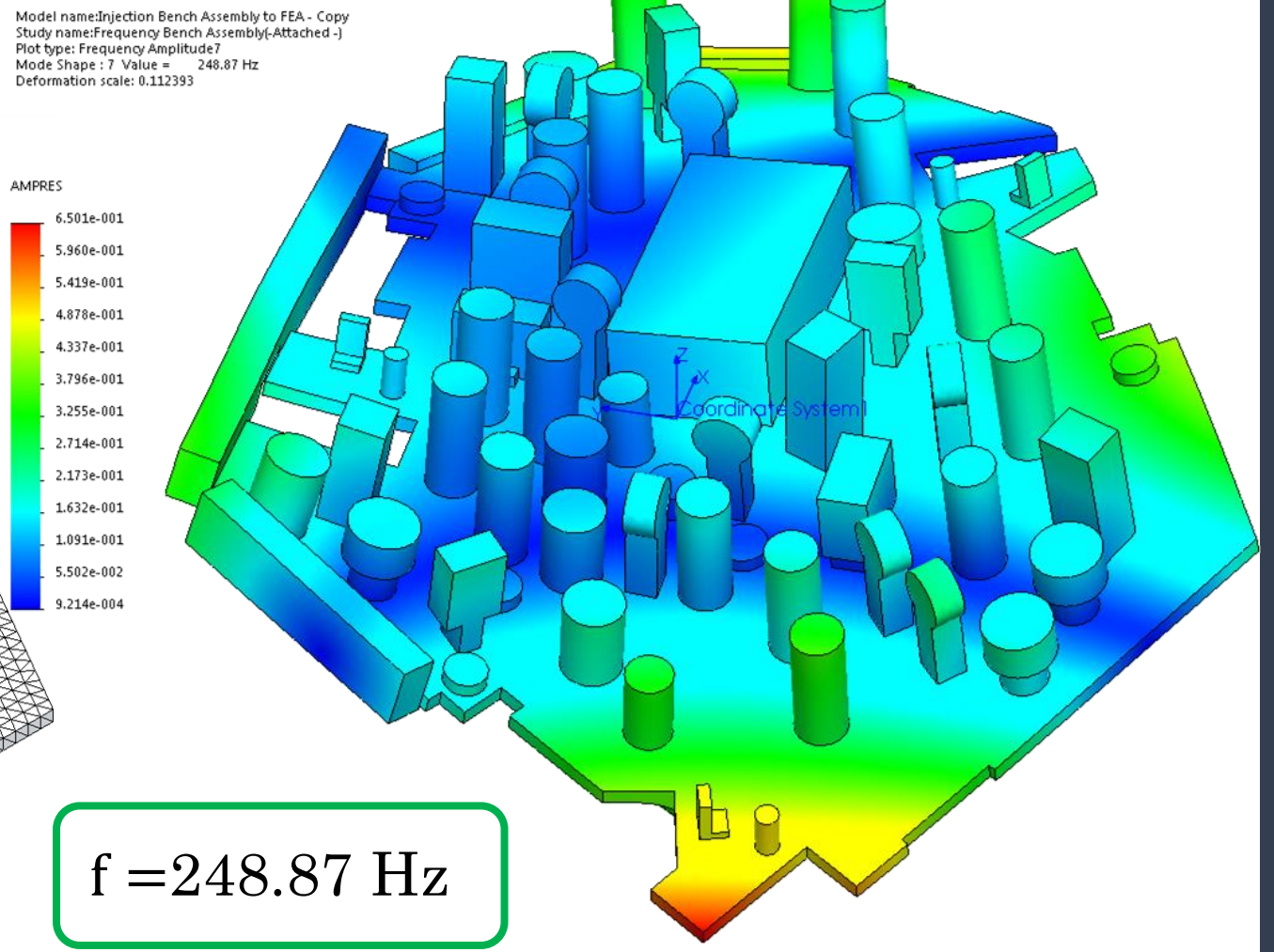




Global Results

- First Resonance Frequency:

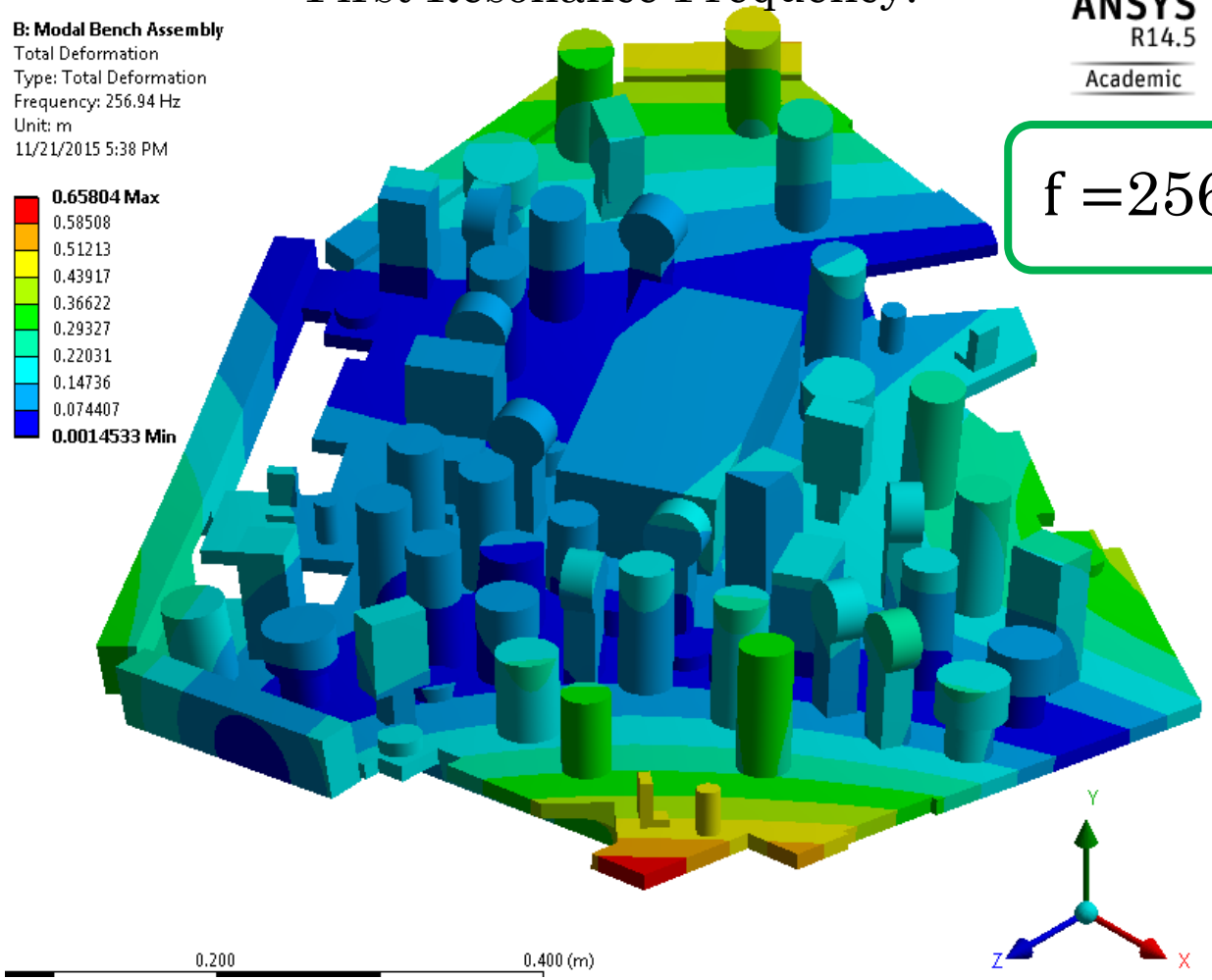




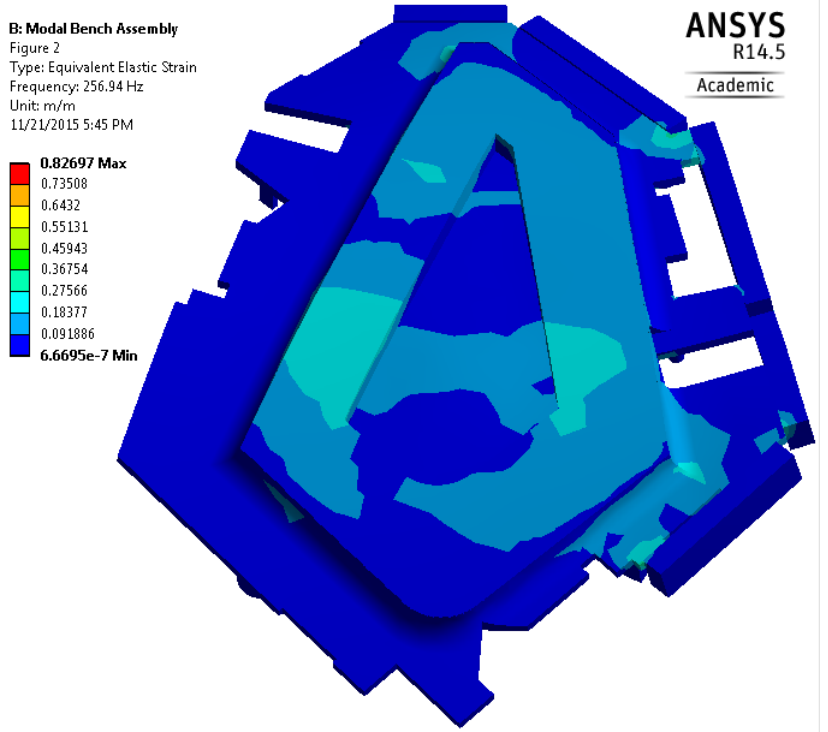
f =248.87 Hz

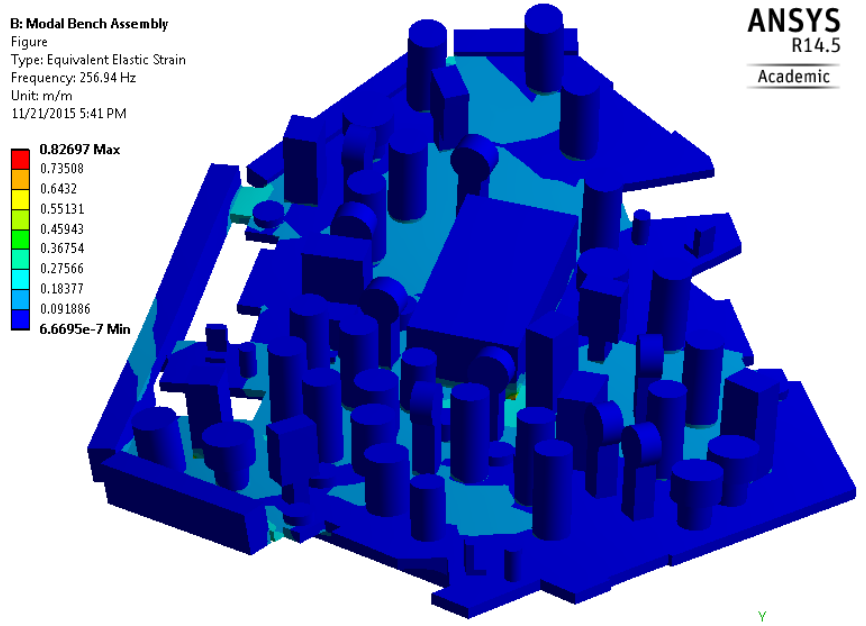
Global Results

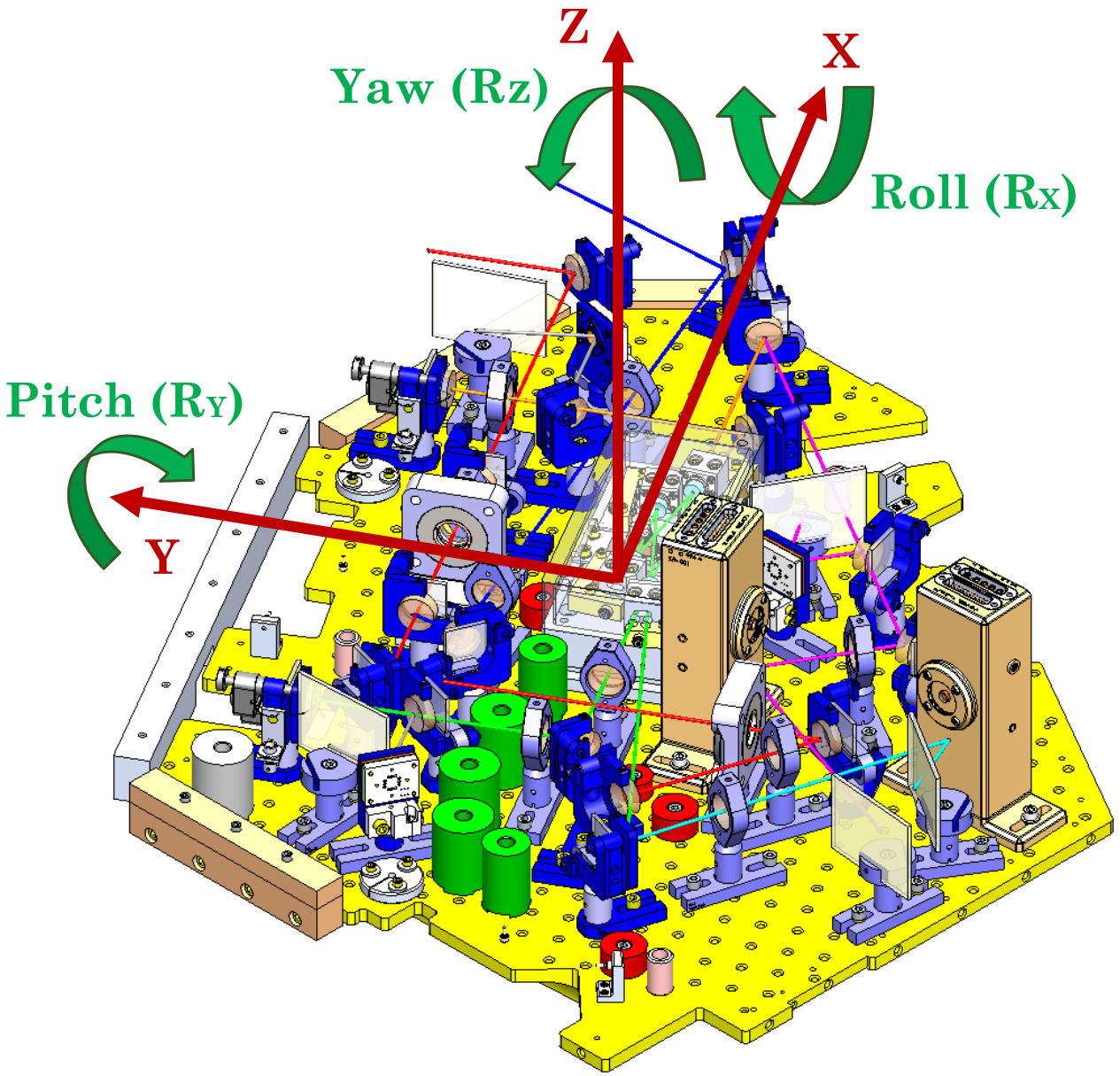
- First Resonance Frequency:



f =256.94 Hz







Mass Properties

D1500302 aLIGO VOPO Suspended Optical Layout.SLDASM

Options...

Override Mass Properties... | Recalculate

☐ Include hidden bodies/components

☐ Create Center of Mass feature

☐ Show weld bead mass

Report coordinate values relative to: Coordinate System2

Mass properties of D1500302 aLIGO VOPO Suspended Optical Layout
Configuration: O3
Coordinate system: Coordinate System2

Mass = 35.999 kilograms

Volume = 0.012 cubic meters

Surface area = 2728991.732 square millimeters

Center of mass: (millimeters)
X = 0.000
Y = 0.000
Z = 7.035

Principal axes of inertia and principal moments of inertia: (kilograms * square millin
Taken at the center of mass.

Ix = (-0.979, -0.204, 0.000)	Px = 659807.600
Iy = (0.204, -0.979, 0.002)	Py = 1427630.261
Iz = (0.000, 0.002, 1.000)	Pz = 2022367.612

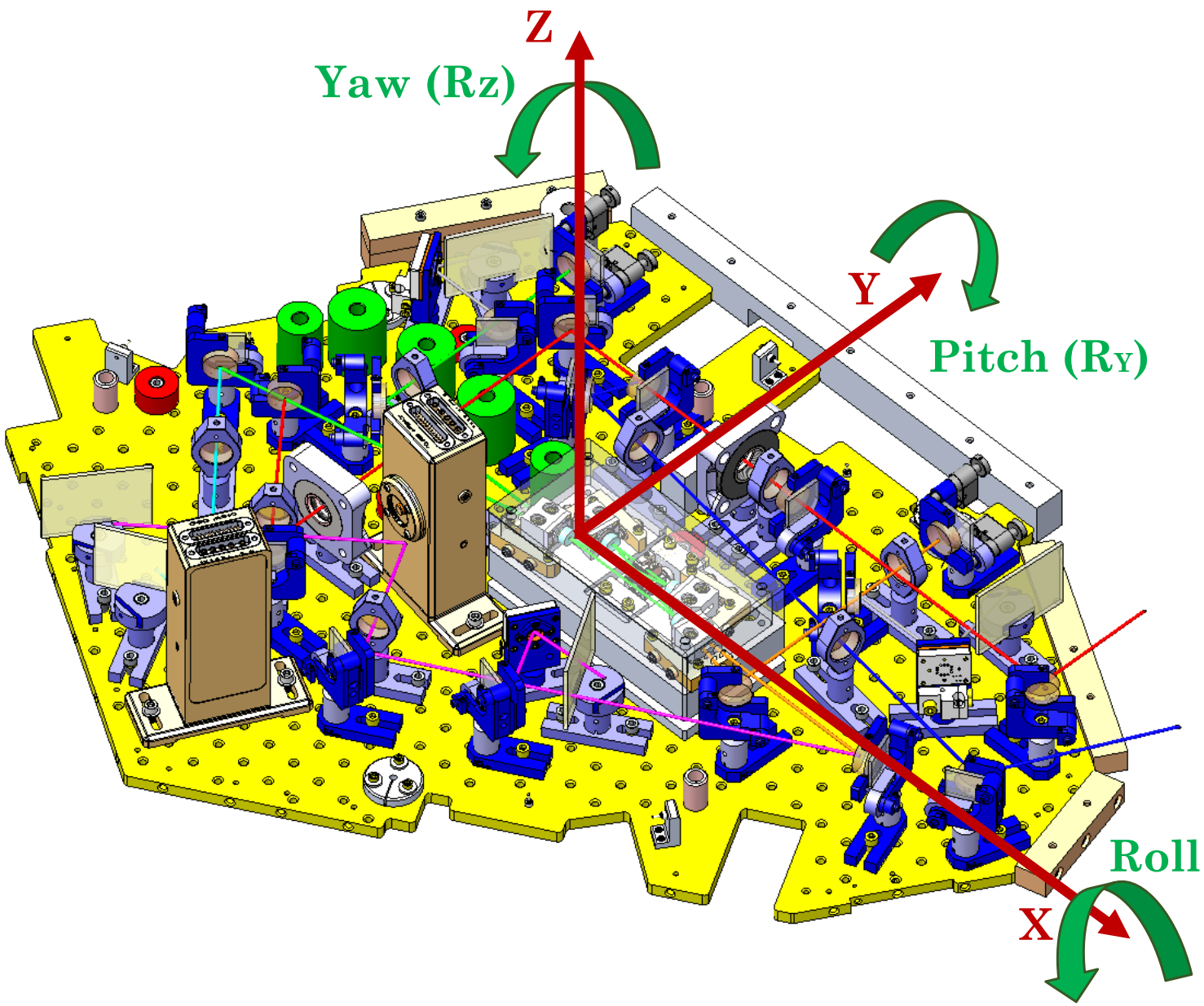
Moments of inertia: (kilograms * square millimeters)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 691660.968	Lxy = 153111.071	Lxz = -317.766
Lyx = 153111.071	Lyy = 1395779.989	Lyz = -1392.785
Lzx = -317.766	Lzy = -1392.785	Lzz = 2022364.516

Moments of inertia: (kilograms * square millimeters)
Taken at the output coordinate system.

Ixx = 693442.414	Ixy = 153111.071	Ixz = -317.848
Iyx = 153111.071	Iyy = 1397561.434	Iyz = -1392.888
Izx = -317.848	Izy = -1392.888	Izz = 2022364.516

Help | Print... | Copy to Clipboard



Mass Properties

D1500302 aLIGO VOPO Suspended Optical Layout.SLDASM

Options...

Override Mass Properties... | Recalculate

Include hidden bodies/components

Create Center of Mass feature

Show weld bead mass

Report coordinate values relative to: Coordinate System2

Mass properties of D1500302 aLIGO VOPO Suspended Optical Layout
Configuration: O3
Coordinate system: Coordinate System2

Mass = 35.999 kilograms

Volume = 0.012 cubic meters

Surface area = 2.729 square meters

Center of mass: (meters)
X = 0.000
Y = 0.000
Z = 0.007

Principal axes of inertia and principal moments of inertia: (kilograms * square meter
Taken at the center of mass.

Ix = (-0.979, -0.204, 0.000)	Px = 0.660
Iy = (0.204, -0.979, 0.002)	Py = 1.428
Iz = (0.000, 0.002, 1.000)	Pz = 2.022

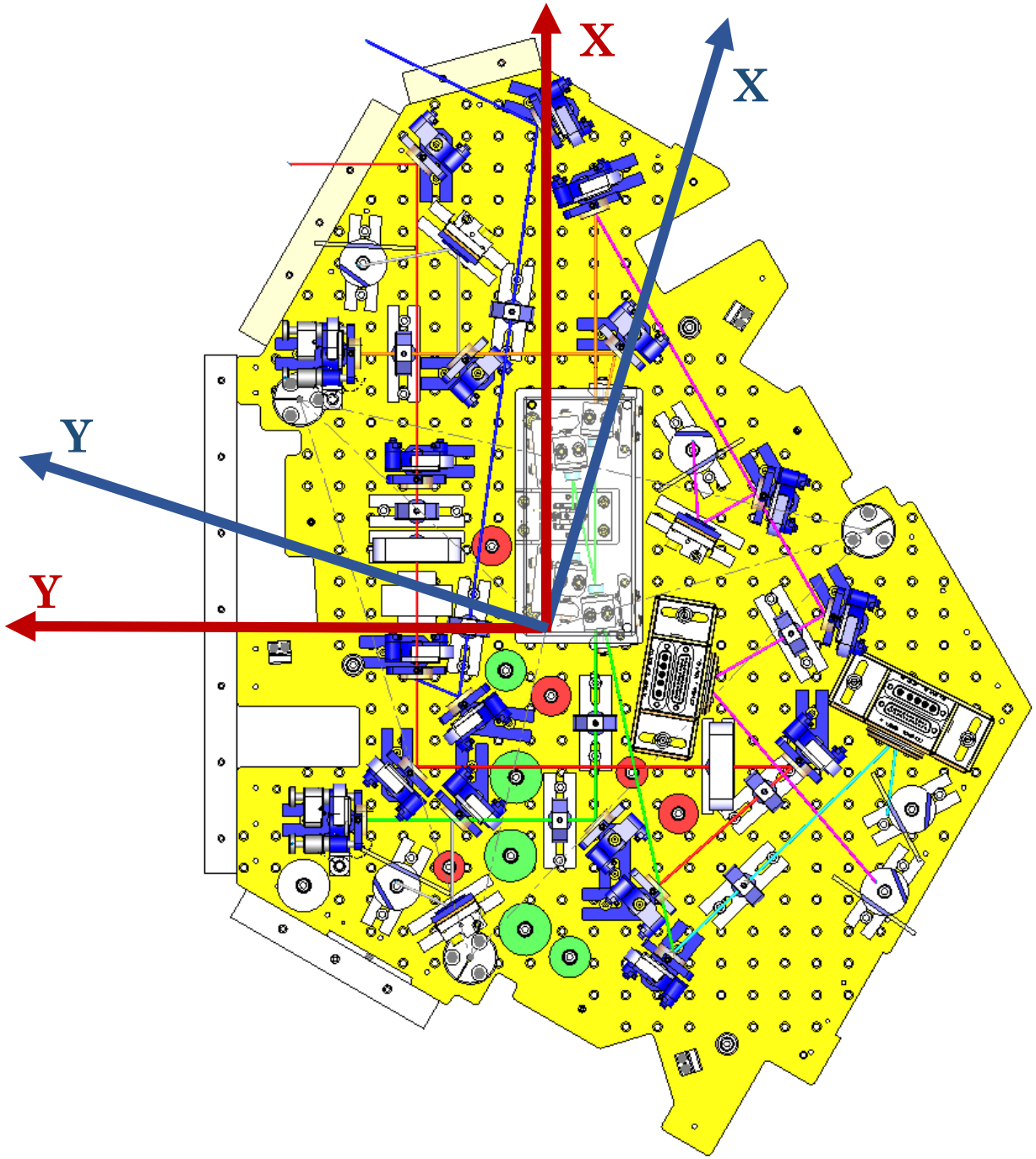
Moments of inertia: (kilograms * square meters)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 0.692	Lxy = 0.153	Lxz = 0.000
Lyx = 0.153	Lyy = 1.396	Lyz = -0.001
Lzx = 0.000	Lzy = -0.001	Lzz = 2.022

Moments of inertia: (kilograms * square meters)
Taken at the output coordinate system.

Ixx = 0.693	Ixy = 0.153	Ixz = 0.000
Iyx = 0.153	Iyy = 1.398	Iyz = -0.001
Izx = 0.000	Izy = -0.001	Izz = 2.022

Help | Print... | Copy to Clipboard



Mass Properties

D1500302 aLIGO VOPO Suspended Optical Layout.SLDASM

Options...

Override Mass Properties... | Recalculate

☐ Include hidden bodies/components

☐ Create Center of Mass feature

☐ Show weld bead mass

Report coordinate values relative to: Coordinate System3

Mass properties of D1500302 aLIGO VOPO Suspended Optical Layout
Configuration: O3
Coordinate system: Coordinate System3

Mass = 35.999 kilograms

Volume = 0.012 cubic meters

Surface area = 2.729 square meters

Center of mass: (meters)
X = 0.000
Y = 0.000
Z = 0.007

Principal axes of inertia and principal moments of inertia: (kilograms * square meter
Taken at the center of mass.

Ix = (-0.908, -0.419, 0.000)	Px = 0.660
Iy = (0.419, -0.908, 0.002)	Py = 1.428
Iz = (-0.001, 0.002, 1.000)	Pz = 2.022

Moments of inertia: (kilograms * square meters)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 0.795	Lxy = 0.292	Lxz = 0.000
Lyx = 0.292	Lyy = 1.293	Lyz = -0.001
Lzx = 0.000	Lzy = -0.001	Lzz = 2.022

Moments of inertia: (kilograms * square meters)
Taken at the output coordinate system.

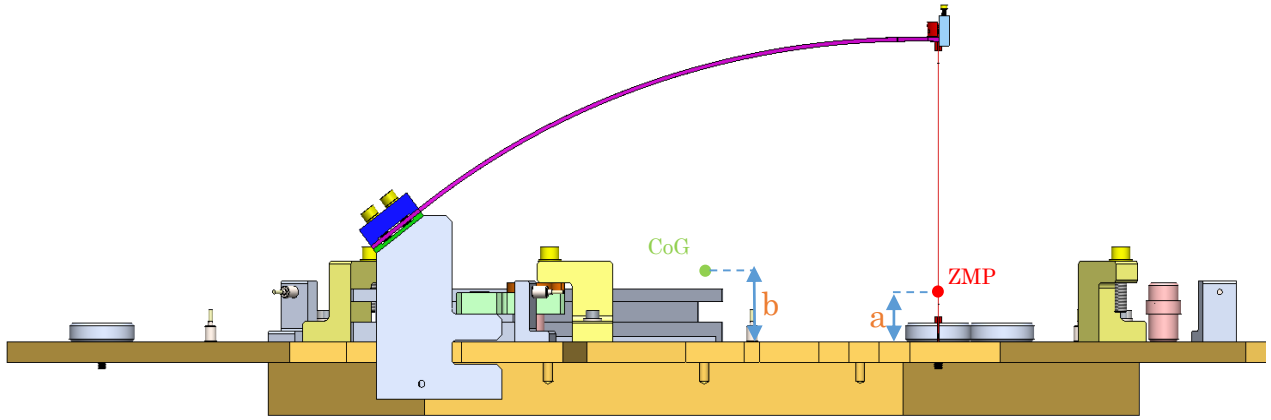
Ixx = 0.796	Ixy = 0.292	Ixz = 0.000
Iyx = 0.292	Iyy = 1.295	Iyz = -0.001
Izx = 0.000	Izy = -0.001	Izz = 2.022

Help | Print... | Copy to Clipboard

Last Version

- Proper calculation

$$\mathbf{M}=\begin{bmatrix} m_u & 0 & 0 & 0 & 0 & 0 \\ 0 & m_u & 0 & 0 & 0 & 0 \\ 0 & 0 & m_u & 0 & 0 & 0 \\ 0 & 0 & 0 & J_{xx} & 0 & 0 \\ 0 & 0 & 0 & 0 & J_{yy} & 0 \\ 0 & 0 & 0 & 0 & 0 & J_{zz} \end{bmatrix} \qquad \mathbf{U}=\begin{Bmatrix} x \\ y \\ z \\ rx \\ ry \\ rz \end{Bmatrix}$$



a = 10.1596 + 3.4117 = 13.5713 mm

b = 7.035 mm

h_f= b – a = -6.5363 mm

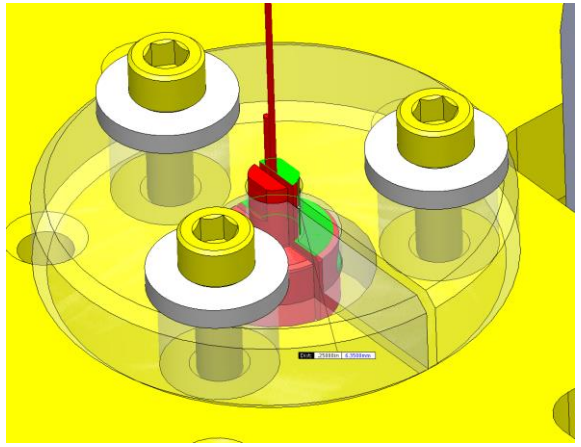
$$\mathbf{K}=\begin{bmatrix} 3k_{xx} & 0 & 0 & 0 & 3k_{xx}h & 0 \\ 0 & 3k_{yy} & 0 & 3k_{yy}h & 0 & 0 \\ 0 & 0 & 3k_{zz} & 0 & 0 & 0 \\ 0 & 3k_{yy}h & 0 & \frac{3}{2}k_{zz}r_s^2+3k_{yy}h^2-m_u gh-m_s gh_s & 0 & 0 \\ 3k_{xx}h & 0 & 0 & 0 & \frac{3}{2}k_{zz}r_s^2+3k_{xx}h^2-m_u gh-m_s gh_s & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{3}{\sqrt{2}}\sqrt{k_{xx}^2+k_{yy}^2}r_s^2+3\frac{GJ_f}{l_f} \end{bmatrix}$$

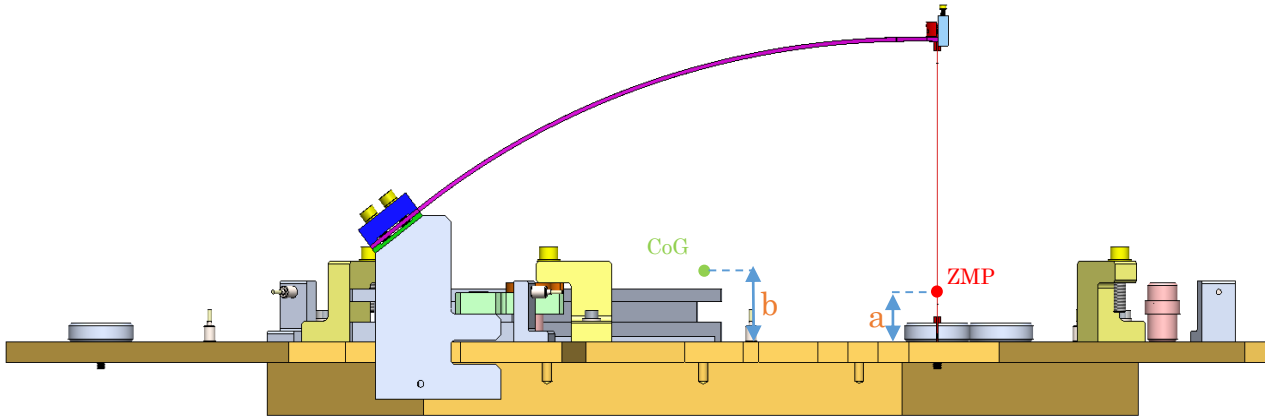
ZMP = 3.4117mm

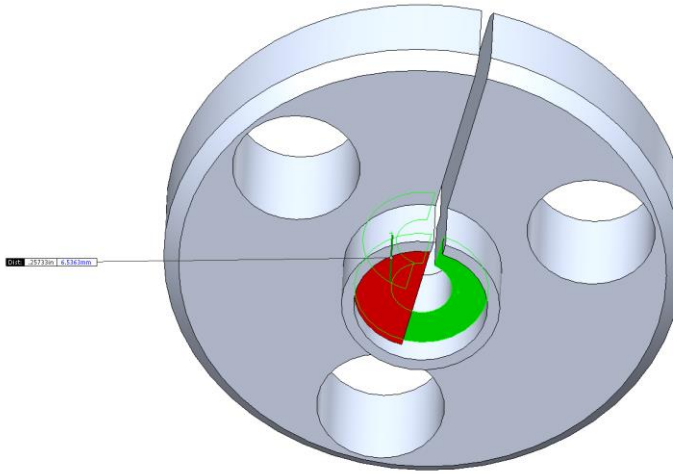
$$M\ddot{U}+KU=0$$

Last Version

- Proper calculation







$a = 10.1596 + 3.4117 = 13.5713$ mm

$b = 7.035$ mm

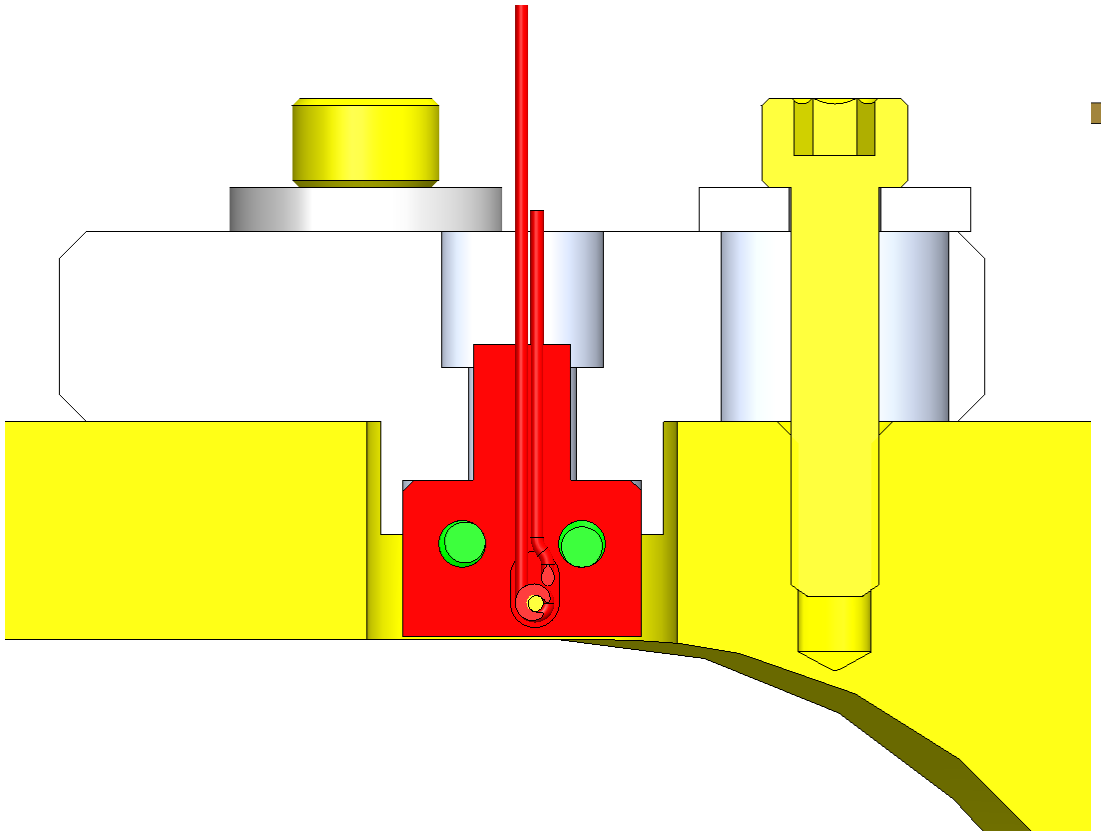
$h_f = b - a = -6.5363$ mm

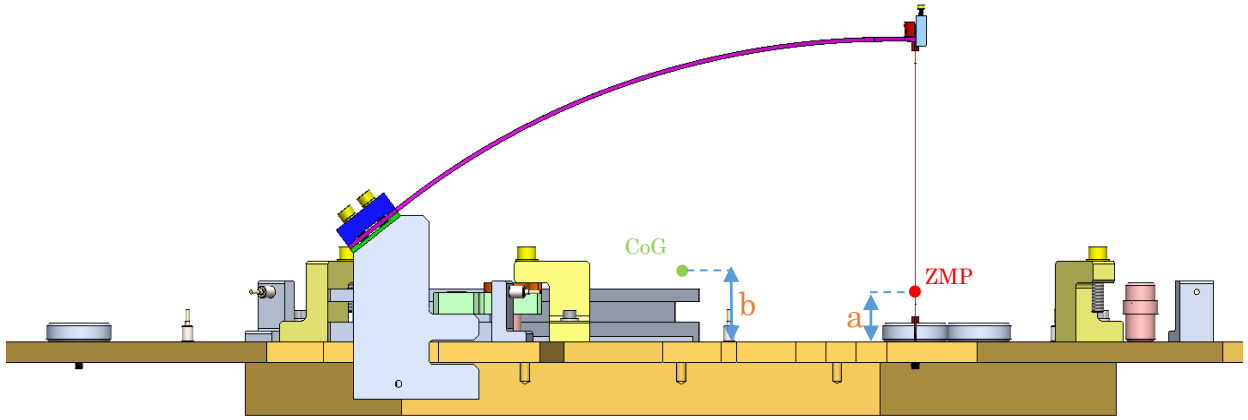
ZMP = 3.4117mm

$$M\ddot{U} + KU = 0$$

Last Version

- Proper calculation





a = 10.1596 + 3.4117 = 13.5713 mm

b = 7.035 mm

h_f= b – a = -6.5363 mm

ZMP = 3.4117mm

$$M\ddot{U} + KU = 0$$

Last Version

- Proper calculation

$$M\ddot{U} + KU = 0$$

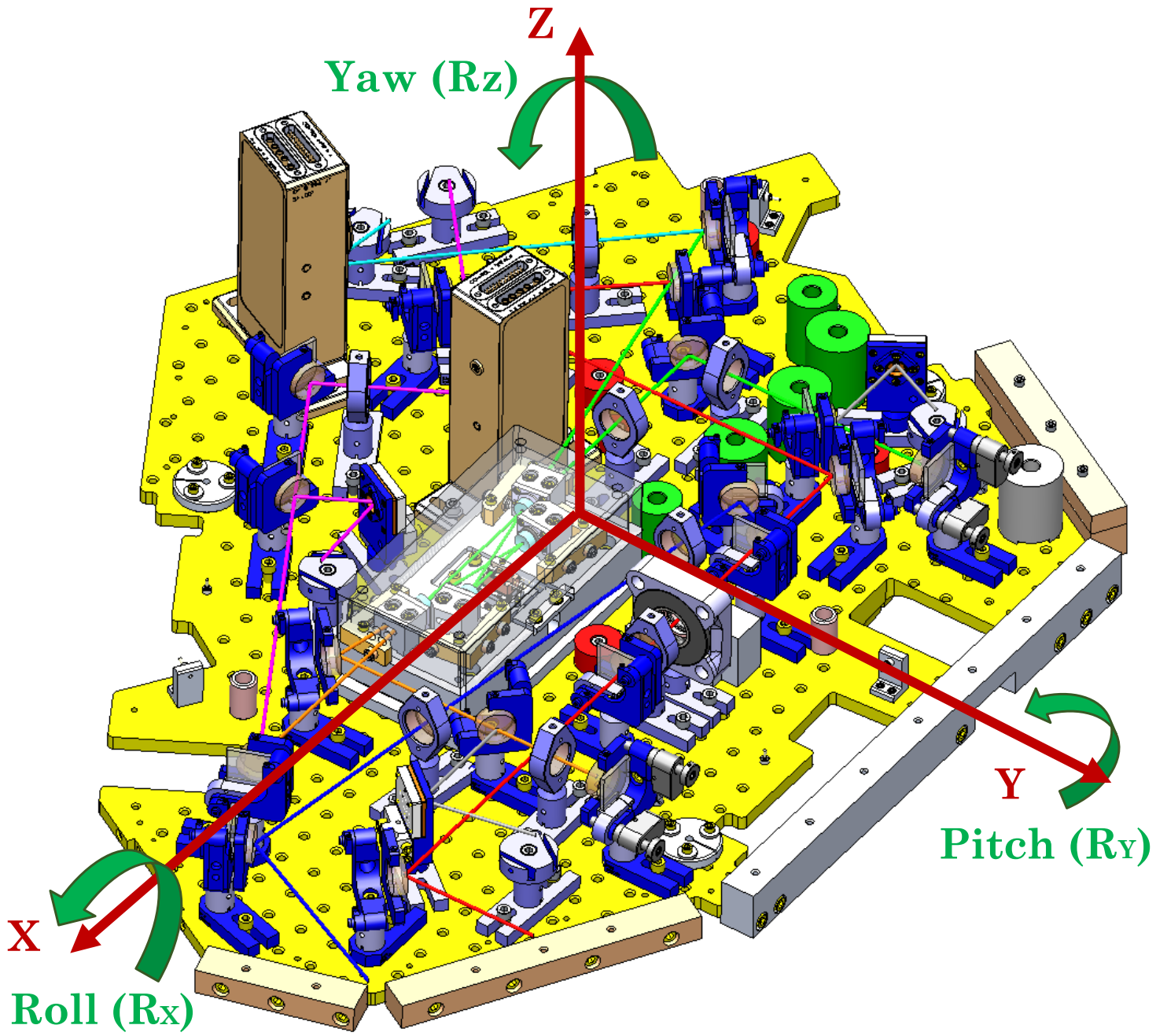
$$\ddot{U} + [M^{-1}K]U = 0$$

$$\omega^2 = eigenvalue(M^{-1}K)$$

$$f = \frac{2}{2\pi}\sqrt{eigenvalue(M^{-1}K)}$$

```
Natural_frequencies =

    1.4175         0         0         0         0         0
         0    1.6222         0         0         0         0
         0         0    1.4190         0         0         0
         0         0         0    2.0666         0         0
         0         0         0         0    1.6277         0
         0         0         0         0         0    1.6114


Mode_shapes =

   -0.8585    0.0215         0         0         0         0
         0         0    0.9667   -0.0059         0         0
         0         0         0         0    1.0000         0
         0         0   -0.2561   -1.0000         0         0
    0.5129    0.9998         0         0         0         0
         0         0         0         0         0    1.0000


Response_variables =

X
Y
Z
RX
RY
RZ
```

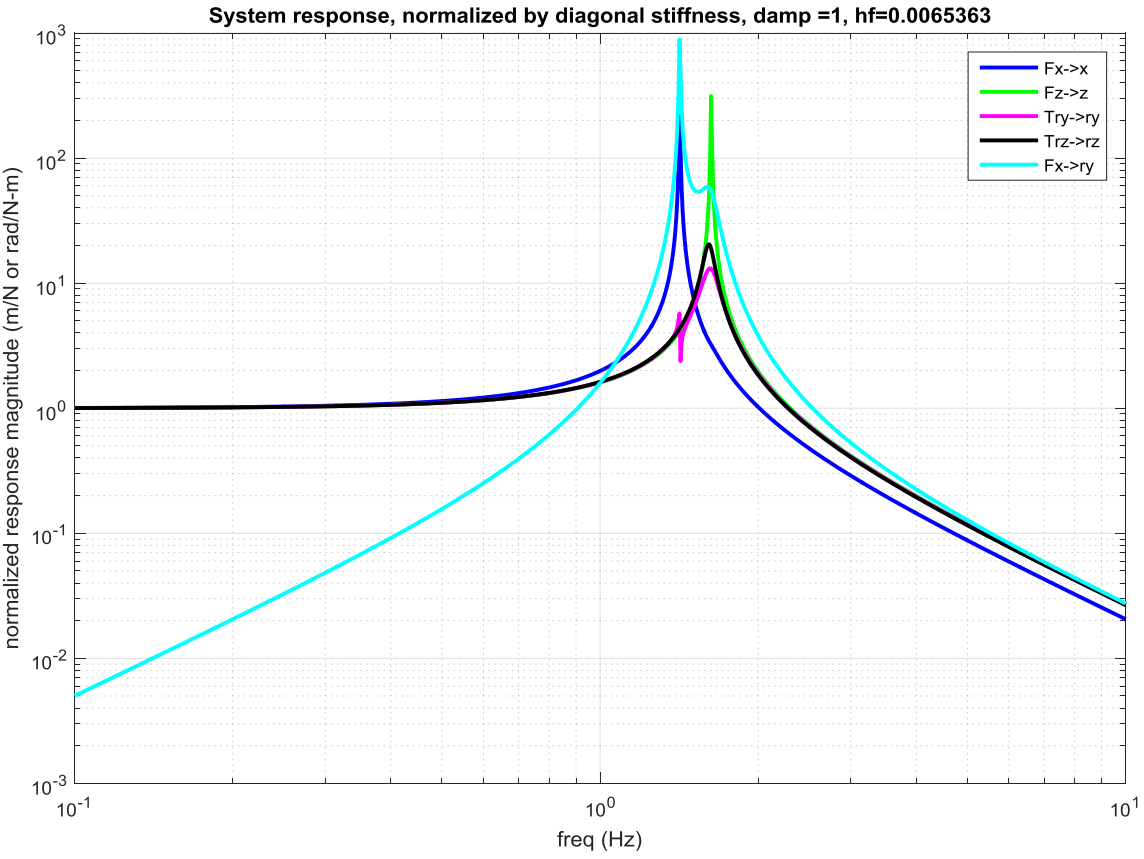
AssemblyFrequencies.m

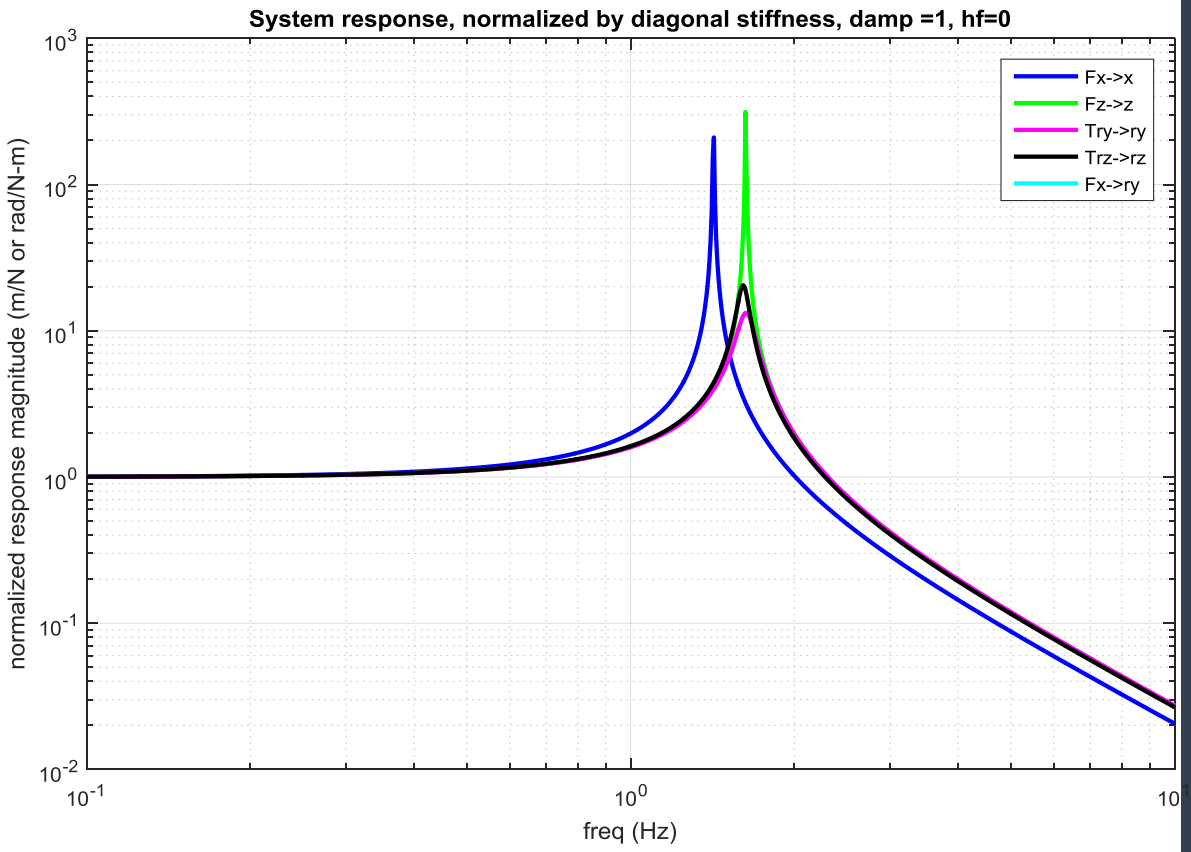


	FREQ. (Hz)
X	1.4175
Y	1.4190
Z	1.6277
Roll	2.0666
Pitch	1.6222
Yaw	1.6114

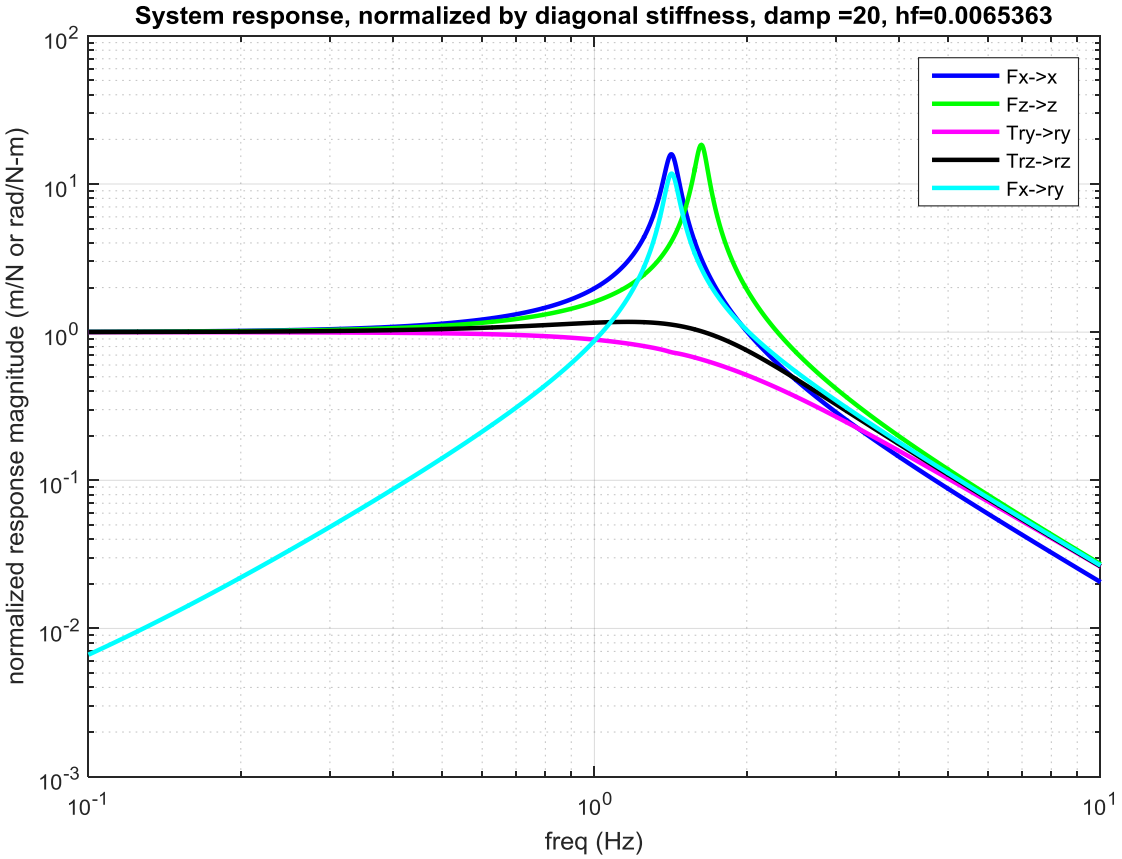
	FREQ. (Hz)	Formulated	Difference %
X	1.4175	1.4203	-0.2
Y	1.4190	1.4203	-0.1
Z	1.6277	1.6277	0.0
Roll	2.0666	2.0825	-0.8
Pitch	1.6222	1.6329	-0.7
Yaw	1.6114	1.6114	0.0

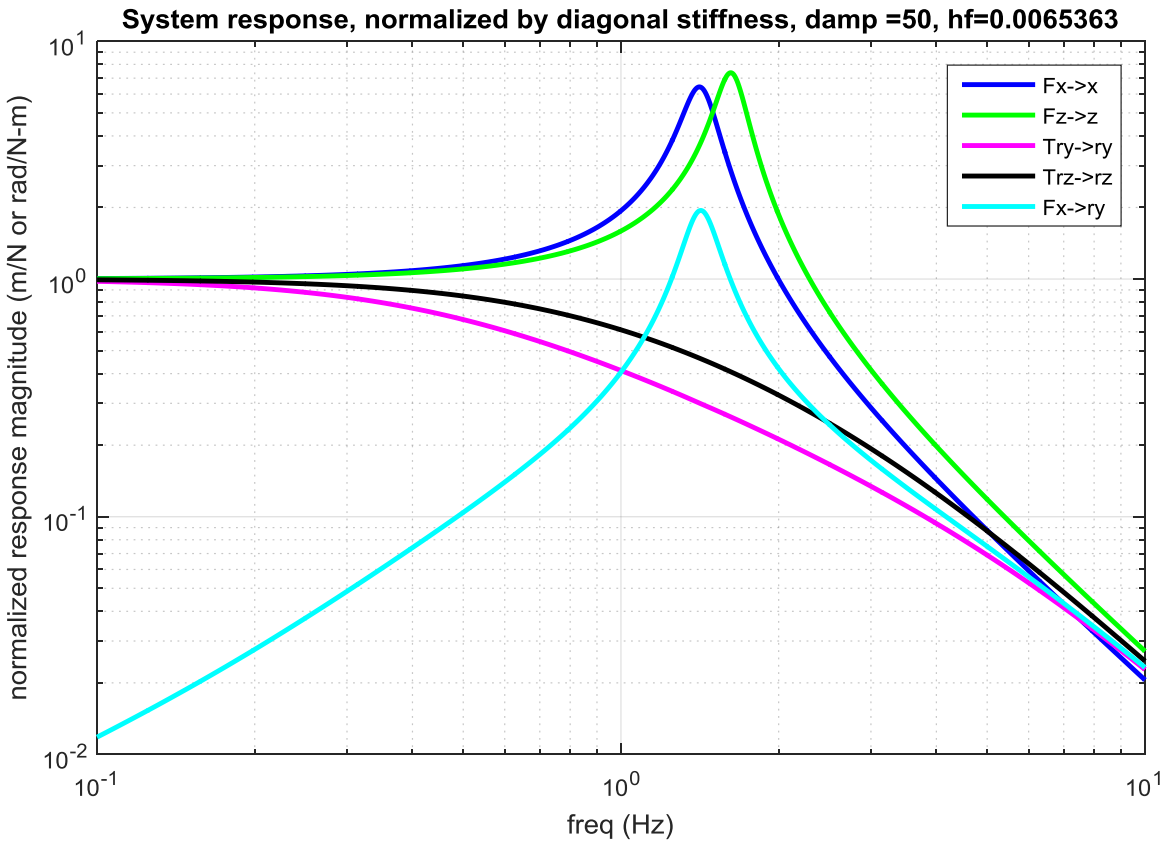
Excitation response





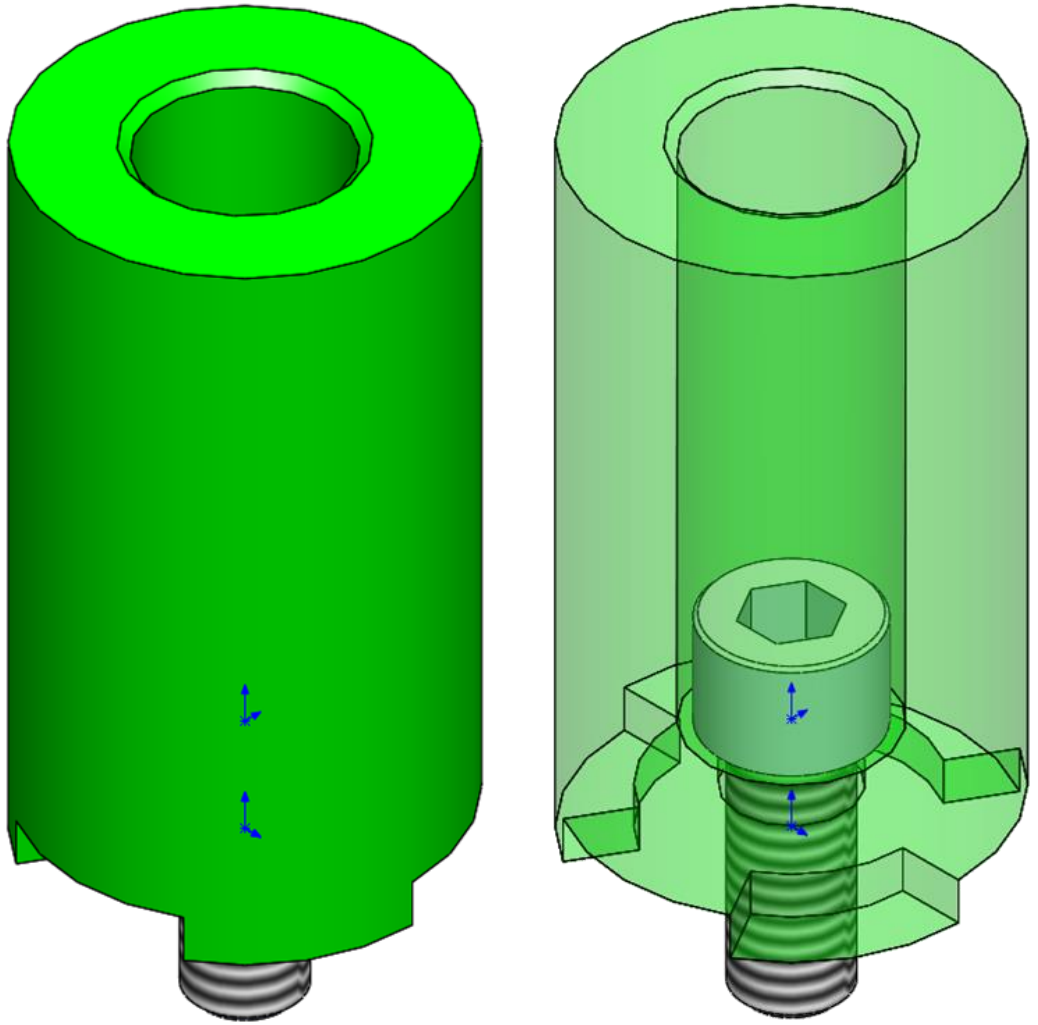
Excitation response





Balancing Masses

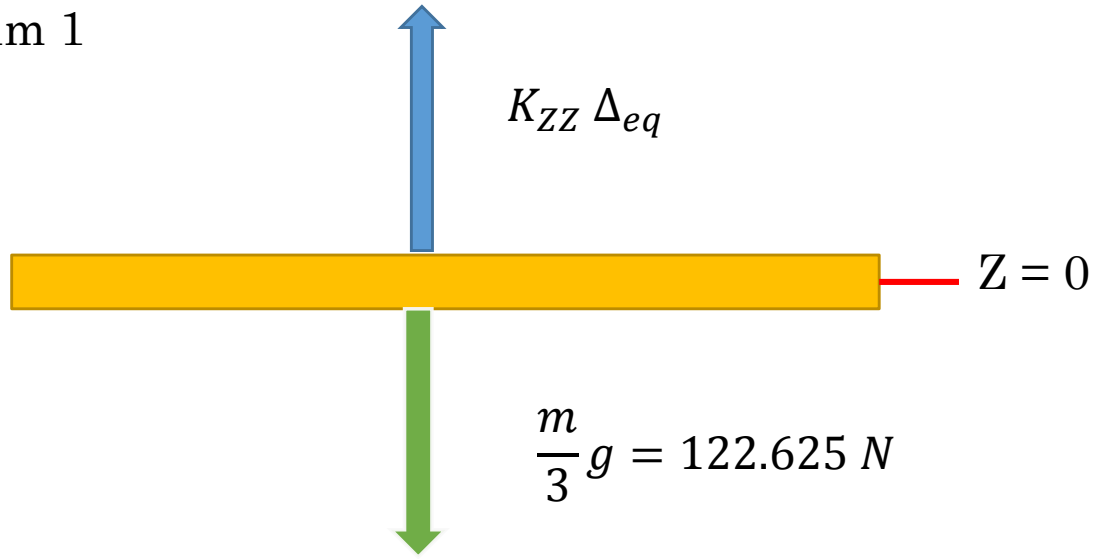
- Masses in a high range of values
  - 25g
  - 53g
  - 76g
  - 100g (x2)
  - 146g
  - 200g
  - 245g
  - 252g
  - 302g
  - 402g
  - 413g
  - 507g
  - 610g
- Maximum height = 2 in (-0.5in beam plane)
- Holo-Kromme SHCS ¼”-20 x 0.625: 6g



Balancing Masses

- Minimum Mass Range Calculation
  - "Perfect" alignment without extra mass addition/removal

Equilibrium 1 blade



$$K_{zz}\,\Delta_{eq} = \frac{m}{3}g$$

$$\Delta_{eq} = \frac{\frac{m}{3}g}{K_{zz}}$$

$$K_{zz} = 1255.1\frac{N}{m}$$

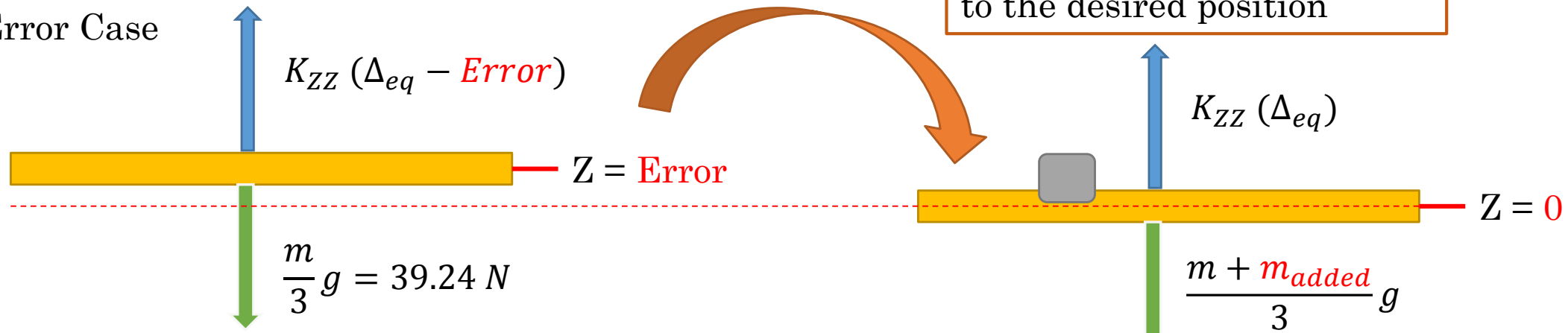
$$m = 36\ kg$$

$$\Delta_{eq} = 93.79\ \text{mm}$$

Balancing Masses

- Minimum Mass Range Calculation
  - Case where height adjustment is required

Error Case



NOTE: Additional mass is added to adjust the height to the desired position

$$K_{zz}(\Delta_{eq} - Error) = \frac{m}{3}g$$

$$m_{added} = \frac{K_{ZZ}\ Error}{g}$$

$$K_{zz}\ \Delta_{eq} = \frac{m + m_{added}}{3}g$$

Error (mm)	0.01	0.05	0.1	0.15	0.2	0.25	0.5	0.75	1	1.5	2	3
Mass to be added (g)	1.28	6.40	12.79	19.19	25.59	31.47	63.97	95.96	127.94	191.91	255.88	383.82

NOTE: The final balancing will be made using screws and washers as they are about the desired weight